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Article

Synergistic Improvement of Production, Economic Return and Sustainability in the Tea Industry through Ecological Pest Management

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Abstract: The use of ecological principles to manage plant pests has attracted renewed attention, but our knowledge related to the contributions of ecological pest management to social and natural sustainability is fragmented. In this study, we compared the performance and resilience of tea production and the economic benefits of tea ecological management (TEM) and tea conventional management (TCM). We show that TEM significantly improved tea biomass and quality, nutritional efficiency, and beneficial insects, but reduced seasonal variation. As a result, economic return increased by $8045/ha in the TEM mode compared to $6064/ha in the TCM mode. These results confirm that TEM is a promising production mode that can reconcile the conflict between the immediate and long-term service of agriculture. However, environmental improvements associated with organic pest control benefit society, and the government should provide adequate financial support to promote the production system.

Keywords: pest management; eco-economic analysis; tea production; ecological resilience; sustainable agriculture

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1. Introduction

Pest management systems can have serious impacts on socioeconomic and ecological functions [1]. In modern agriculture, pests, including harmful insects and infectious microbes, are mainly controlled by pesticide applications [2]. While improving crop yield and quality thus immediately benefits farmers, the widespread application of these chemical reagents in time and space has tremendously damaged agricultural ecosystems, such as promoting pest evolution [3] and reducing biodiversity [4]. The deterioration of ecosystems may eclipse the immediate economic benefits associated with the chemical control of pests, reducing crop resistance to future biotic and abiotic stress and thereby greatly affecting social and natural sustainability [5,6]. Indeed, despite continued innovation and the increased spraying of various chemical agents, pest outbreaks have occurred more frequently in many agricultural ecosystems [7], reducing the production potential of major crops by nearly half [8–10]. To make matters worse, in some cases, pest outbreaks become more rampant as control efforts increase [11].

As an alternative to chemical agents, the use of ecological principles to manage agricultural pests has received renewed theoretical and empirical attention. It can be achieved in a variety of ways, such as increasing crop and practical diversification, regulating crop density, and using green manures and biological management [12] to foster natural enemies and competitors of pests or to improve environments supporting the immunity development and stress tolerance of crops [13,14]. Among them, crop diversification is considered a promising practice that can regenerate balanced biotic and abiotic interactions by enhancing key elements of biodiversity, increasing resource efficiency, reducing pest prevalence, and stabilizing plant function [15–18]. It is agreed that a major factor contributing to the high risk of crop damage by pests in managed agricultural systems and semi-managed forestry systems is intensification and monoculture. On the other hand, plant pests in natural systems are placed in a context of ecological and environmental heterogeneity, which tempers the demographics and evolution of associated pests [18–21] and contributes to the rare documentation of rampant pests in nature. In infectious agricultural diseases, ecological management such as through crop diversification increases crop production and stress resistance through the negative regulation of pathogen reproduction [22], transmission [23], and evolution [24–27] and the positive regulation of soil microbe communities and nutrient availability [15,20]. Similar phenomena were observed in plant–insect interactions [28].

However, our understanding of the role of ecological pest management on social and natural sustainability is fragmented. Most empirical research on this topic has focused on the impact of such a management strategy on some elements of sustainable development, rather than on the synergistic social and natural services it provides. There is concern that ecological pest management alone may not be enough to guarantee control efficiency, production, and immediate economic return [29]. This uncertainty clouds the enthusiasm of farmers to adopt the eco-friendly pest management strategy. On the other hand, policymakers are also unclear about the potential economic benefits that the management provides to society, which are important for setting monetary and/or other relevant incentives to promote the practice.

Tea (*Camellia sinensis*) is an important beverage and high-value crop, contributing 42 billion dollars to the world economy every year [30]. China is one of the main regions in the tea industry, creating millions of jobs in rural areas [31]. Leafhopper, *Empoasca onukii Matsuda* (Hemiptera: Cicadellidae), is one of the major biotic constraints in the tea industry and can cause up to 10~15% of economic losses [32]. Although spiders, *Theridonn octomacutatum Boes. et str.* (Arcneida: Theridum), the natural enemies of the leafhopper, are ubiquitous in many tea gardens and can greatly reduce leafhopper density [33,34], this pest is still mainly controlled by pesticide spraying, but the effectiveness of this management strategy is questioned. In addition to increasing production costs, pesticide residues and ecological damage such as reduced pesticide efficacy, population density of natural enemies, and biodiversity have become the main concerns in the management of tea pests by chemical reagents. Pesticide residues greatly reduce tea quality and marketing price. Reduced pesticide efficacy increases the cost of achieving a similar level of pest control, while reduced biodiversity may generate negative externalities that can lead to long-term damage to tea production and other ecological services. Tea, as a perennial crop, can be harvested continuously after establishment. However, after several years of consecutive harvests, yields and quality tend to decline, severely impacting the economic sustainability of tea farmers. Indeed, local farmers are increasingly encountering trade barriers due to high levels of pesticide residues. As a result, the farmers and government are increasingly interested in managing tea pests, nourishing natural enemies, and improving the ecological services of tea gardens. Furthermore, increasing the awareness of environmental safety and natural resource depletion also requires tea farmers to seek more sustainable forms of tea production [35]. These challenges call for the replacement of traditional pest management strategies with more sustainable strategies that can serve the immediate and long-term economic needs of tea farmers and society, such as ecological pest management. TEM is based on keeping a healthy agro-ecosystem of tea populations using ecological solutions, including the deployment of tea population density, diversified trees, grasses, and green manures, and the practice of organic fertilization, biological pest management, and alternating harvests [12].

In this study, tea production data collected from tea plantations in Anxi county with two different pest management modes over three consecutive years were analyzed in parallel with economic and ecological effects to develop a more profitable, effective, and eco-friendly tea production strategy. The specific goals of this study were to (1) compare the density of tea pests and their natural enemy between ecological and conventional management systems, (2) evaluate the immediate economic and long-term ecological impacts of different pest management systems, and (3) provide policy and practical advice to stakeholders such as the government and farmers in sustainable agricultural production.

2. Materials and Methods

2.1. Experimental Site

The experimental sites were located in Taozhou (25°22′ N, 117°45′ E), Huqiu (24°56′ N, 117°22′ E), and Longjuan (24°57′ N, 117°49′ E) in Anxi county, southern Fujian, China (Figure 1). The county is one of the main Wulong tea production areas in China. It has a humid, subtropical monsoon climate with an average annual rainfall of ~1700 mm, an effective accumulated temperature of 4801 °C, and an average daily temperature of 21.9 °C [36,37]. These climatic and soil conditions are conducive to tea plants. Insect pests, particularly the leafhopper, are the main biotic stress in the Wulong tea industry.

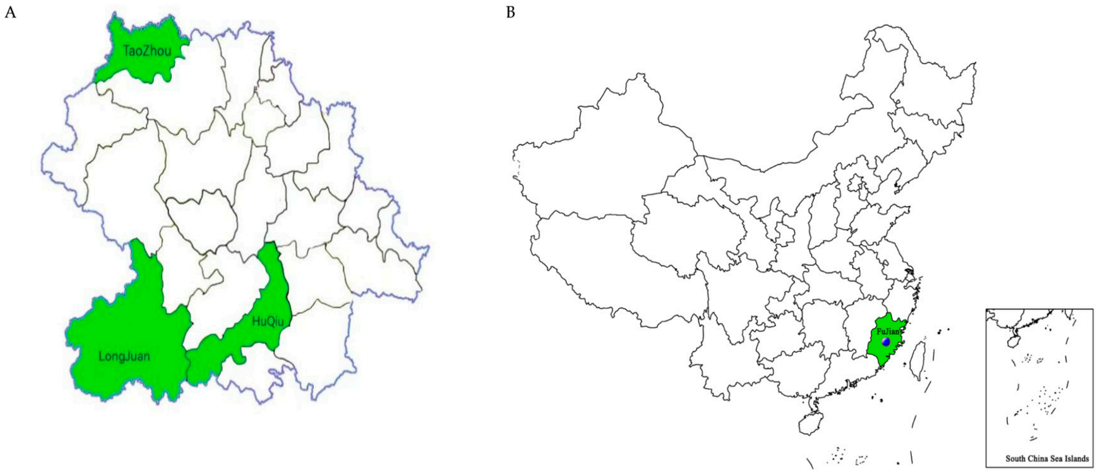

Figure 1. The map showing the geographical distribution of the three experimental sites located in Anxi county, China. (**A**) Location of the experimental sites in Anxi county. (**B**) Location of Anxi county in China. Adobe Illustrator Artwork 17.0 software was used to create the map.

2.2. Experimental Design and Management

The tea plantations have been established in these towns for many years. They were managed either with an ecological (TEM) or a conventional approach (TCM). The plantation sizes for TEM and TCM ranged from 50 to 150 and 15 to 20 ha, respectively. In each town, the two types of plantations were separated by ~1 km of woodland. TCM plantations were monoculture, with high population density and short tea varieties. In TCM mode, compound fertilizers (N:P:K = 16:16:16, total nutrient $\geq$ 48%) from Anhui Liuguo Chemical Co., Ltd., Tongling, China were applied three times at the rate of 1500 kg/ha each year. Weeds were controlled twice a year with herbicides, and pesticides were used every 8 days to control pests, continuing from tea sprouting to picking. The teas were picked manually three times a year. In contrast, the TEM plantations were diversified by patchily planting tall tea varieties with pasture grass and other trees, alternating harvest times, or reducing the population density of tea trees, as described previously [10]. Soil nutrients in the TEM plantations were provided by intercropping with green crops such as soybeans in addition to 1500 kg/ha of humic acid fertilizer (organic matter 33.37%, N 2.7–3.4%, P 4.8–6.5%, K 5.4–6.7%, M 1.6–1.9%, Fujian Haoyujia Biotech. Co., Ltd., Nanping, China). Weeding was performed manually as needed. Due to the green crops, the weed density in

TEM plantations was largely reduced, and only tall weeds were required to be manually removed. Pests were controlled agronomically and/or biologically, such as by trimming injured branches, spraying marine, and tending to natural enemies. The teas were picked manually twice a year.

2.3. Data Collection and Parameter Estimates

Field tea data were collected twice a year for three years (2016–2018), resulting in a total of six data points. Hereafter, they were defined as T1 to T6, respectively. Each time, three fields were selected randomly from a plantation, and data from each field were collected from five sites with one site in the center of the unit and two sites each at the ends of the field [16,17].

The total number of leafhoppers, the main insect pest of tea plants, and spiders, their natural enemy, were recorded in spring and autumn (30 April–4 May 2016; 20–25 September 2016; 3–8 May 2017; 30 September–4 October 2017; 1–5 May 2018; 1–4 October 2018). The numbers of leafhoppers and spiders were determined by the plant-flapping (on the roots) approach using a porcelain plate (40 cm × 30 cm) coated with a layer of engine oil, as described previously [38,39]. To catch the insects, porcelain plates inserted obliquely near the roots of tea trees were tapped three times with a hand or a stick. The numbers of the insects were determined from 20 porcelain plates at each of the five sampling sites, resulting in 100 plates from a field or 300 plates from a plantation.

Dry weight, fresh weight, and dry matter content (dry weight/fresh weight × 100) were recorded in spring and autumn (1–7 May 2016; 24 September–3 October 2016; 3–7 May 2017; 1–3 October 2017; 30 April–2 May 2018; 1–7 October 2018). To generate these data, five sampling points were selected from each plantation, with a 1 dm^2 iron frame. Fresh leaves were processed, sealed, and stored. There were 180 samples of dry leaves, and each sample weighed 600 g. Caffeine, polyphenol, and amino acid contents were determined from 600 g dry leaves according to GB/T 8312.2002, GB/T 8313-2008, and the ninhydrin solution chromo method, respectively [40,41].

To investigate the effect of the management mode on soil physicochemical properties, 300 g soil samples were collected from the topsoil layer (~5 cm) at five plum blossom sites on 4 December 2015, 12 December 2016, 4 December, and 12 August 2018 (hereafter defined as T1 to T4, respectively) with a total of 120 samples. pH values were measured by the potentiometric method. Soil organic matter (SOM) was determined by potassium dichromate oxidation spectrophotometry. Available nitrogen was determined by the soil alkali diffusion method. Available phosphorus was determined by the Olsen method, and available potassium was determined by atomic absorption spectrophotometry [42–45].

Unlike many crops, tea leaves must go through many processing steps before reaching the market. Biological mass such as leaf dry weight collected during harvest cannot fully reflect the marketing yield of tea production. For this reason, the marketing yield was generated from a semi-structured survey, as previously described, and a total of 180 tea farmers in the experimental county were interviewed. Yield stability was evaluated by Wricke's ecovalence (W_i^2) and the Sustainable Yield Index (SYI). Yields with a lower W_i^2 or SYI were more stable on spatiotemporal scales. W_i^2 and SYI were calculated using the following formulas [46,47]:

$$W_i^2 = \sum_{j=1}^{q} \left(X_{ij} - m_i - m_j - m\right)^2 \tag{1}$$

where X_{ij} is the yield of treatment i at time j (i = 0, TCM; i = 1, TEM); m_i is the average yield of treatment i over the experimental time; m_j is the average yield of all treatments at time j; and m is the average yield of all treatments over the experimental time. W_i^2 is 0 when there is no spatiotemporal variation in parameter measurement.

$$SYI = \left(\overline{Y} - \delta\right)/Y_{max} \tag{2}$$

where $\overline{Y}$ is the average yield of the treatment over the experimental time, δ is the standard deviation of the yield of all treatments over the experimental time, and Y_{max} is the maximum yield of the treatment over the experimental time. SYI ranges between 0 and 1.

Economic analyses were also performed using data generated from the survey. Marketing price, government subsidy, and production costs associated with land rent, consumable materials (e.g., fertilizers, pesticides), and labor (seedling, weeding, fertilizing, managing, harvesting, etc.) were calculated by farm gate price, actual government support, and expenses [15,48]. The data about the income fluctuation and the indicators of tea farmers' management intentions were collected through a semi-structured interview schedule, as described previously [49]. The income satisfactory index was scored as follows: 2 = increased, 1 = no change, and 0 = decreased. The willingness to continue farming was scored as follows: 1 = continue and 0 = do not continue.

Revenue (R), profit (NP), and profit margin (PM) were calculated using the following formulas [13]:

$$\mathrm{R} = \mathrm{G} \times \mathrm{P} + \mathrm{S} \quad (3)$$

$$\mathrm{NP} = \mathrm{R} - \mathrm{C} \quad (4)$$

$$\mathrm{PM} = (\mathrm{NP}/\mathrm{C}) \quad (5)$$

where G, P, S, and C are the tea production, tea marketing price, government subsidy, and total production cost, which were collected through the semi-structured interview schedule.

2.4. Statistical Analysis

A one-way ANOVA was performed to evaluate the effects of management mode on biological, ecological, and economic traits including leafhoppers, spiders, the relative abundance of spiders to leafhoppers, production indices (dry matter weight, fresh tea weight, and specific gravity), quality indices (the contents of polyphenols, caffeine, and amino acids), soil properties (pH value, the contents of SOM, N, P, K), and economic indices (NP, PM, income satisfactory index and willingness to manage tea plantation). These statistical analyses were conducted using IBM SPSS 19.0 software (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Effects of Management Mode on Pest Control

The ANOVA revealed a significant effect of management mode on mean spider density and its relative abundance to leafhoppers ($p < 0.05$). Spider density and its relative abundance to leafhoppers were significantly higher in the tea ecological management (TEM) mode than in the tea conventional management (TCM) mode (Table 1 and Figure 2). Although TEM had a lower leafhopper density than TCM, the difference between the two modes was not significant. Spider density gradually increased over time in the TEM mode, but such a trend was not found in the TCM mode (Figure 2). Leafhopper density oscillated and reduced over time in both modes. The relative abundance of spiders to leafhoppers increased over time in both modes, but this trend of continuous improvement was more pronounced in the TEM mode than in the TCM mode (Figure 2).

Table 1. The effects of management mode on the leafhopper pest and its enemy.

Mode	Spider	Leafhopper	The Relative Abundance of Spiders to Leafhoppers %
TCM	21 ± 14 a	119 ± 83 a	21.13 ± 16.29 b
TEM	30 ± 11 b	88 ± 75 b	33.91 ± 19.83 a
P	0.000	0.011	0.000

Note: The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$).

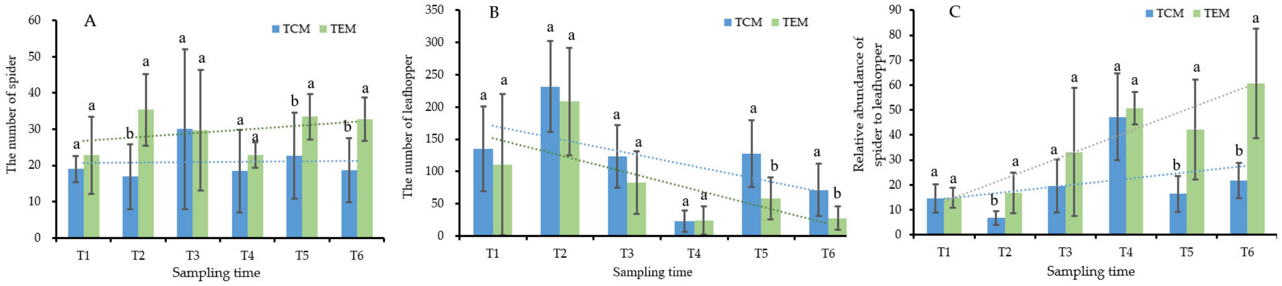

Figure 2. The effects of management mode on the leafhopper pest and its enemy. The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$). (**A**) The number of spiders, (**B**) the number of leafhoppers, and (**C**) the relative abundance of spiders to leafhoppers. TCM = tea conventional management; TEM = tea ecological management. T1 = spring 2016; T2 = autumn 2016; T3 = spring 2017; T4 = autumn 2017; T5 = spring 2018; T6 = autumn 2018.

3.2. Effects of Management Mode on the Soil Physicochemical Properties

Soil physicochemical properties, including the contents of organic matter (SOM), available nitrogen (N), available phosphorus (P), and available potassium (K), remained relatively constant over the sampling times through the growing season in both modes (Figure 3). For TCM, the pH value also did not change over the sampling times, but for TEM it slowly increased. The soil pH values and the contents of available K for TEM were higher than those for TCM, but the contents of SOM, available N, and available P were not different between the two modes (Table 2).

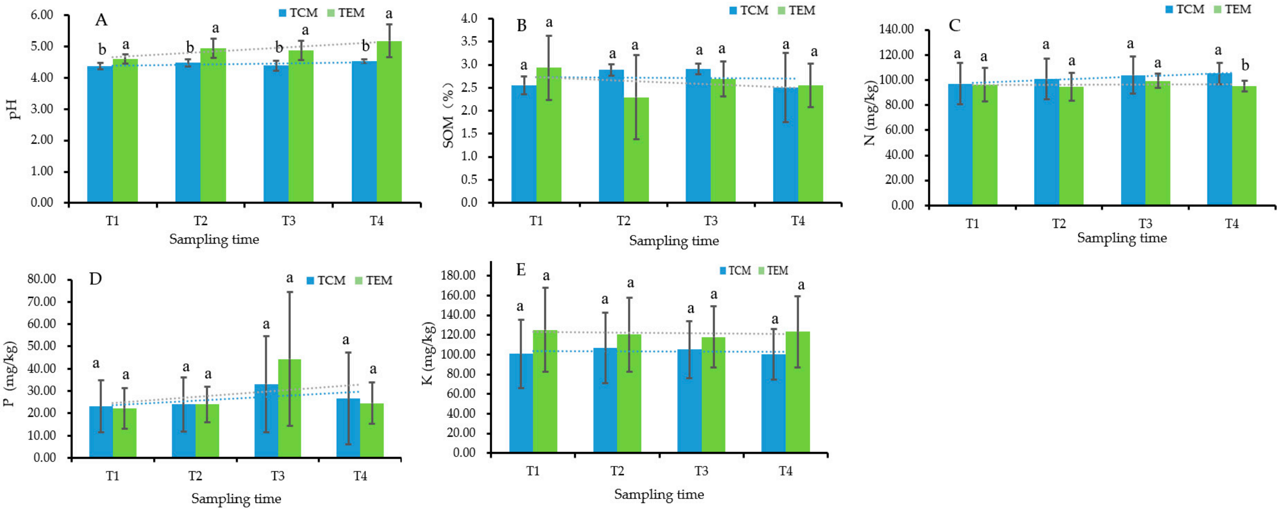

Figure 3. The effects of management mode on the soil physicochemical properties. The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$). (**A**) pH value, (**B**) soil organic matter (SOM), (**C**) available nitrogen content (N), (**D**) available phosphorus (P) content, and (**E**) available potassium (K) level. TCM = tea conventional management; TEM = tea ecological management. T1 = winter 2015; T2 = winter 2016; T3 = winter 2017; T4 = winter 2018.

Table 2. The effects of management mode on the soil physicochemical properties.

Mode	pH Value	SOM %	N mg/kg	P mg/kg	K mg/kg
TCM	4.45 ± 0.13 b	2.71 ± 0.44 a	101.81 ± 15.18 a	26.69 ± 17.47 a	102.79 ± 31.72 b
TEM	4.90 ± 0.39 a	2.62 ± 0.69 a	96.32 ± 9.78 b	28.76 ± 19.44 a	121.63 ± 37.83 a
P	0.000	0.368	0.017	0.541	0.004

Note: The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$).

3.3. Formatting of Mathematical Components

The ANOVA also revealed that the management mode significantly affected fresh weight, yield, SYI, and amino acid content (Tables 3 and 4). TEM resulted in higher fresh weight, *SYI*, and amino acid content but lower yield than TCM. TEM also yielded higher dry matter, polyphenol, and caffeine contents than TCM, but the difference between the two modes was not significant. The specific gravity of dry tea and W_i^2 were also not affected by management mode. In general, tea productivity remained constant over time in both modes (Figure 4). For tea quality indices, polyphenol and caffeine contents increased slightly over time in both modes, but the variation was more pronounced for TEM (Figure 5). On the other hand, amino acid content slightly decreased over time, but the trend is less pronounced in the TEM mode.

Table 3. The effects of management mode on the tea production indices.

Mode	Fresh Weight (g/dm^2)	Dry Weigh (g/dm^2)	Specific Gravity (%)	Yield (Kg/ha)	W_i^2	*SYI*
TCM	38.89 ± 15.06 b	10.66 ± 3.71 b	28.03 ± 4.13 a	787.81 ± 6.67 b	953.66 ± 206.11 a	0.32 ± 0.07 b
TEM	45.03 ± 14.96 a	12.17 ± 4.11 a	27.80 ± 5.19 a	616.50 ± 19.45 a	688.98 ± 353.11 a	0.38 ± 0.04 a
P	0.007	0.010	0.740	0.000	0.070	0.043

Note: The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$).

Table 4. The effects of management mode on the tea quality indices.

Mode	Tea Polyphenols Content%	Caffeine Content %	Amino Acid Content %
TCM	14.98 ± 3.64 a	3.58 ± 0.54 a	1.72 ± 1.03 b
TEM	15.21 ± 8.59 a	3.75 ± 0.57 a	2.50 ± 1.22 a
P	0.817	0.065	0.000

Note: The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$).

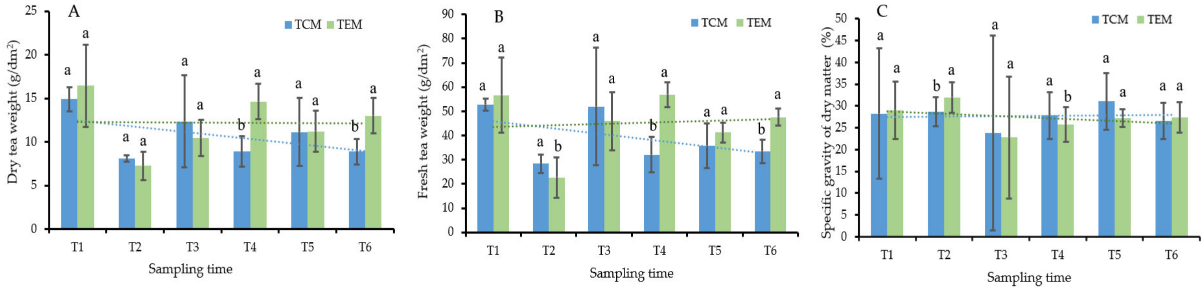

Figure 4. The effects of management mode on the tea production indices. The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$). (**A**) Dry tea weight, (**B**) fresh tea weight, and (**C**) specific gravity of dry matter. TCM= tea conventional management; TEM = tea ecological management. T1 = spring 2016; T2 = autumn 2016; T3 = spring 2017; T4 = autumn 2017; T5 = spring 2018; T6 = autumn 2018.

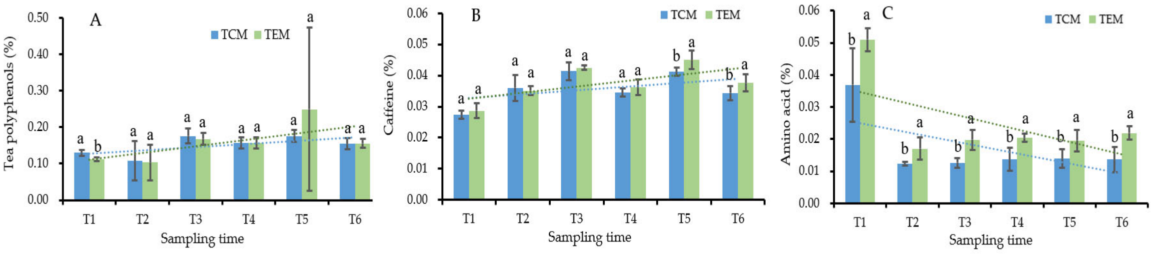

Figure 5. The effects of management mode on the tea quality indices. The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$). (**A**) Tea polyphenols, (**B**) caffeine, and (**C**) amino acids. TCM = tea conventional management; TEM = tea ecological management. T1 = spring 2016; T2 = autumn 2016; T3 = spring 2017; T4 = autumn 2017; T5 = spring 2018; T6 = autumn 2018.

3.4. Effects of Management Mode on Economic Benefits

Management mode significantly influenced production cost, profit, revenue, profit margin, and willingness to manage tea plantation but did not affect the income volatility index, and TEM performed significantly or marginally better than TCM (Table 5). For TEM, the production cost gradually declined while the profits, especially the profit margin of production, increased over time (Figure 6). On the other hand, the cost gradually increased while the profits and profit margin of production gradually reduced over time in the TCM mode. The revenue in both modes did not change obviously over time.

Table 5. The effects of management mode on the tea quality indices.

Mode	Cost USD/ha	Revenue USD/ha	Profit USD/ha	Profit Margin	Income Volatility Index	Willingness to Manage Tea Plantation
TCM	7836 ± 248 a	13,905 ± 115 b	6064 ± 260 b	0.78 ± 0.06 b	0.2593 ± 0.44 a	0.1852 ± 0.39 b
TEM	6549 ± 729 b	14,485 ± 449 a	8045 ± 796 a	1.27 ± 0.23 a	1.6296 ± 0.56 a	0.9444 ± 0.23 a
P	0.000	0.000	0.000	0.000	0.140	0.024

Note: The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$).

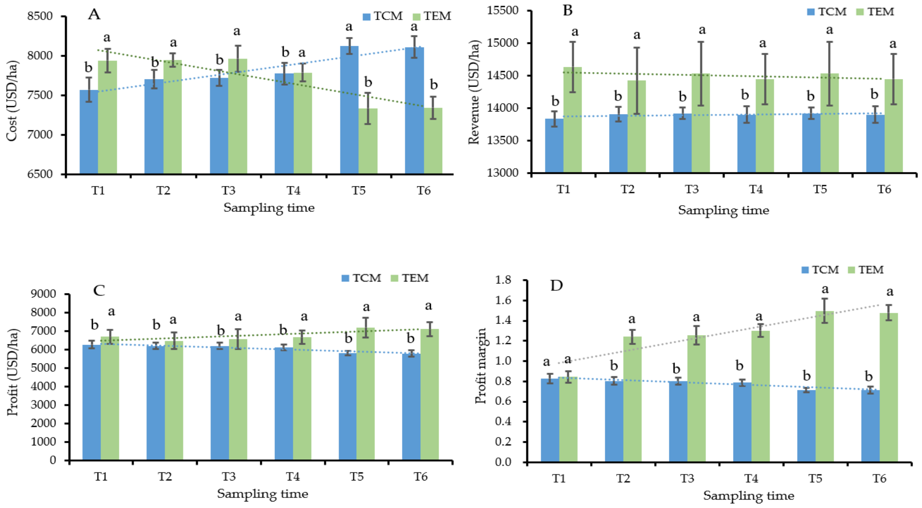

Figure 6. The effects of management mode on the economic benefits. The different letters labeled in columns are significantly different according to Duncan's test ($p < 0.05$). (**A**) Cost, (**B**) revenue, (**C**) profit, and (**D**) profit margin. TCM = tea conventional management; TEM = tea ecological management. T1 = spring 2016; T2 = autumn 2016; T3 = spring 2017; T4 = autumn 2017; T5 = spring 2018; T6 = autumn 2018.4.

4. Discussion

Agriculture provides a variety of services to human society by producing food, fiber, and medical materials and preserving ecological functions and natural landscapes. Sustainable agriculture aims to provide these services to meet the needs of both current and future socioeconomic development [50]. To achieve this, agricultural practices should balance the direct, short-term socioeconomic impacts related to crop production, food security, and farmer income with the indirect, long-term social and natural impacts related to ecological resilience, biodiversity, and soil fertility. These multiple services are often difficult to reconcile in current agricultural production concepts, which usually seek the single target of high yields supported by high energy and chemical inputs but largely overlook the documented damages on ecological function and resilience [51]. Our findings indicate that these multiple agricultural services can be coordinated largely through ecological pest management in the tea production system. Compared with TCM (tea conventional management), TEM (tea ecological management) reduced pest (leafhopper) density and production cost but at the same time improved physicochemical properties (Tables 2 and 3), resulting in increased overall profits despite a lower marketing yield. The indicators of tea quality such as caffeine, amino acids, and polyphenol contents [52] were also significantly improved by TEM. TCM plantations were applied with ~240 kg each of N, P, and K but only 45, 75, and 90 kg of N, P, and K were applied to TEM plantations, respectively. Despite the substantially lower mineral supplies in TEM plantations, the K content in the soils was higher than that in the TCM plantations, while the P content of the two modes was not different. With a few exceptions, there only appeared a significant difference in pH value for the soil physicochemical properties between the two modes (Figure 3), which can be supported by the previous study [53]. This means that pH value could be primarily taken into consideration in improving soil physicochemical properties and biological activity. The reduction in the leafhopper pests, the enhancement of tea quality, and the improvement of soil fertility may be related to the increase in beneficial organisms such as spiders, which otherwise could be killed by pesticides in TCM, together with improvements in nutrient efficiency and other ecological factors [54]. The intercropping and green manure in the TEM plantations can not only prevent the growth of weeds and the loss of nutrients and water but also increase the replenishment of other mineral elements [55–60]. The healthier natural ecosystem retained in TEM plantations allows tea plants to allocate more energy and resources for growth and immunity development [61]. These studies parallel previous results in insect and pathogen systems, showing that ecological management through diversifying habitats negatively regulates pest density, virulence, and evolution but positively regulates enemy demographics, soil nutrients, and microbial richness in tea and other crop ecosystems [20,61,62].

Agricultural sustainability can be measured by the spatial and temporal stability of production and profit [63,64]. Tea production and its income are strongly influenced by climatic and marketing conditions and therefore often fluctuate dramatically from year to year [61]. Nonetheless, TEM has significantly improved the yield and economic stability of tea production compared to TCM, as reflected in the smaller volatility indices and/or seasonal trends of yield and profit (Table 5, Figure 6). Production stability and stable or even reducing costs over time are especially important for smallholders who cannot afford additional investments and/or economic uncertainty, particularly in less developed countries [65]. The higher stability in the TEM mode may contribute to the lasting satisfaction and interest of farmers in adopting ecological pest management relative to traditional pest management for tea production in this area and other parts of the world such as India [66]. Due to this resilience, ecological production has been increasingly used to tackle issues that go beyond pest management to many other stresses, such as damage from extreme weather events, and has fortified agricultural economies in Asia–Pacific regions, generating a yearly benefit of US $15–20 billion [67].

Only the actual cost and income associated with tea production were included in the economic analyses. The positive externality to society and ecology was difficult to reflect in money and was not included in the numerical analyses of economic benefits associated with TEM. For example, improved nutrient efficiency implies that fewer fertilizers will be needed in the following seasons, reducing the monetary input for farmers to purchase chemicals and the social and natural resources to produce the chemicals [68]. Similarly, no or fewer pesticide residues in soils improve the function of ecosystems for future production, reducing investment in land restoration thereby generating additional economic benefits for farmers and society [69]. The exclusion of these positive externalities from the calculation of profit analysis undoubtedly underestimates the synergistic benefits of ecological production and affects the adoption of TEM. The government and farmers should monetize the ecological benefits when considering financial incentives and calculating production costs associated with the production system.

The leafhopper density of the two modes fluctuated greatly (Figure 2B), which could provide evidence for the view that leafhopper populations are significantly impacted by environmental factors including temperature, rainfall, humidity, sunshine, etc. [70,71]. TEM surprisingly reduces organic matter in the soil even despite continuous supplementation by green manure and humic acid fertilizer. A previous study showed that these tea plantations were rich in organic matter [72]. High organic matter in the soil combined with species diversification in TEM enriches microbial communities and diversity [69]. It has been revealed that microbial communities such as mycorrhizal fungi have considerable effects on the accumulation of soil organic matter through modifying nitrogen availability [18,73], and the rich and diverse microbial communities in TEM plantations enhance soil organic matter decomposition. Climatic effects on vegetation may also affect the subsurface and change microbial structures, thereby altering ecosystem biogeochemistry and accelerating organic decomposition in TEM plantations [74]. Therefore, it is necessary to consider fertilizer application in tea plantations along with the background fertility of soils, water management, and other practices.

5. Conclusions

In conclusion, our findings show that TEM can improve the performance and resilience of tea production, thereby increasing farmer income. These may be associated with an improved ecosystem that supports tea plant growth and immunity but is not beneficial to pests. The economic benefits of TEM in this study are certainly underestimated due to technical constraints, which prevent us from monetizing the ecological benefits but should be reflected in decisions related to financial incentives and costs. This technical shortcoming needs to be addressed in future studies.

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