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RESEARCH PAPER

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Sustainable green tea production through agroecological management and land conversion practices for restoring soil health, crop productivity and economic efficiency: Evidence from Northern Vietnam

Viet San Le[1,2,3] | **Laetitia Herrmann**[1,3] | **Lambert Bräu**[1] | **Didier Lesueur**[1,3,4,5,6]

[1]School of Life and Environmental Sciences, Faculty of Science, Engineering and Built Environment, Deakin University, Geelong, Victoria, Australia

[2]The Northern Mountainous Agriculture and Forestry Science Institute (NOMAFSI), Phu Tho, Vietnam

[3]Alliance of Bioversity International and International Center for Tropical Agriculture (CIAT), Asia hub, Common Microbial Biotechnology Platform (CMBP), Hanoi, Vietnam

[4]Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), UMR Eco&Sols, Hanoi, Vietnam

[5]Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement (INRAE), Institut de Recherche pour le Développement (IRD), Eco&Sols, University of Montpellier (UMR), CIRAD, Montpellier, France

[6]Rubber Research Institute, Chinese Academy of Tropical Agricultural Sciences, Haikou, China

Correspondence
Didier Lesueur, Centre de Coopération Internationale en Recherche Agronomique pour le Dévelopment (CIRAD), UMR Eco&Sols, Hanoi, Vietnam.
Email: didier.lesueur@cirad.fr and d.lesueur@cgiar.org

Abstract

Tea is a very important cash crop in Vietnam as it provides crucial income and employment for farmers in poor rural areas. Unfortunately, the dominance of long-term, conventional tea cultivation has caused severe soil health degradation and environmental pollution. At the same time, as tea production may provide a better net income compared with other annual crops such as rice and vegetables, farmers have been converting parts of their allocated land to cultivate tea plants. Little is known about the benefit of agroecological management as an alternative to conventional tea management practices, and thus, there is a need to understand how it can improve tea yields, quality and the livelihoods of the farmers. Conducted in Northern Vietnam from 2019 to 2022, this study examined the impacts of agroecological tea management practices on soil health indicators, tea yield and quality, and net income of tea farmers. We showed that agroecological management practices significantly enhanced soil organic matter by 0.8% and soil pH by 0.5 units on average. Conversely, conventional management based on chemical fertilizer applications, significantly increased soil total nitrogen by 0.15%–0.2%. No significant differences were observed between soil texture and other soil chemical characteristics. Soil biological parameters were also significantly higher in agroecological tea soil and root samples than in conventional tea plots. Average AMF frequency and intensity of the agroecological tea roots were 98% and 37%, respectively, compared with 73% and 15% of the conventional tea roots. Likewise, soil macrofauna and mesofauna abundance in the agroecological tea plantations was 76 individuals/m^2 and 101 individuals/100 g fresh soil on average, respectively, while that of conventional tea farms were 34 and 63 individuals/100 g fresh soil, respectively. Interestingly, a comparison between the converted and nonconverted lands did not show any significant effect of the conversion on soil physicochemical and biological characteristics, apart from tea root AMF colonization. Conventional tea management consistently

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resulted in higher tea yield and yield components, even though the differences were not always statistically significant. Despite lower tea yields, agroecological tea adopters earned around USD 8400 ha/year more than the farmers still practicing conventional management. This study shows that it is economically and environmentally more sustainable to produce organic tea than conventional tea, and our results should encourage more farmers to adopt such agroecological practices in Northern Vietnam.

KEYWORDS
agroecological and conventional management, soil health, tea production, Vietnam

1 | INTRODUCTION

Tea (*Camellia synesis* Kotze) has been cultivated for centuries and plays an important role in economic development and social sustainability in Vietnam (Bui & Nguyen, 2020; Viet San et al., 2021). Currently, tea plantations cover an area of around 130,000 ha, with over 1 million tonnes of fresh tea leaves being produced annually (Viet San et al., 2021). Since 2010, Vietnam has been among the top five leading tea exporters worldwide, with the annual revenue from tea exports over USD 200 million per annum (Van Ho et al., 2019). In Vietnam, tea is mainly grown in the Northern mountainous areas, where the conventional management method has been the dominant practice (Doanh et al., 2018; Viet San et al., 2021). Long-term intensive application of agrochemicals under conventional tea cultivation in this region has resulted in a range of serious issues, such as soil health and environmental degradation, human health concerns and reduced tea quality (Van Ho et al., 2019; Viet San et al., 2021). However, recently Vietnam has experienced an increasing transition from conventional tea cultivation to other alternatives such as organic and agroecological tea management practices (Ha, 2014; Van Ho et al., 2019). Apart from existing conventional tea areas, tea growers also convert their allocated croplands such as paddy rice and vegetable fields to cultivate tea crops. These conversions have been driven by the growing interests in greater economic efficiency of tea production, high tea quality and an increased awareness of agrochemical detrimental effects on human health and the environment (Doanh et al., 2018; Viet San et al., 2021).

Soil health can be defined as the capacity of soil to provide ecosystem services and it has been typically assessed by considering all the attributes including soil physical, chemical and biological properties (Ippolito et al., 2021; Williams et al., 2020). Different agricultural management practices can lead to long-term and differing effects on soil health properties (Bai et al., 2018). For instance, conventional agriculture, which employs intensive agrochemical inputs has been widely known to negatively impact soil health in comparison with conservation and organic farming (Singh et al., 2020; Viet San et al., 2021). By contrast, the role of agroecology in restoring soil health, providing sustainable food production and environmental benefits has been increasingly recognized worldwide (Dumont et al., 2021; FAO, 2020; Nicholls & Altieri, 2018). Agroecological practices aim at optimizing agroecological processes, environmental and public health whilst minimizing social-ecological costs from agricultural activities (FAO, 2020; Kerr et al., 2021). For tea farming, numerous studies outside Vietnam have indicated the positive impacts of agroecological practices on soil health properties and tea quality indicators, such as the application of organic fertilizers (Gu et al., 2019; Han et al., 2021; Lin et al., 2019) and organic mulching (Zhang, Huiguang, et al., 2020; Zhang, Yang, et al., 2020). Similar positive outcomes have also been recorded from other agroecological practices such as intercropping (Wen et al., 2019; Zhang et al., 2017), agroforestry (Tian et al., 2013) and integrated pest/disease management (Mamun & Ahmed, 2011; Shrestha & Thapa, 2015). However, all these studies focused on the impacts of agroecology tea management on soil microbial communities and their structures. Soil fauna and root mycorrhization with arbuscular mycorrhizal fungi (AMF) have been largely undocumented, while they play a key role in the decomposition of the organic matter and the mineral plant nutrition.

Land use change will also have significant and direct impacts on soil health because of subsequent alterations of management practices, vegetation cover and soil organism communities (Graham et al., 2021; Rasouli-Sadaghiani et al., 2018). Previous studies have consistently reported serious degradation of soil health as the consequences of converting forestlands and grasslands to croplands (Berkelmann et al., 2020; Gholoubi et al., 2018; Yang & Zhang, 2014). Yet, how crop conversion affects soil health properties and which mechanisms are involved have received less attention and in the specific case of tea plantations, several studies showed the negative impacts of land conversion from forestlands or perennial croplands to tea cultivation (Gholoubi et al., 2018; Wu et al., 2020; Zheng et al., 2020). These studies, however, did not focus on tea soil fauna communities, root AMF, as well as tea productivity, quality and the economic value of the conversion.

This study was designed to investigate how different management practices and land use history affect soil physical, chemical and biological properties, tea productivity, quality and economic efficiency in four communes of the Thai Nguyen province. The outcomes of this study will develop an understanding of the role of soil physico-chemical properties, root arbuscular mycorrhizal fungi and soil fauna communities in maintaining soil health and tea productivity and quality in the Acrisol soils in Thai Nguyen province as well in Northern region of Vietnam, and the sustainability of agroecological tea management practices in the region in comparison with the conventional approach.

2 | MATERIALS AND METHODS

2.1 | Study site description and experimental design

This study was conducted in 4 neighbouring communes including Tan Cuong, Phuc Xuan, Phuc Triu and Quyet Thang, which are in the Northwest border areas of Thai Nguyen city, Thai Nguyen province, the largest tea-producing province in Northern Vietnam (Figure 1). This region is characterized by a tropical monsoon climate, with four distinct seasons with an annual mean temperature of approximately 23°C (Dao et al., 2021). The mean annual precipitation ranges from 1500 to 3000 mm, and the peak of the rainy season is from May to September (Xuan et al., 2013). Land areas used for tea production are generally slightly sloping (8–15°C), and the soil type is classified as acrisols according to FAO/WRB classification system (FAO, 1998). Agroecological tea management practices refer to tea plantations that have received organic manure (chicken, cow and/or buffalo compost, 2.5–3 tonnes/ha/year) and commercial organic fertilizers (3–4 tonnes/ha/year), organic mulching (crop straw, wood chips, tree barks and Fern), integrated pest and disease management

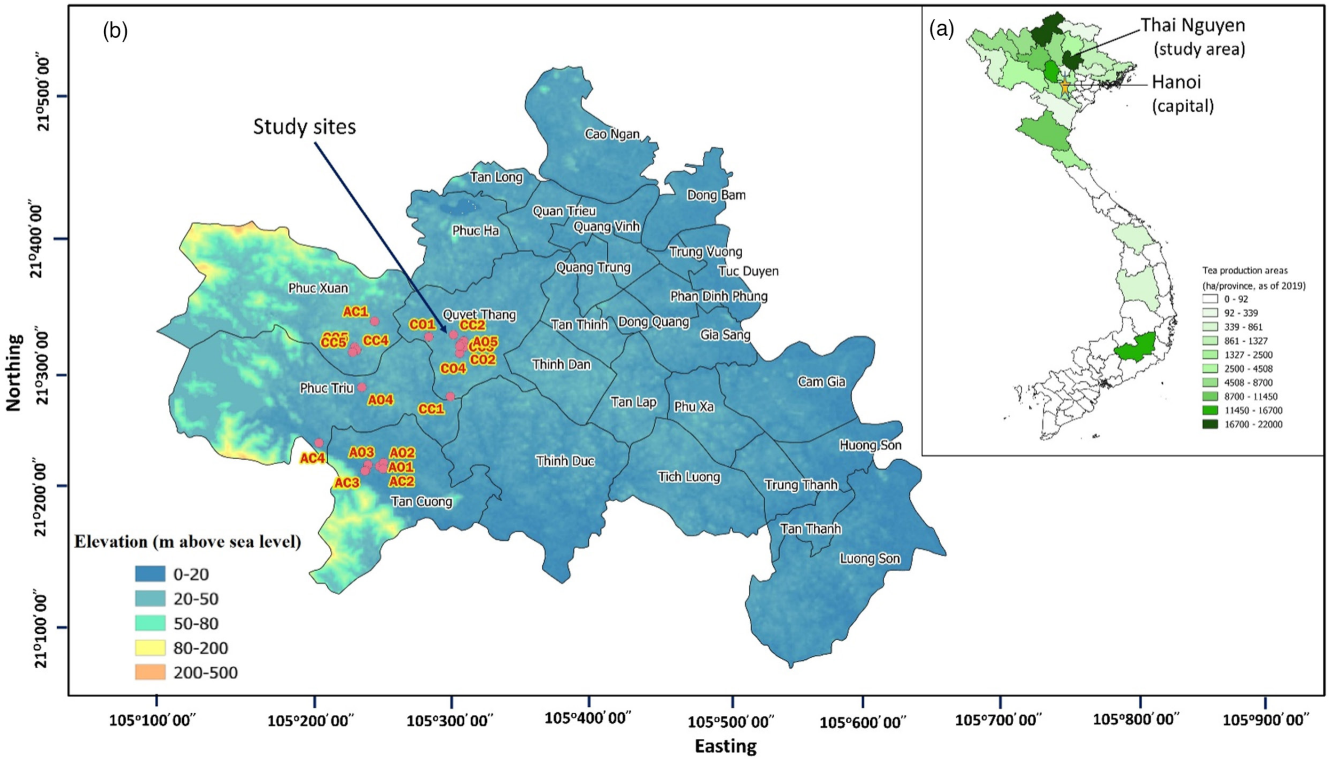

FIGURE 1 Location of Thai Nguyen province in the Vietnam map with tea production areas (a), and the research sites in Thai Nguyen city, Thai Nguyen province (b). AO1, AO2, AO3, AO4, AO5—agroecological original plantations; AC1, AC2, AC3, AC4, AC5—agroecological converted plantations; CO1, CO2, CO3, CO4, CO5—conventional original plantations; CC1, CC2, CC3, CC4, CC5—conventional converted plantations.

(IPM/IDM, manual control and biopesticides) as the main pest and disease control method for at least 5 consecutive years to the date of sampling (Tables S1-S6). These agroecological tea plantations were granted the VietGAP certification, a voluntary standard accreditation providing the criteria and requirements for safe and sustainable agriculture production issued by the Vietnamese government (Hoang, 2020; My et al., 2017). Since 2017, these tea fields have been in transition to organic tea production, which means that no chemical fertilizers and pesticides have been applied since then to comply with the certification requirement. Conventional tea plantations were subjected to traditional management method, with NPK (3–3.5 tonnes/ha/year) and urea (100–150 kg/harvest/ha) as main nutrient supplies (Table S2); chemical pesticides as main pest and disease control method. Each experimental tea plot has an area ranging from 1000 to 5000 m^2, and the tea variety is LDP1 (the variety that was crossed between Dai Bach Tra variety originally imported from China and PH1 variety from India), 6 years old (2019). In addition, all investigated tea plantations were irrigated regularly using underground water.

2.2 | Tea production economic efficiency

Primary data concerning economic aspects of tea production were conducted using a household survey over 3 years from 2019 to 2021, which consisted of 35 households that adopted agroecological tea production and 31 conventional tea-producing households from the 4 communes listed above. To ensure the credibility of this study, we have closely collaborated with local agricultural agencies and tea cooperatives to select the most representative tea-growing households in the 4 communes, where about 70% of the total tea production areas of the city are produced. Criteria for selecting the representative households for interview included the production areas (at least 1000 m^2 for one selective plot), identity of tea variety and tea ages being cultivated (LDP1 variety, 6 years old as of 2019), household investment capacity and labor availability (number of working adults), tea farming experience and having equal access to extension services and technological support. The production economic efficiency of the two tea production management systems was compared using the equation as follows:

$$NI = \sum_{i=1}^{n} R_i - \sum_{i=1}^{n} E_i$$

where: *NI* is the net income that a tea-growing household earns from one hectare (ha) of tea production, either adopting agroecological or conventional management practices. R_i is the total income per ha by selling tea fresh leaves, and any subsidies from government and other agencies for each type of cultivation method (r_1, r_2, ... r_n). E_i is the total expenses for tea production per ha and any related costs, such as fertilizers, pesticides, labor costs, irrigation equipment, machinery and other tools (e_1, e_2 ... e_n).

All the amounts were converted from Vietnam Dong (VND) to USD, adopting the current exchange rate (1 USD = 23,200 VND).

2.3 | Soil and root sampling and analyses

A total of 20 tea plantations from the 66 households mentioned above (10 agroecological and 10 conventional plantations), were selected from the 4 communes (Tan Cuong: 7 agroecological plots; Quyet Thang: 1 agroecological, 5 conventional plots; Phuc Xuan: 4 conventional plots and Phuc Triu: 2 agroecological, 1 conventional plots), with the objective to study the impact of different tea management methods on soil physicochemical and biological properties, as well as tea yield and yield components. Apart from meeting the criterion set out for all 66 plantations, these 20 plots have minimum areas of 1500 m^2 and are located within a small area (2.5 km^2 radius) to reduce the soil variability.

Of the 20 tea plots, 10 plots were converted from annual croplands and 10 were original tea soils. Converted lands were soils used for one season as rice paddies and other annual crops such as maize, peanut and vegetable. These plots are flat (slope $< 10^0$), used for flood irrigation and have been converted to plant tea (1st tea generation) by adding hill soils on top (1–2 m deep). Original tea plantation soils were hill soils that have been used for tea plantations for at least 2 tea generations (15–30 years). They are slightly sloping ($10–15^0$) with thick topsoil, never been flooded (Tables S1 and S2).

A sampling area (6 m × 9 m) was located in the center of each experimental field for conducting soil and root sampling. First, soil macrofauna was collected in the morning to avoid the effect of heat from the sun and other intensive activities such as tea harvesting and other sampling, as some macrofauna retreat quickly. In the center of each sampling area, a soil sample of 20 × 20 × 20 cm was dug, 20–30 cm away from the tea trunk, then all the soils were quickly collected into basins. Soil macrofauna was harvested by carefully hand-sorting the soils and then preserved in 50 ml plastic tubes containing 70% alcohol and then stored at 4°C until being identified to group levels. Likewise, about 200 g of fresh soil was sampled from holes with dimensions of 10 × 10 × 20 cm and stored in medium size resealable plastic bag, then immediately stored in a cool box containing ice blocks at the fields for analysing soil mesofauna. These soil samples then were transported immediately after sampling into the lab and stored at 4°C. Soil macrofauna and mesofauna were sampled at different dates within the same week.

Following the soil fauna sampling, 12 soil samples were collected per plot, distanced by 3 m in width and 4 m in length from each other. Surface soil samples (0–20 cm deep) were collected, then mixed well and large stones removed. About 500 g of soil was then stored in a large-size resealable plastic bag, air-dried and kept at room temperature for physicochemical analyses. At the same time, 12 finest tea root samples (30–40 g per sample) were collected within a circle of 1 m from the same points for soil sampling then contained in paper envelopes and air dried for AMF analyses.

Soil physicochemical analyses included soil texture (Kilmer & Alexander, 1949), soil pH (H_2O) (1:5 Soil: water suspensions), soil OM (Walkley & Black, 1934), available Phosphorus (P) (Olsen & Sommers, 1982) and total Nitrogen (N) (Kjeldahl method, as described by Archibald et al., 1958). Fine roots were dried in an oven at 40°C following sampling, and AMF staining was implemented using the ink and vinegar method (Vierheilig et al., 1998). The frequency (F%) and the intensity (M%) of AMF colonization were assessed following the technique described by Trouvelot et al. (1986). Generally, 15 root fragments of 1 cm taken from each sample were observed and the presence and the intensity of colonization were recorded based on the scores (from 0 to 5) of each fragment.

Soil mesofauna was extracted using two protocols: the heated funnel as described by Edwards (1991) and the modified centrifugal method (Dritsoulas & Duncan, 2020). For the funnel method, a thin layer of fine fresh soil (50 g per sample) was spread on a fine sieve or a small plastic basket and applied heat on top for 72 h. Under the effect of heat, soil mesofauna moved downward and was collected in the plastic tubes, which were tightly connected to funnels and filled with 70% alcohol.

For the second method, fresh soil samples (50 g) were initially sieved using a mosquito net (mesh size ≈ 1 mm) to remove large materials and the fine materials that passed through were then filtered through a 400-mesh sieve to get a bulk subsample containing soil mesofauna and organic matter. The subsample was continuously filtered through a 38-mesh sieve, discarded materials that passed through and collected the remaining materials into 2–4 centrifuge tubes (total volume ≈ 50 ml), and centrifuged at 1700 revolutions per minute (RPM) for 5 minutes to remove organic debris and precipitate soil mesofauna and soil particles in the decanted supernatant. The subsample was then filtered again with the 38-mesh sieve, and the remaining materials were mixed with sucrose solution (1.3 M) and centrifuged (1700 rpm, 1 min) to suspend soil mesofauna in the supernatant for collection. Soil mesofauna were then preserved in 70% alcohol solution and identified at the group level, using a dissection microscope. Soil macrofauna extraction was undertaken within a week from the time of soil sampling.

2.4 | Tea yield, yield component and quality measurement

Tea yield and yield components in the two production systems were compared for 3 consecutive years, from 2019 to 2021. In the region, tea growers usually conduct 8 harvests per annum, starting in late February/early March and ending in late November/December with an interval of 30–45 days between harvest, depending on the seasons. The present research was conducted in LDP1 variety, which will be 9 years -old in 2022 and is in the middle of its life cycle. Tea yield components including density of tea shoots/m^2 and average weight of a shoot were measured by randomly placing a quadrat (1 m × 1 m) at the center of each trial plot during the harvest days then manually picked all tea shoots presenting in the quadrats, with 5 replicates per plantation. All harvested tea shoots (1 bud and 2 leaves) then were counted to assess the density, and 100 tea shoots were randomly selected for assessing their weight. Tea yield (tonnes of fresh leaves/ha/year) was measured by recording the weight of all fresh tea shoots harvested from the research sites from 2019 to 2021.

A total of 60 samples were randomly picked by tea farmers from the 20 selected tea plantations, each contained approximately 500 g of fresh tea leaves (one bud and two leaves). After being harvested, the green tea samples were immediately sent to the Northern Mountainous Agriculture and Forestry Science Institute (NOMAFSI) for processing and sensory assessment, adopting the standard TCVN 3218–2012 issued by the Ministry of Science and Technology of Vietnam in 2012 (Cuong, 2011; Luyen et al., 2014). Fresh tea samples were processed as follows: Light wilting → Enzyme destruction by drying in a barrel rolling → Rub → Drying in barrel rolling → Final green tea product, all of which were undertaken at the Tea Research and Development Center (NOMAFSI). Afterwards, a recognized panel of 9 highly trained and experienced members (4 female and 5 male), who are mainly senior tea researchers from NOMAFSI, were recruited to take part in the sensory evaluation, which was conducted in a panel room (22°C ± 1, free of food/drink odours, fluorescent lighting) for evaluating and presenting marks for the intensity of the target tea quality attributes, including the appearance of dried tea leaves, colour, smell and taste of the tea brew. In the test, 3 g of each dried tea sample was coded with 3 digits in random order and served to each panelist simultaneously for evaluating the appearance of the dried tea. In the meantime, a tea infusion was prepared by putting 3 g of the same dried tea into 150 ml boiled water (93–95°C) for 5 min, and then, the mixtures with the same codes as the dried samples were served and the sensory properties were evaluated. The panelist could discuss the selected representative descriptors for each attribute according to the standard TCVN 3218–2012, then independently decided the marks for each attribute, using the five scale marks in which 5 is the highest mark given to the best attribute and 1 mark is for the poorest attribute. The average marks of each sensory attribute were based on the marks given by 9 panelists, and the overall marks were calculated using the equations:

$$D = \sum_{i=1}^{4} D_i . k_i$$

where: D is the overall marks used to calculate the final grade of the tea quality as follow: very good: 18.2–20; good: 15.2–18.1; moderate: 11.2–15.1; poor: 7.2–11.1 and failed: ≤7.1. D_i is the panel average marks of the attribute i (appearance, colour, taste and smell). k_i is the important index for the attribute i as follows: appearance (1% or 25% if by percentage), colour (0.6% or 15%), taste and smell (1.2% or 30%).

2.5 | Statistical analyses

Data used in this study were analysed using Microsoft® Excel, XLSTAT (Addinsoft, 2016) and R software. Comparison data of economic efficiency between conventional and agroecological cultivation methods were subjected to one-way analyses of variance (ANOVA), while the different effects of cultivation management and land conversion practices on tea root AMF colonization, tea soil fauna compositional communities, tea yield and yield components, as well as sensory indicators, were determined using two-way ANOVA. Soil physicochemical data were ln(x) transformed and the normal distribution verification was performed before two-way ANOVA. To examine the differences between levels within each factor, Tukey-HSD tests were performed for post-hoc comparisons. In addition, a principal component analysis (PCA) was employed to assess the correlations between the soil characteristics and the mycorrhization indicators. Furthermore, soil fauna diversity indexes were performed using the *vegan* package in R version 4.0.3 (Oksanen et al., 2013).

3 | RESULTS

3.1 | Production economic efficiency

Table 1 compares the economic indicators between the agroecological and conventional tea production systems from 2019 to 2021 in 4 communes in Thai Nguyen city, Northern Vietnam. Overall, agroecological tea production requires significantly more inputs but provides significantly higher incomes for the adopters. Agroecological management requires investments in organic fertilizers (USD 5215), pesticides (USD 679) (Tables S1-S6) and labor cost (USD 6401) per hectare of tea. In comparison, the expenses of conventional tea farmers in the same categories were significantly lower (USD 3368 for fertilizers, USD 482 for pesticides and USD 4581 for labor cost). A similar trend was also observed in other costs (irrigation equipment, machinery, tools for growing and harvesting, etc.), where agroecological tea households needed to spend more than USD 770 year^{-1} ha^{-1}, compared with USD 605 invested by conventional tea growers. In total, farmers producing organic tea need to invest US 13,000 ha^{-1}, those producing conventional tea invest around USD 9000 ha^{-1}. However, households who adopted agroecological tea cultivation methods made significantly more money at the end of the year, which accounted for around USD 24,000 (year^{-1} ha^{-1}) compared with the nonadopters (USD 15,636 year^{-1} ha^{-1}). This was mainly attributed to the difference in selling prices of fresh tea leaves, as the average price for conventional tea products was around USD 1 lower than that for the agroecological tea products for each kg (USD 1.7 vs. 2.78). In addition, agroecological tea growers have been subsided by either local government agencies or organic fertilization companies, worth around USD 411 (year^{-1} ha^{-1}), mainly via supplies of commercial organic fertilizers without any cost or with low interests. The aim of this initiative is to promote sustainable tea and other crop production in the province and country, which was not available for conventional tea production.

3.2 | Soil physicochemical parameters and AMF colonization

Soil physicochemical properties (soil texture, soil pH, OM, available P and total N) and AMF colonization are presented in Table 2. Soils of the trial tea plantations were mainly clay loam in texture, with the proportions of sand and clay ranging from 30% to 40%, and soil texture properties across the treatments did not show any significant differences, suggesting that soil types among the experimental plots were similar. Regarding the soil chemical properties, agroecological management practices resulted in significant increases in soil pH and organic matter contents, compared with the conventional tea management approaches, regardless of land use history. Highest soil pH (4.69 ± 0.3) was observed in agroecological converted soils, while the lowest pH (4.11 ± 0.19) was recorded in the conventional original plots, indicating that all tea plantation

TABLE 1 Comparison of economic efficiency of the agroecological and conventional tea production systems from 2019 to 2021 in Northern Vietnam.

	2019		**2020**		**2021**		**Mean (2019–2021)**	
Indicators/year	**Agroecological**	**Conventional**	**Agroecological**	**Conventional**	**Agroecological**	**Conventional**	**Agroecological**	**Conventional**
Area (ha^{-1})	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Fresh yield (tonnes year^{-1} ha^{-1})	14.65	15.84	14.22	15.44	14.29	15.25	14.38^{a} (1.12)	15.51^{b} (0.91)
Price (USD kg^{-1})	2.65	1.65	2.55	1.60	2.45	1.52	2.55^{b} (0.26)	1.59^{a} (0.15)
Subsidy (year^{-1} ha^{-1})	425.00	0.00	425.00	0.00	385.00	0.00	411.67^{b} (23.09)	0.00^{a} (0.00)
Revenue (USD)	***39,247.00***	***26,136.00***	***36,686.00***	***24,704.00***	***35,395.50***	***23,180.00***	***37,109.67^{b}*** (2654.90)	***24,673.33^{a}*** (2485.42)
Fertilizers (year^{-1} ha^{-1})	5323. 00	3889.00	5158.00	3275.00	5165.00	2941.00	5215.33^{b} (480.6)	3368.33^{a} (427.84)
Pesticides (year^{-1} ha^{-1})	685.00	485.00	682.50	496.00	670.50	465.00	679.33^{b} (56.09)	482.00^{a} (25.71)
Labor cost (year^{-1} ha^{-1})	6638.00	4680.00	6240.00	4575.00	6325.00	4490.00	6401.00^{b} (209.60)	4581.67^{a} (95.17)
Other costs (year^{-1} ha^{-1})	836.00	620.00	755.00	606.00	722.00	589.00	771.00^{b} (58.66)	605.00^{a} (32.89)
Total (USD)	**13,482.00**	**9674.00**	**12,835.50**	**8952.00**	**12,882.50**	**8485.00**	***13,066.67^{b}*** (880.36)	***9037.00^{a}*** (579.40)
Net income (USD)	**25,765.50**	**16,462.00**	**23,850.50**	**15,752.00**	**22,513.00**	**14,695.00**	***24,043.00^{b}*** (1686.87)	***15,636.33^{a}*** (1290.50)

Note: Average values for 35 agroecological tea households and 31 conventional tea adopters. Different letters indicate differences at significance $p < .05$ level, according to the Tukey (HSD) tests. Standard deviation values are given in brackets.Values in bold indicating the most significantly economic indicators of the tea production systems. Soil conversion practice did not have a significant impact on economic indicators of tea production.

TABLE 2 Soils' physicochemical characteristics and AMF root colonization frequency (F%) and intensity (M%) of the tea plantations with different management practices and land use history.

Plantations	Soil texture			Soil chemical characteristics				AMF colonization	
	Sand (%)	Silt (%)	Clay (%)	pH (H_2O)	OM (%)	Available P (mg/100 g)	Total N (%)	F (%)	M (%)
Agroecological original	42.15^{a} (4.80)	19.57^{a} (2.28)	38.28^{a} (3.07)	4.52^{ab} (0.39)	3.08^{b} (0.21)	48.38^{a} (4.25)	0.22^{a} (0.09)	98.33^{c} (4.12)	34.95^{c} (3.45)
Agroecological converted	41.18^{a} (5.71)	22.57^{a} (3.75)	36.25^{a} (4.25)	4.69^{b} (0.30)	3.04^{b} (0.30)	38^{a} (3.32)	0.23^{ab} (0.09)	97.46^{c} (5.06)	37.88^{c} (3.62)
Conventional original	38.33^{a} (6.23)	20.27^{a} (3.96)	41.40^{a} (4.39)	4.11^{a} (0.19)	2.32^{a} (0.23)	39.14^{a} (3.24)	0.37^{b} (0.021)	66.95^{a} (7.59)	10.11^{a} (3.05)
Conventional converted	34.39^{a} (6.56)	24.87^{a} (3.90)	40.74^{a} (4.18)	4.23^{a} (0.28)	2.30^{a} (0.26)	42.33^{a} (3.12)	0.30^{ab} (0.018)	80.3^{b} (7.24)	20.51^{b} (4.17)

Note: Average values for 25 and 45 samples per site group for soil characteristics and AMF assessment, respectively. For each variable, values followed by different letters are significantly different at $p < .05$ (pairwise comparisons of the means using the Tukey (HSD) tests). Standard deviation values are given in brackets.

Abbreviation: F%, frequency of mycorrhization; M%, Intensity of mycorrhization.

soils were strongly acidic. Average soil OM contents (%) in agroecological tea sites were greater than 3.0, compared with 2.32 and 2.30 of conventional original and conventional converted plots, respectively. By contrast, total nitrogen (%) was greater in conventional tea soils (0.37 and 0.30) compared with agroecological tea soils (0.22 and 0.23 for original and converted soils, respectively), while available P contents remained almost the same whatever the treatments (Table 2). The highest P availability content was found in agroecological original plantation soils (48.38 mg/ 100 g soil), while the lowest was observed in agroecological converted gardens (38 mg/ 100 g soil). Interestingly, soil conversion practices did not lead to any significant changes in the soil characteristics, regardless of the cultivation approaches.

In this study, the roots of tea plants were colonized by native AMF, but the frequency (F) and intensity (M) varied greatly from 67% to 98% and 10% to 38%, respectively (Table 2). Tea root mycorrhization responded significantly to different tea management practices, regardless of converted or nonconverted soils. Highest F was observed in the plantations that practiced both agroecological management and soil conversion, which accounted for 38%. This proportion was more than 3 times higher than the lowest figure for tea root samples collected from conventional original farms. While the average proportion of AMF frequency of tea roots was close to 85%, the figure for AMF intensity was only approximately 26%.

The principal component analyses (PCA) of the soil physicochemical indicators and tea root mycorrhization parameters are presented in the Figure 2a,b. The first two axes together explained nearly 52% of the cumulative variability. The first axis (F1), which accounted for approximately 32% of the accumulated variability, was closely related to soil chemical indicators including OM, N total and soil pH (0.610; −0.619 and 0.45, respectively). By contrast, soil texture (silt and clay) was strongly linked to the third axis (F3), which represented around 16% of the variation in the dataset. Root mycorrhizal F and M were strongly linked to the first axis (0.688 and 0.806, respectively) and significantly correlated with soil OM, soil pH and soil total N.

The PCA observation charts clearly show the positioning of the agroecological and conventional tea farms but were unable to distinguish between the converted and nonconverted plantations. The observations were well-distributed along the F1 axis, indicating that tea management methods significantly impacted soil chemical properties such as soil pH, soil OM and total N, rather than the soil texture. Also, agroecological tea plantations were mainly distributed to the right side, suggesting a positive impact of the management practice on soil OM and AMF root colonization but negatively link to soil total

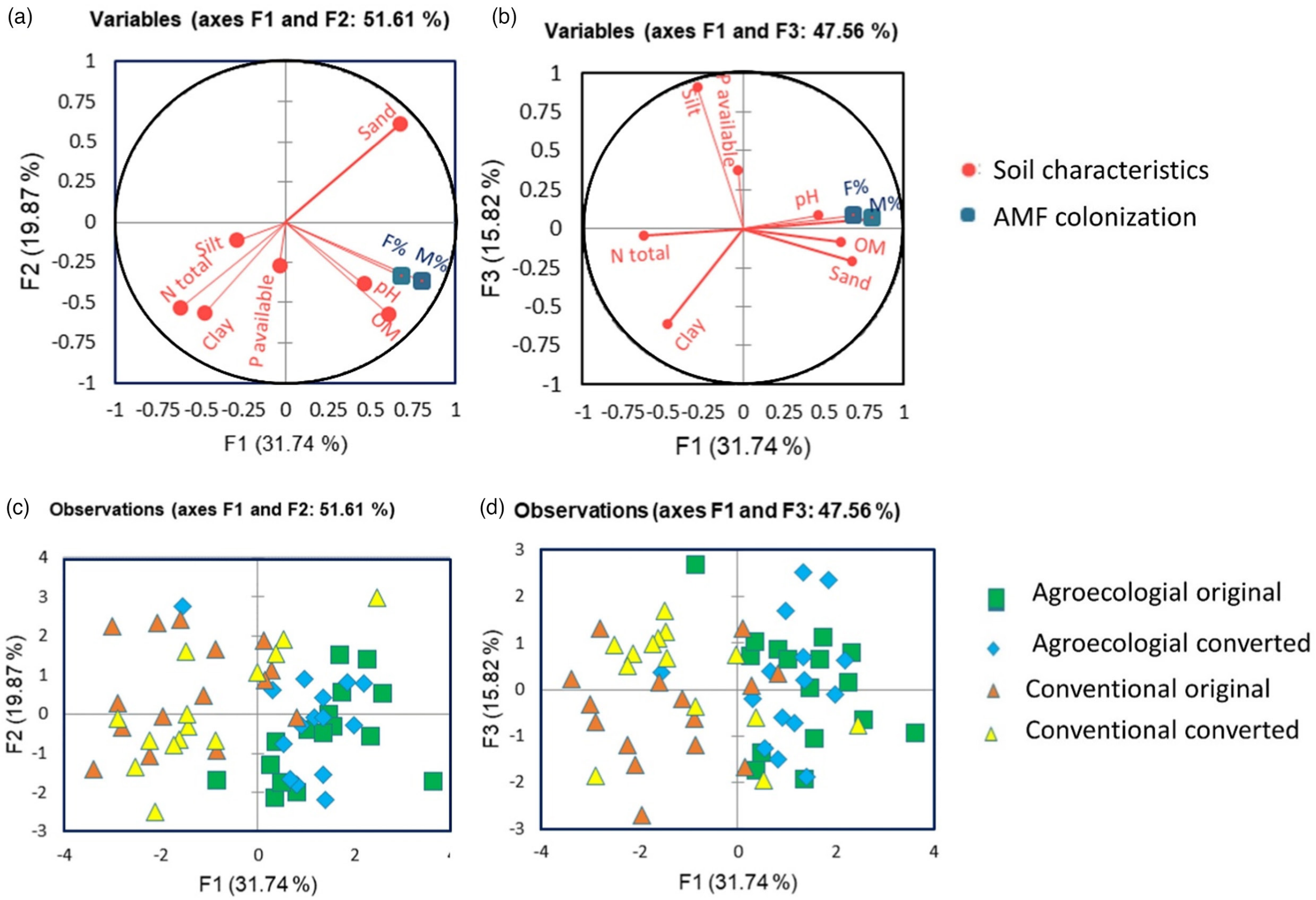

FIGURE 2 Principal component analysis (PCA) of soil characteristics and the AMF colonization of tea roots collected from agroecological and conventional tea plantations. (a, b) variable correlations with F1–F2 and F1–F3 axes, respectively. (c, d) sample ordinations along with F1–F2 and F1–F3, respectively; each point represents a single sample.

N. By contrast, the conventional tea farm observations were predominantly distributed to the left, meaning they have lower values of soil OM, soil OM and F and M values about root mycorrhization but greater values of soil total N compared with the agroecological tea plantations (Figure 2c,d).

3.3 | Soil fauna

Ecological indices of soil macro and mesofauna are presented in Figure 3 and Tables S4–S6. First, densities of soil fauna in agroecological original and agroecological converted were 68 and 86 individuals/m^2, respectively, while for conventional original and conventional converted treatments, the values were only 33 and 37 individuals/m^2, respectively. The abundance of soil mesofauna was strongly affected by management practices but was not always significantly different by extracting methods. With regards to the results obtained about mesofauna with the 2 different protocols, by centrifugation extraction, we found 92, 129, 58 and 68 (ind./100 g fresh soil) for agroecological original, agroecological converted, conventional original and conventional converted treatments, respectively, while the values extracted by employing funnel method were 80, 101, 58 and 68 (ind./100 g fresh soil), respectively. Community richness and Shannon index were also significantly different between the agroecological and conventional treatments ($p < .05$, Figure 3 and Table S4) but did not statistically differ between the extraction methods. For both soil mesofauna and macrofauna, the highest values of richness and Shannon index were recorded in agroecological converted and agroecological original treatments, which approximately doubled than the figures in conventional converted and conventional original treatments, regardless of the extraction methods. By contrast, soil conversion and its interaction with the cultivation approach did not result in any significant difference in the soil fauna community indices and diversity index.

For soil fauna community composition, only 8 different soil fauna groups and 13 soil mesofauna groups were found in the experimental tea plots. Among the groups, earthworms were the dominant soil macrofauna species, accounting for nearly 34%, followed by centipedes and

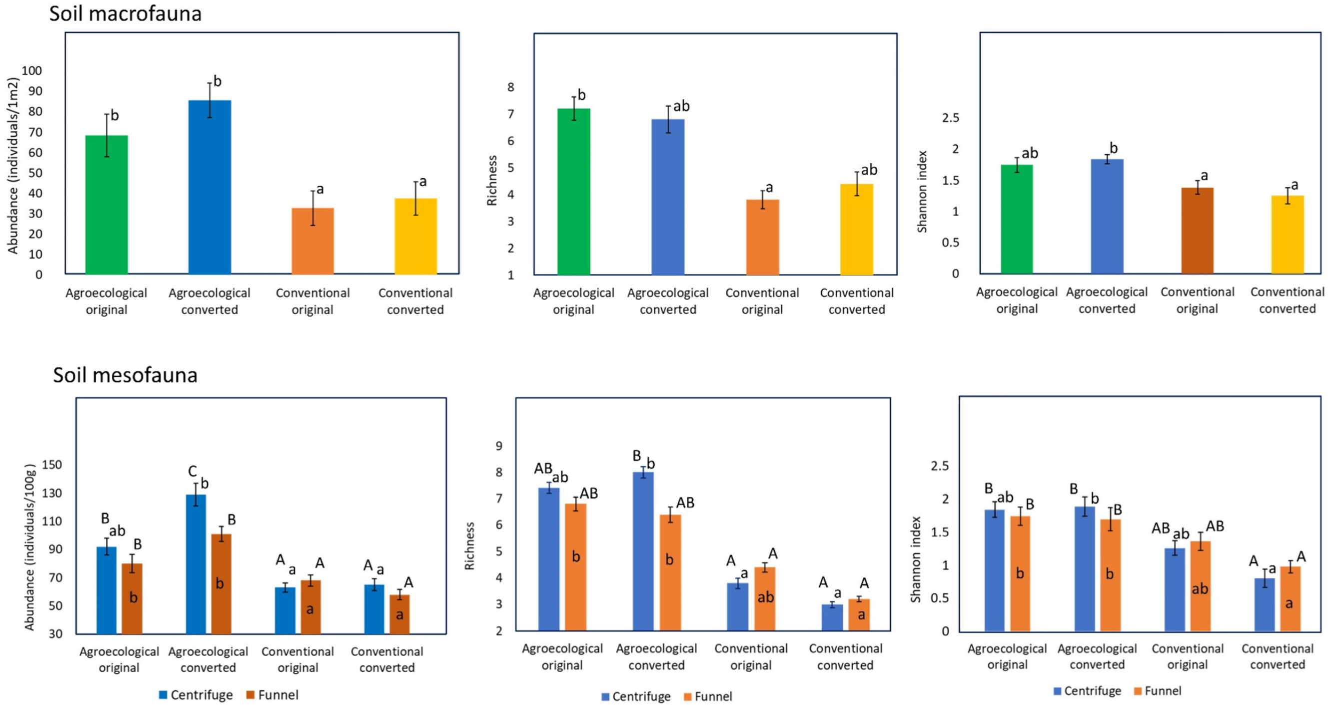

FIGURE 3 Variations in diversity indexes of the soil macrofauna (above) and mesofauna (below) observed in agroecological and conventional tea plantations. Average values for 10 samples per site group. Lower-case letters indicate a difference in abundance (individuals/m^2 ± SD for soil macrofauna and individuals/100 g fresh soil ± SD for mesofauna), richness and Shannon diversity (mean ± SD) between management practices at significance <0.05 level, while capital letters indicate the differences between soil mesofauna extraction methods at significance <0.05 level.

millipedes. Different tea cultivation methods also lead to a significant difference in the abundance of earthworm, centipede, spider and millipede species, while the impacts on other groups were not significant. For soil mesofauna, oribatei, millipede and enchytraeids were the most abundant groups, regardless of the extraction techniques. Interestingly, apart from millipedes, other mesofauna group intensities were not significantly affected by both cultivation and soil conversion practices (Tables S5 and S6).

3.4 | Tea yield, yield component and quality assessment

From 2019 to 2021, tea yield and its components recorded in conventional tea plantations were consistently higher than those from agroecological plots, but these increases were not always significantly different (Table 3). Average tea yield ranged from around 14.1 tonnes to more than 16.3 tonnes year^{-1} ha^{-1}, while the average shoot density and weight of 100 shoots varied from nearly 580 to 700 (shoots/m^2) and 31.8 to 36.6 (g), respectively. The conventional converted tea plantations produced the highest tea yield over the observation period, which accounted for 16.3, 16.0 and 15.9 (tonnes year^{-1} ha^{-1}) for the years 2019, 2020 and 2021 on average, respectively, while the lowest yield was recorded in the agroecological original treatment over the observed period, which ranged from 14.19 to 14.59 tonnes year^{-1} ha^{-1}. Also, there was a reduction in tea yield and yield components in 2020 and 2021, compared with the figures in 2019. Over the 8 annual harvests, tea yield, number of shoots and shoot biomass were highest in the July and August/September harvests, which are summer times in the research areas, and then dropped quickly in the following harvests. The yield and shoot densities of tea harvested in the summer seasons were generally doubled than that in the first (spring) and last yearly harvests (winter seasons; Figure 4).

Figure 5 presents the sensory evaluation results of the green tea samples including dried tea leaf appearance, colour, smell and taste of the tea infusion. Among the four attributes, the average marks for tea leaf appearance were significantly higher in conventional tea products (4.51 and 4.56 for conventional original and conventional converted tea leaves, respectively), compared with the agroecological dried tea (4.08 for agroecological original and 4.07 for agroecological converted tea leaves). By contrast, average marks given for smell and taste of agroecological tea infusion were significantly greater than for the conventional products. Agroecological original teas obtained the highest marks for both the brew aroma and taste,

TABLE 3 Tea yield and yield components as affected by different tea cultivation methods (agroecological vs conventional) and land use history (converted and nonconverted).

Plantations	2019 Shoot density	2019 Shoot weight (100 shoots)	2019 Yield (tonnes/ha)	2020 Shoot density	2020 Shoot weight (100 shoots)	2020 Yield (tonnes/ha)	2021 Shoot density	2021 Shoot weight (100 shoots)	2021 Yield (tonnes/ha)
AO	633^{a} (112)	31.8^{a} (2.95)	14.59^{a} (1.11)	577^{a} (31.58)	32.6^{a} (3.64)	14.32^{a} (0.85)	592^{a} (63.61)	32.1^{a} (1.51)	14.19^{a} (0.86)
AC	640^{a} (52)	33.2^{a} (3.11)	15.05^{a} (0.76)	584^{a} (62.61)	31.2^{a} (3.27)	14.64^{a} (0.68)	608^{a} (35.33)	33.5^{a} (1.50)	14.48^{a} (0.57)
CO	687^{a} (13.1)	35.8^{b} (3.11)	15.89^{ab} (0.95)	635^{ab} (63.94)	34.0^{b} (3.87)	15.51^{a} (0.74)	615^{b} (89.62)	33.9^{ab} (4.61)	15.33^{ab} (0.66)
CC	696^{a} (58)	36.6^{b} (2.66)	16.32^{b} (0.43)	647^{b} (108)	33.6^{b} (1.14)	16.04^{a} (0.50)	656^{b} (68.58)	34.3^{b} (2.91)	15.93^{b} (0.50)

Note: Shoot density (shoots/m^2), shoot weight (weight of 100 tea shoots), yield (tonnes of fresh tea leaves ha^{-1} year^{-1}). Average values for 15 samples per site group per year (shoot density and shoot weight) and 40 samples per site group per year (tea yield). For each variable, values followed by different letters are significantly different at $p < .05$, according to the Tukey (HSD) tests. Standard deviation values are given in brackets.

Abbreviations: AC, agroecological converted; AO, agroecological original; CC, conventional converted; CO, conventional original.

which amounted to 4.63 and 4.61, respectively, while the lowest marks were given to the conventional converted (4.15) and conventional original (4.18). Conversely, there was no significant difference in the marks given for the colour of tea brew, which accounted for 4.5 on average. Overall, agroecological tea products obtained a significantly greater mark (≈18) compared with the tea products that were conventionally cultivated (≈ 17.3). As a result, all the green tea samples studied obtained the 'Good' grade (total marks: 15.2–18.1) (Figure 5). As for the qualitative sensory description, all the dried tea leaves were young green, wiry, downy and creepy, even though the intensity of the creepiness and colour appearance were different. Also, the colour of converted and nonconverted tea brew was qualitatively different, regardless of the management method. Infusions of tea samples harvested from nonconverted farms were green and bright, while that of converted tea plantations were pale yellow-green, clear and medium bodies. The intensities of the fragrance and freshness (aroma) and sweetness after testing (taste) were also clearly different among agroecological and conventional tea products, which are crucial factors affecting the evaluation marks given to each type of infused tea (Figure 5).

4 | DISCUSSION

4.1 | Production economic efficiency

Aside from the environmental advantage, economic benefit has been considered as one of the most important drivers for moving from conventional to agroecological and organic farming, not only for tea production (Bui & Nguyen, 2020; Qiao et al., 2016; Viet San et al., 2021) but other cropping and livestock systems (Bouttes et al., 2019; Eyhorn et al., 2018). Our study shows that the agroecological tea farming provides a significantly greater net income for tea farmers compared with conventional tea management. This finding is similar to a number of studies (Deka & Goswami, 2021; Doanh et al., 2018; Tran, 2008) reporting that organic tea adopters earned a higher net income compared with the nonadopters, which mainly resulted from the premium price of organic tea products to offset the increased labour costs and yield reduction. Previous investigations also indicated that as new and more complex production systems, agroecological and organic farming required more capital investment than the conventional or traditional production systems, and it has been generally believed that only large-scale farms could afford this (Azadi et al., 2011; Bui & Nguyen, 2020). Our study confirmed this as the annual investments for labour, pesticides and organic fertilization and other maintenance costs for agroecological tea management method

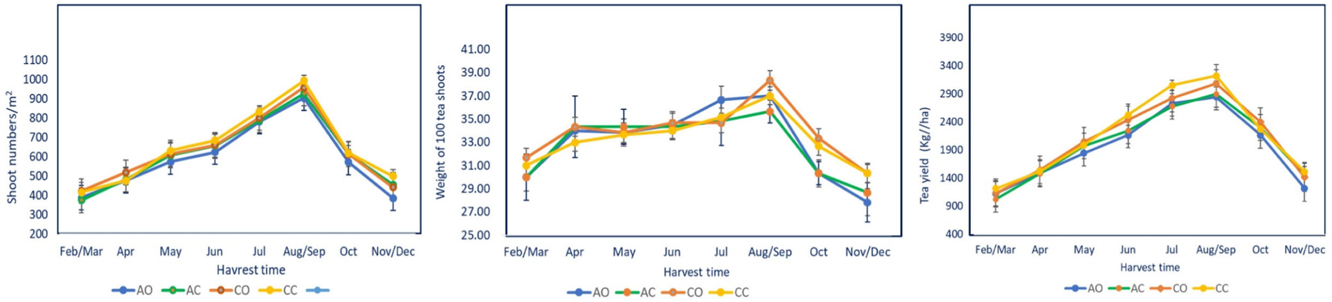

FIGURE 4 Tea crop yield and yield component changes over the yearly harvest times observed from 2019 to 2021 in agroecological and conventional tea plantations. For tea shoot number and shoot weight, the means were based on 45 samples per site group, while the average yields were for 120 samples per site group. AC, agroecological converted; AO, agroecological original; CC, conventional converted; CO, conventional original.

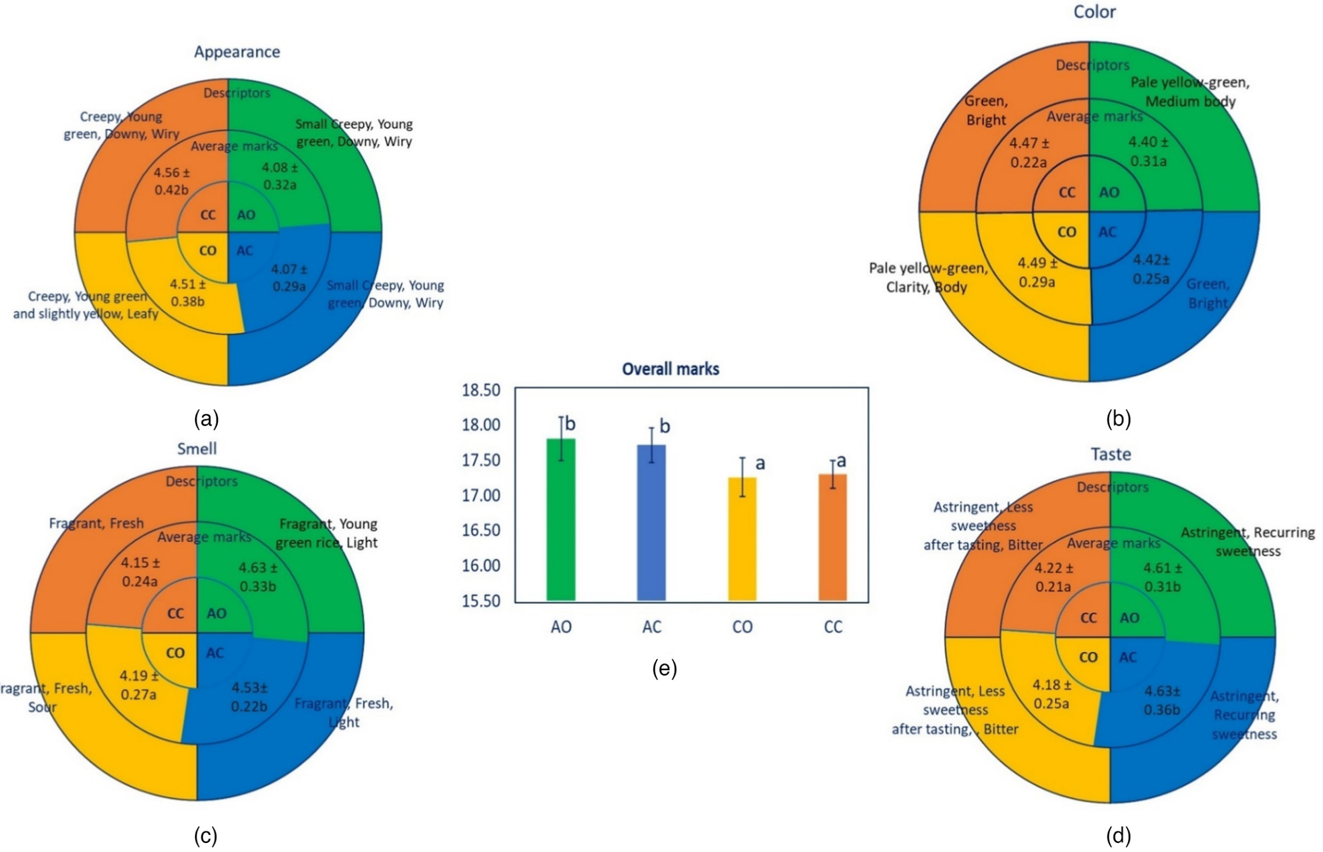

FIGURE 5 Sensory evaluation of green tea samples from agroecological and conventional tea plantations. (a) Appearance, (b) colour, (c) smell, (d) taste and (e) overall marks of the sensory properties. Sensory marks are given in an average of 60 samples per site group with standard deviation values. Different letters indicate a significant difference at $p < .05$ (pairwise comparisons using the Tukey (HSD) test). AC, agroecological converted; AO, agroecological original; CC, conventional converted; CO, conventional original.

were significantly higher than those of conventional tea farmers. Instead of investing in chemical fertilizers and pesticides, agroecological tea growers need to spend more on alternatives such as organic fertilizers, biofertilizers, nanofertilizers and biopesticides, which are generally more expensive due to the technical complexity, limited availability and larger required amounts compared with the chemical inputs (Duran-Lara et al., 2020; Essiedu et al., 2020). Surprisingly, we observed that numerous small tea farms in the research region with a total area of less than 1000 m^2 have been converted to practice organic and agroecological methods over the past 5 years. It is possible that a significant difference in the selling price of agroecological tea products, along with the subsidies from local governments and other agencies, has encouraged tea growers to apply agroecological management practices (Doanh et al., 2018; Qiao et al., 2016). Recently, a growing concern regarding the harmful effects of agrochemicals on human health and the environment also plays a part in promoting tea farmers from converting their conventional tea to organic management practices (Doanh et al., 2018; Viet San et al., 2021).

4.2 | Soil physicochemical properties and AMF colonization

Agroecology has long been known to benefit soil chemical and biological properties, while the negative impacts of conventional farming practices on soil health have been widely recognized (Gianinazzi et al., 2010; Cárceles Rodríguez et al., 2022). Our study showed that soil pH and OM content observed in agroecological tea plantations were significantly higher than the figures for the conventional tea plots, while total N was higher in conventional systems, which could be attributed to several mechanisms. First, the intensive use of synthetic chemical fertilizers of conventional tea adopters, particularly nitrogen to ensure tea productivity, and as a replacement for soil fertility loss, has caused serious tea soil acidification because of the nitrification processes (Li et al., 2015;Viet San et al., 2022; Yan et al., 2020). We noted that conventional tea farmers in the studied region used up to 1200 kg/ha/year of single nitrogen fertilizers (urea, ammonium nitrate) for ensuring high tea productivity and replacing soil nutrient loss, excluding the N amount from NPK compound annual applications. When an intensive amount of nitrogen fertilizer is applied, around 2700 kg/ha/year, tea plants can only absored around 18.2%, and the majority (up to 52%) will be stored in the tea soils, which can lead to an increase in soil nitrogen (Chen & Lin, 2016; Xie et al., 2021). Also, tea plants take up the nutrient directly and an equivalent proton is subsequently excreted into the rhizosphere, causing hydrogen ion concentration to increase (Viet San et al., 2022; Yan et al., 2020). By contrast, agroecological tea growers employed organic and biofertilizers as the main soil nutrient supplies, which can restore soil pH because of their buffering capacity and higher pH values compared to that in tea acidic soils (Cornelissen et al., 2018; Gu et al., 2019; Ji et al., 2018). Increasing tea plantation age and plant density can also accelerate soil acidification, as tea roots could release organic and carbonic acids into the rhizosphere, decreasing soil pH (Hui et al., 2010; Viet San et al., 2022). Additionally, organic fertilizers and organic mulches that have been applied in the plantations such as fern (*Gleichenia linearis*), Acacia and Eucalyptus barks, rice straw and other plant residues supplemented a high input of organic materials into the tea soils, which can also increase tea soil organic carbon storage and organic matter (Cu & Thu, 2014; Li et al., 2014; Viet San et al., 2021). Tea plants prefer acidic soil with optimal soil pH values from 4.5 to 5.5, but strongly acidic soils could lead to numerous consequences for tea growth and quality, such as nutrient leaching and imbalance, and heavy metal toxicity (Ni et al., 2018; Zhang, Huiguang, et al., 2020; Zhang, Yang, et al., 2020). With regards to soil available P, our results are constrasted with the study by Han et al. (2013) who indicated that available P concentrations were significantly different between organically and conventionally managed tea farms. This may be due to the inorganic (mainly NPK compounds) and organic fertilization by conventional and agroecological tea adopters in the region providing an equivalent amount of phosphorus for tea plantation soils. Supplying a sufficient amount of phosphorus is essential for tea growth and productivity, as the vigorous growth of young tea trees and frequent harvests of tea leaves require a large demand for P, thereby reducing the total P content of the tea plantation soils (De Schrijver et al., 2012; Wu et al., 2020). Soil P availability also plays a key role in affecting plant mycorrhization (Herrmann et al., 2016; Wang et al., 2020).

Arbuscular mycorrhizal fungi (AMF) have been widely known to be associated with a wide variety of plants and play a key role in plant nutrition by providing access to soil-derived nutrients (Bhantana et al., 2021; Herrmann et al., 2016). AMF communities are affected by a number of environmental factors, such as soil characteristics, host plants and cultivation methods (Ji et al., 2022; Xu et al., 2017). In our study, the average AMF frequency (F) and intensity (M) of the agroecological tea roots were significantly greater than in conventionally managed tea plantations. This finding is similar to observations made by Wu et al. (2020) who indicated that organic tea management significantly increased tea soil AMF contents, while Wang et al. (2017) revealed that long-term application of chicken manure strongly modified tea soil fungal communities. Singh et al. (2008) also showed that the average AMF frequency of roots collected from natural and cultivated tea plantations was 77.6% and 86.5%, and intensity was 11.3% and 23.9%, respectively. Likewise, stimulation of AMF growth by the incorporation of different organic amendments such as rice straw and organic compost has been widely reported in other cultivars (Hammer et al., 2011; Qin et al., 2015). By contrast, numerous studies indicated that mineral fertilizers, especially N and P, adversely affected AMF growth in tea plantations (Toman & Jha, 2011; Wu et al., 2020), in arable soil (Lin et al., 2012) and in rotation system (Qin et al., 2015). It was reported that AMF prefers a near neutral or alkaline soil pH for optimal growth and are strongly correlated with phosphorus level in soil, therefore, intensive application of mineral fertilizers changed the soil pH and P volume in the rhizosphere, thus affecting AMF communities (Helgason & Fitter, 2009; Ma et al., 2021). Furthermore, we observed that the availability of P in this study was negatively correlated with tea root AMF frequency and intensity, suggesting that tea plants may find the necessary elements in the soil and thus the symbiosis with AMF was less profitable (Herrmann et al., 2016; Van Geel et al., 2016).

In our study, tea root AMF frequency and intensity observed in converted tea soils were significantly higher than in original tea plantation soils. These findings are consistent with previous investigations, which have reported that land use changes significantly affected soil fungal communities, which could be attributed mainly to alteration in soil environmental factors, in which soil pH is a proxy (Monkai et al., 2018; Wu et al., 2020; Zheng et al., 2020). Since the highest root mycorrhizal intensity was only 38% across all the trials, it suggests that other options such as the application of bioinoculants containing effective AMF should be introduced to improve tea root mycorrhization, and subsequently soil health and plant growth (Bag et al., 2022; Shao et al., 2018). It has been reported that AMF's incorporation significantly enhanced soil-accessible P concentrations and encouraged P absorption by tea plants, as well as improved tea growth characters (root biomass, plant height) and quality indicators such as amino acids, polyphenolic compounds, caffeine, total protein content and sugars (Cao et al., 2021; Mei et al., 2019; Shao et al., 2021).

4.3 | Soil macro and mesofauna

Intensive agriculture is known to have long-lasting and negative effects on soil biota, making soil food webs less diverse and composed of smaller bodied organisms (Liiri et al., 2012; Tsiafouli et al., 2015). In this study, the abundance, richness and Shanon index of soil macro and mesofauna were significantly greater in agroecological treatments compared to those of conventional tea plots (Table S5 and S6; Figure 3). However, compared with the previous studies of soil faunal communities in tea and other cropping systems, these indices are significantly lower. For instance, a worldwide investigation conducted in 41 countries indicated that soil macroinvertebrate abundance in cropping systems ranged from 232 to 867 individuals/m^2 (Lavelle et al., 2022). Yu et al. (2021) also found up to 26 different soil faunal groups in tea cultivars, with the Shannon index value of 4.65. In our study, the number of soil macrofauna individuals/ m^2 was only from 37 to 86, and only 8 groups of soil fauna occurred in tea plantations, regardless of the tea soil management practices. Strongly acidic soils could be one of the key factors that negatively affect soil faunal communities. For example, it was reported by Han et al. (2007) that in tea plantations, a low soil pH ($pH < 4$) could lead to a loss of up to 70% of soil biota. Greater abundance of soil fauna communities of organic and agroecological farming over its conventional counterparts have been widely reported (Domínguez et al., 2014; Sofo et al., 2020). Manure and organic mulching applications have been widely recognized to positively affect soil faunal communities and functional structures, since these practices not only provided readily available food sources but also regulated soil temperature and moisture (Jiang et al., 2021; Wang et al., 2016). Particularly, Murray et al. (2006) found that organic fertilization directly supplied detritus and indirectly modified the soil nutrient environment for fauna, which subsequently induced an increase in soil faunal abundance. By contrast, conventional agriculture consistently has negative impacts on soil biota, which could be attributed to the detrimental effects of intensive agrochemical inputs, monocropping that systematically simplifies soil food web diversity and microclimate modification because of residue removals. Likewise, Domínguez et al. (2014) suggested that the nonuse of agrochemicals would be enough to produce shifts in soil faunal diversity.

Several studies have also examined the effect of different extraction methods on diversity indices and communities of soil fauna. Active methods such as the Baermann funnel and passive approaches such as filtering and flotation-centrifugation are among the most recognized practices for sampling and extracting soil fauna, which are based on different physicochemical principles of soil fauna (Domingo-Quero & Alonso-Zarazaga, 2010). Dritsoulas and Duncan (2020) indicated that passive extraction methods consistently recovered significantly more soil microarthropods compared with the active techniques. This is in accordance with our findings since the ecological indices (abundance, richness and Shannon index) derived from the centrifugation method were constantly greater than the figures for the funnel techniques, though the differences were not always significant (Figure 3). In addition, the present study results on soil fauna composition are consistent with some previous studies, which indicated that earthworm is the dominant soil macrofauna groups in tea plantations (Jamatia & Chaudhuri, 2017; Kahneh et al., 2022).

4.4 | Tea yield, yield components and green tea sensory quality

Organic and agroecological farming typically have lower harvest yields in comparison to conventional agriculture, which has raised concerns about the potential role of these farming methods as a sustainable strategy in meeting the increasing demand for food and other agricultural services (Schrama et al., 2018; Seufert et al., 2012). Several studies have reported tea harvest yield gaps between conventional and organic tea farming systems (Deka & Goswami, 2021; Doanh et al., 2018; Qiao et al., 2016). This is consistent with our findings since agroecological tea adoption consistently produced less tea harvest yield than the conventional tea implementation over the 3 years of observations (differences were not always significant—Table 3). Agroecological and organic tea farming systems rely on nonchemical inputs such as organic materials and biofertilizers for maintaining crop productivity while restoring soil health and mitigating environmental pollution (Gui et al., 2021; Viet San et al., 2021). In return, these resources may not provide enough sufficient macro- and micronutrients, such as nitrogen and phosphorus for crops to grow and obtain as high yields as a conventional method that employs the intensive application of synthetic fertilizers, especially during the transition period (the first 3–5 years since the conversion from conventional to organic farming management) (Doanh et al., 2018; Han et al., 2018). A comprehensive investigation by Seufert et al. (2012) also revealed that the yield gap between conventional and organic farming systems could be up to 34%, depending on conditions such as site characteristics, crop types and level of intensification. Han et al. (2018) also concluded that tea yields in organically managed agroecosystems are generally 8%–20% lower compared to those in conventional systems. However, our observations in 66 different tea plantations from 2019 to 2021 showed that the yield difference between conventional and agroecological tea systems was less than 8% on average (Table 1). In the studied regions, the agroecological tea adopters invested heavily in organic fertilizers, biofertilizers, organic mulches and other organic materials such as soybean or fish powder, to replace mineral fertilizers, as well as labour costs for weed, pest and disease management, all practices positively contributed to increased tea yield. In addition, the difference in the duration taken from conventional to agroecological farming could play a significant part in reducing the yield gap between conventional and agroecological farming systems, since longer application duration would lead to positive changes in abiotic and biotic soil properties leading to a more efficient, spatially and temporarily stable farming system (Schrama et al., 2018).

Our findings about the tea leaf appearance are in line with the study by Luyen et al. (2014) who indicated that green tea leaves harvested in Tan Cuong commune, Thai Nguyen province were greener, less leafy, wirier and more creepy than tea leaves produced from other regions of the country, which were mainly attributed to the differences in geography, climate, cultivation practices and processing method. Also, the fragrance, fresh and light smell of the brewed teas, intensity of the astrigence, sweetness and bitterness in the taste found in the present study were similar to previous reports concerning the sensory attributes of green tea (Luyen et al., 2014; Tang et al., 2020). Previous studies have indicated that the smell and taste of green tea are mainly driven by the plant chemical components, such as the tea polyphenol with the bitter taste and the astringency, while the sweet, umami taste of green tea generally originates from amino acids, especially theanine, which accounts for about 65% of the total amino acid content in tea leaves (Pongsuwan et al., 2008; Tang et al., 2020). Finally, cultivation practices such as the application of cow manure could alter the metabolism of amino acid, sugar and fatty acids in tea shoots, thus enhancing the human sensory preference for tea brewed aroma and taste (Sun et al., 2021). This correlated with our results that agroecological tea management practices, which employed organic manure as the main nutrient supply, provide a significant difference in sensory marks for tea products. Since the aroma and taste of tea products are key factors determining the quality grade of tea and its market price (Qin et al., 2013; Su et al., 2021), a significant increase in these quality indicators as a result of organic tea management practices would enhance economic benefits for the adopters. Sumi and Kabir (2018) reported that the taste, natural content and the nutrient value of organic tea make it a popular choice for health-conscious customers. Qiao et al. (2016) also indicated that organic tea produced in Wuyuan, China fetches a premium price and consistent purchase orders for organic tea products have been offered, providing stability and incentives for tea farmers for adopting and expanding organic tea production.

5 | CONCLUSION

This comprehensive study compared the impacts of agroecological and conventional tea management practices on soil health properties, tea productivity, economical benefit and quality in Thai Nguyen province as well as in Vietnam. We show that converting conventional tea adoption to agroecological management practices significantly increased tea root AMF intensity by up to 24%, soil macro and mesofauna by 110% and 60%, respectively. Organic fertilizers and manure incorporations also significantly reduced soil acidification rates because of their naturally alkaline characteristics and provided supplement organic matters, thus improving soil OM, AMF colonization and soil faunal abundance and diversity. By contrast, soil conversion from paddy and other annual crop fields to tea plantations did not lead to any significantly adverse effects on soil health properties, suggesting that this practice could be as effective as cultivating tea in nonconverted lands. Despite the lower tea yields, the agroecological management method led to a significant increase in net income for tea farmers, which was mainly driven by the premium price of agroecological tea products and other credits from supporting agencies. These practices, therefore, could be scaled up in Northern Vietnam and other regions, which share similar natural and socioeconomic conditions for more environmentally sustainable economic tea production.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Didier Lesueur https://orcid.org/0000-0002-6694-0869

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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