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Agroecological Practices and the Typology of Milk Production Systems in Brazilian Rural Settlements

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ABSTRACT

This study aimed to conduct a typological analysis of 100 dairy farms in rural settlements in Euclides da Cunha Paulista, São Paulo State, Brazil. Variables related to agroecological practices were used in cluster analysis. The following two groups were identified: Traditional extensive dairy farms (G1) and Modern sustainable dairy farms (G2). Socioeconomic, production, and agroecological variables were used in exploratory factor analysis, generating three factors/typological indicators. Factors were named production scale (F1), socioeconomic level (F2), and cow health, reproduction, and milking practices (F3). Production scale was the factor accounting for most of the variance in the dataset. Differences in indicator scores between dairy farm groups were assessed by the Mann–Whitney *U*-test ($p < 0.05$). The Modern sustainable dairy farm group had a larger production scale ($p < 0.05$), indicating that, among the analyzed systems, production capacity is associated with investment in more sustainable practices. There were no differences in scores for socioeconomic level or cow health, reproduction, and milking practices between groups ($p > 0.05$). Actions are necessary for the studied dairy farms to enhance their production capacity, particularly those comprising group Traditional extensive (59%), thereby maximizing their investment power and promoting the adoption of more sustainable management practices.

KEYWORDS: multivariate analysis; agroecology; dairy production systems; smallholder agriculture

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ABBREVIATIONS

KMO, kaiser-meyer-olkim; TE, Traditional extensive; MS, Modern sustainable; L, liters

INTRODUCTION

The global agricultural sector is under pressure to increase production to meet the growing food demand while ensuring sustainability. Although agricultural production has intensified in recent years, some of the adopted practices have exacerbated environmental problems [1–3]. In this context of environmental and social challenges, world milk production is projected to grow at 1.6% per year until 2029. This rate is faster than that of other major agricultural products and is expected to be more expressive in low-income countries [4].

Brazil is a prominent milk producer, currently ranking third in milk volume in the global market, with about 36.5 million tonnes produced in 2020, behind the United States of America and India, which produced 101.2 and 87.82 billion tonnes of milk, respectively [5]. With such an expressive production volume, dairy farming contributes significantly to the economic development of the country. Dairy products represent an important share of the national agricultural market, with an annual growth of 2.43% between 2008 and 2016, above the world average [6].

Southern and southeastern Brazilian states concentrate a larger number of dairy farms and have higher milk yields. Nevertheless, dairy businesses are widespread throughout the entire country, albeit with large differences in production scale, characterizing a highly heterogeneous sector [7–9]. It should also be noted that dairy farms have nationwide importance, particularly family-based systems, owing to the positive impact they generate at the regional level [8]. Milk production often serves as the main income-generating activity in family farms, including in rural settlements created by the agrarian reform [10,11].

Although recent reports suggest an increase in production efficiency in Brazilian dairy farms, resulting in yield gains, milk production and yield values still fall short of those of other countries, such as the United States, Canada, and the Netherlands [12]. This increase in production volume can be attributed to intensification of dairy farming activities. However, this growth has brought about an increase in environmental impacts resulting from inadequate management practices, in addition to aggravating challenges related to animal health, animal welfare, and economic and social pressures, raising concerns about the long-term viability of milk production systems [13].

Among the practices that can effectively promote sustainability in production systems, one that takes center stage is agroecology. Agroecology is a scientific discipline that lays the methodological foundation for developing sustainable agricultural models and rural development strategies rooted in ecological principles [14]. Agroecological production models commonly rescue ancestral values and knowledge while also incorporating scientific and technological advances, thereby providing solutions for the production of pesticide-free, clean foods at any scale of production [15].

The development of agroecology has been accompanied by a broader adoption of ecologically based dairy farming. Ecological dairy farms are agrosystems that embrace sustainable practices, typically including the gradual introduction of ecological pasture management, increased forage diversity, afforestation, breeds adapted to local environmental conditions

[16], pest and disease management programs potentially including phytotherapy and homeopathy [17], minimal use of agrochemicals, and reduced dependence on external resources. Furthermore, ecological production systems tend to offer better working conditions, enhancing social sustainability [18].

Several studies have reported the sustainability challenges faced by dairy farms, mostly related to environmental impacts, production costs, animal welfare, working conditions, income generation, and policy impacts [7,19,20]. A major challenge currently faced by agents operating in agricultural systems is to supply the population with agricultural products without causing environmental degradation or producing negative social and economic impacts. It is consensus that actions must be taken to foster the adoption of more sustainable practices. Studies carried out in Brazil showed that farmers' actions aimed at improving the economic, social, and environmental sustainability of dairy farms contribute to the long-term survival of the agribusiness [7,21].

Further research is needed to gain a more objective understanding of the diversity of Brazilian dairy farms and of which system components influence sustainability. Typological analysis has been applied in dairy research, including in the study of the Brazilian milk production sector [7,22]. In view of the low level of adoption of sustainable management practices in Brazilian dairy farms, this study aimed to conduct a typological analysis of dairy farms in rural settlements in Euclides da Cunha Paulista, São Paulo State, Brazil, based on ecological practices.

Our research questions are based on the following aspects: (a) do farmers who use agroecological practices have a structural, socioeconomic, and milking practice typology that is different from farmers who use conventional production practices? and (b) what are the main typological characteristics that distinguish farmers who use agroecological practices from those who do not? Based on these questions, three hypotheses were defined: h1: producers using agroecological practices have a larger scale structural typology compared to producers using conventional production practices; h2: farmers using agroecological practices have better socioeconomic typology results compared to farmers using conventional production practices; and h3: farmers using agroecological practices have better typology results related to milking practices compared to farmers using conventional production practices. Scientifically, the results of this research allow the analysis and discussion of the relationship between dairy systems using agroecological production practices and the characteristics of the typology of these systems and their rural farmers. In an applied sense, the results of this research could contribute to the creation of public and/or private strategies to strengthen dairy production towards sustainability.

MATERIALS AND METHODS

The study was conducted in Euclides Da Cunha Paulista, one of the 32 municipalities of a microregion known as Pontal do Paranapanema (between 20° and 24°S and 50° and 54°W), in the westernmost part of São Paulo State, Brazil (Figure 1). According to the Köppen and Geyser classification, the climate is tropical with a dry season (Aw), with an average temperature of 21.9 °C and mean annual rainfall of 1370 mm [23].

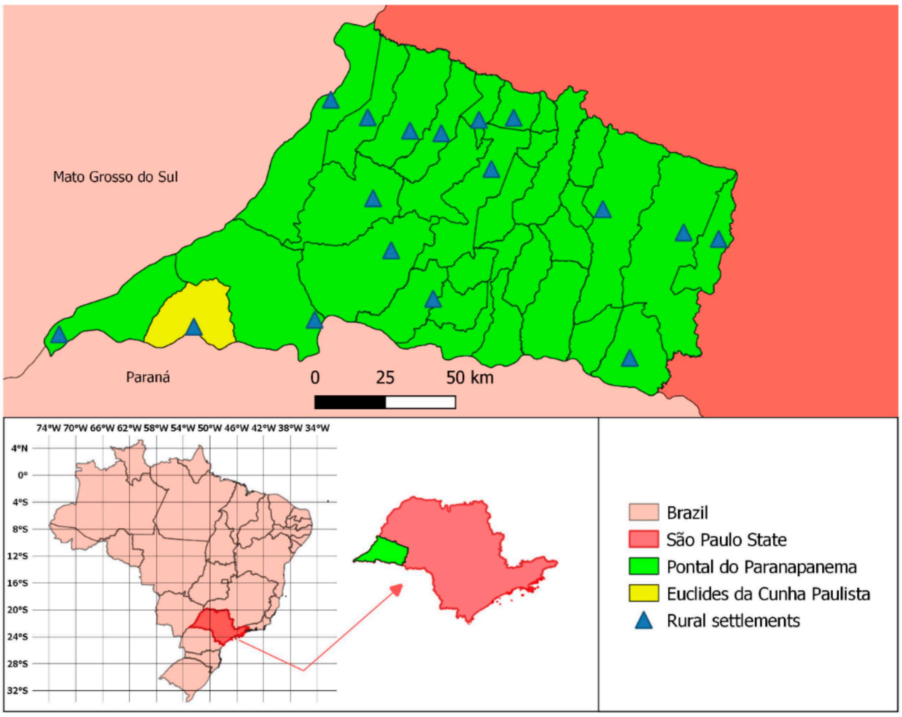

Figure 1. Location map of rural settlements in Euclides da Cunha Paulista and other municipalities of Pontal do Paranapanema, São Paulo State, Brazil. Source: the authors.

The region is characterized by very sandy, low-fertility soils that are easily carried by water when the protective vegetation is removed. There is a history of land appropriation and multiple conflicts related to unlawful land acquisition, with disputes between indigenous peoples, small squatters, and farmers, which led to intense degradation of native vegetation [24]. During this period, which became more intense from 1919, native forests underwent a dramatic reduction, and the landscape was altered by extensive cattle ranching and disorderly farming practices on heavily degraded soils, producing one of the most devastated regions in São Paulo State [25].

In the 1980s, with intensification of the Brazilian Agrarian Reform, several rural settlements were created in Pontal do Paranapanema. Currently, the region houses 6272 families in 117 settlements located in 17 municipalities as part of the National Agrarian Reform Program and the São Paulo State Public Plans for the Utilization and Valorization of Land Resources (Figure 1). Euclides da Cunha Paulista contains 10 rural settlements with the capacity for housing 653 families [26,27].

Over time, dairy farming became the primary economic activity of Pontal do Paranapanema rural settlements [28–30], attributed to the establishment of pastures on low-fertility soils even before settlements were created. Although these dairy farms have a low level of technological adoption and low yields, the activity serves as a reliable source of income, providing subsistence for families and contributing to their permanence on the land [29]. In these dairy systems, important technologies that could increase productivity and consequently profitability for these farmers, such as the artificial insemination of animals, the production of preserved fodder to offer at times of the year when there is a shortage of pasture, the provision of balanced feed according to the animal category, among other practices and technologies, are not often used. This is mainly due to the lack of financial resources to acquire and technical knowledge about the importance of using these technologies. Nevertheless, there are several challenges from the point of view of sustainability. Dairy farming in Pontal do Paranapanema was introduced to already-degraded pastures, depends greatly on external inputs, and is characterized by high production costs and low levels of technical knowledge [29]. Moreover, there are problems related to the inadequate adoption of conventional production practices, such as excessive use of agrochemicals and intense environmental degradation, resulting in soil erosion and contamination of natural resources [30].

Data Collection

Data collection was carried out on site by a single researcher. A total of 100 dairy farms in 10 rural settlements of Euclides da Cunha Paulista, São Paulo State, Brazil, were randomly selected and visited between June and November 2021. The survey was carried out with the dairy farmer—owner of the production system after they agreed to participate in the research. First, farmers were informed of the study objectives and were assured that participation was voluntary and all data collected were confidential. Semi-structured questionnaires contained 31 questions divided into three sections, as follows: Section 1 (8 questions), socioeconomic variables; Section 2 (12 questions), technical and production variables; and Section 3 (11 questions), agroecological variables (Table 1). Responses were either metric or ordinal. For ordinal responses, scores ranged from 2 to 10 at 1-point intervals. The highest score indicated the adoption of sustainable ecological or animal production practices, whereas the lowest score indicated a lack of adoption of sustainable practices. Several studies used ordinal responses for the quantification of practices or actions adopted in agricultural systems [31].

The variables analyzed in the current study were adapted from previous studies examining sustainability issues in dairy farming [7,22,32–34]. The scores for each question were given by the farmers. No different scores or weights were assigned to any situation. The interviewer put the questions to the farmers, and they freely and spontaneously gave scores between 2 and 10 points. The score given by the farmer was recorded by the interviewer. After applying the form, the interviewer made observations of the facilities used by the farmer, which made it easier to conduct qualitative interviews in a more appropriate way.

Table 1. Socioeconomic, technical and production, and agroecological variables analyzed in the study.

Variable	Response type	Statistical analysis
Socioeconomic variables		
V1. Dairy farming experience (years) V2. Age of farm operator (years) V3. Workforce size V4. Family workers (%)	Metric	Factor analysis
V5. Level of education of farm operator V6. Participation in farmers' groups V7. Sources of income (production diversification) V8. Future perspectives	Ordinal (2 to 10)	Factor analysis
Technical and production variables		
V9. Total farm size (ha) V10. Milk production area (ha) V11. Number of dairy cows V12. Number of cows in milk V13. Mean milk yield per cow (L cow^{-1} day^{-1}) V14. Total daily milk yield (L day^{-1}) V15. Mean annual yield per area (L $year^{-1}$ ha^{-1}) V16. Calving interval (months) V17. Annual number of mastitis	Metric	Factor analysis
V18. Milking process V19. Milking hygiene V20. Health and reproductive control	Ordinal (2 to 10)	Factor analysis
Agroecological variables		
V21. Soil management V22. Pesticide use V23. Fertilizer use V24. Pasture management V25. Forage species V26. Winter/dry season strategy V27. Source of supplementary feed V28. Water supply V29. Pasture afforestation V30. Medicine use V31. Waste management	Ordinal (2 to 10)	Cluster analysis

Source: [7,22,32–34].

Data Analysis

The data were tabulated using Microsoft Office Excel and subsequently analyzed using Jamovi software version 1.8 [35] and R software version 4.0 [36]. The following statistical tests were applied: descriptive analysis, hierarchical cluster analysis, exploratory factor analysis, and tests of means to assess differences between farm groups.

Hierarchical cluster analysis was used to group farms according to ecological practices (V21 to V31, Table 1). This exploratory technique allows verifying the existence of similar behaviors among farms in relation to certain variables, identifying groups that are internally homogeneous and externally heterogeneous [37]. The model used for hierarchical clustering is given by equation (1).

$$d[k,(ij)] = max[d(k,i), d(k,j)] \quad (1)$$

This agglomerative algorithm calculates the shortest distance between elements *i* and *j* using the distance matrix d_{ij}. Agglomeration was performed using complete linkage and Euclidean squared distance metrics [38].

Exploratory factor analysis was used to identify correlations between variables and extract factors, or groups of interrelated variables, resulting in structural reduction of the dataset and generation of typological indicators (factors) [38]. Factors were extracted by principal component analysis with varimax rotation. The Kaiser-Meyer-Olkin (KMO) test and Bartlett's sphericity test were used to evaluate the suitability of the data for factor analysis. Variables with factor loadings greater than 0.5 were retained [38]. The exploratory factor analysis model is described in equations (2 to 7).

$$X_1 = a_{11} \times F_1 + a_{12} \times F_2 + \cdots + a_{1m} \times F_m + e_p \quad (2)$$

$$X_2 = a_{21} \times F_1 + a_{22} \times F_2 + \cdots + a_{2m} \times F_m + e_p \quad (3)$$

$$X_p = a_{p1} \times F_1 + a_{p2} \times F_2 + \cdots + a_{pm} \times F_m + e_p \quad (4)$$

where X_p is the p-th score of the standardized variable (p = 1, 2, ..., m), F_m is the extracted factor, a_{pm} is the factor loading, and e_p is the error.

The factor score of each dairy farm was estimated by multiplying the standardized variable score by the corresponding factor score coefficient (equations (5 to 7)):

$$F_1 = d_{11} \times X_1 + d_{12} \times X_2 + \cdots + d_{1j} \times X_{jp} \quad (5)$$

$$F_2 = d_{21} \times X_2 + d_{22} \times X_2 + \cdots + d_{2j} \times X_{jp} \quad (6)$$

$$F_j = d_{j1} \times X_1 + d_{j1} \times X_2 + \cdots + d_{jp} \times X_{jp} \quad (7)$$

where F_j is the j-th extracted factor, d_{jp} the factor score coefficient, and p the number of variables [38].

To define the typology factors, we used as input variables in the exploratory factor analysis those related to the socioeconomic and techno productive typology of the farmers (V1 to V20—Table 1).

Finally, dairy farm groups were subjected to typological analysis based on ecological practices. Typological analysis is used to identify specific practices of different groups. Normality was assessed by the Kolmogorov–Smirnov and Shapiro–Wilk tests and homogeneity of variance by Levene's test. As the data were found to be non-normally distributed, a non-parametric test (Mann–Whitney *U*-test, $p < 0.05$) was used [39].

RESULTS

The evaluated dairy farms were heterogeneous with regard to structural, production, and socioeconomic characteristics. The mean total farm size was 19.89 ± 9.40 ha, with 16.21 ± 9.16 ha being used for milk production (81% of the total area). The amount of land (81% of total area) dedicated for dairy production includes the land used for pasture and other crops needed to feed the dairy herd, such as corn production. The fact that most of the land is devoted to milk production indicates the economic dependence of the families on this activity (Table 2). This strong link was confirmed by the future perspective of participants: 97% of farmers had the intention of maintaining or increasing production. It is noteworthy that 51% of dairy farms performed at least one other activity, and 2% performed more than three economic activities. Other areas of the property (19% of total area) include permanent conservation areas such as forest and/or water sources and family living areas.

Regarding milk production, the total daily milk yield was 68.85 ± 49.75 L day^{-1}, and the average annual milk production per cow was as follows 2168.55 ± 727.85 L year^{-1}. The mean herd size was 19.39 ± 11.11 and the number of cows in milk was 9.65 ± 5.28. The mean yield per cow was 7.11 ± 2.39 L day^{-1} and the annual yield per area was 1716.84 ± 1153.80 L ha^{-1} year^{-1} (Table 2). Farm operators had a mean age of 50.96 years, with 20.23 years of experience in dairy farming (Table 2). During the study, it was observed that most of the herds were composed of crossbred dual-purpose animals and few producers bred specialized dairy cows. Among the most common crosses observed were those between Holstein, Girolando and Jersey animals and Nelore cattle. In addition, we observed that male animals were not kept on farms but were often sold to other farmers.

Table 2. General characteristics of dairy farms (n = 100) analyzed in the study.

Variable	Min	Max	Mean	Standard deviation
Total farm size (ha)	7.00	50.00	19.89	9.40
Milk production area (ha)	2.50	45.00	16.21	9.16
Herd size (heads)	4.00	60.00	19.39	11.11
Number of cows in milk (heads)	2.00	30.00	9.65	5.28
Mean milk yield per cow (L cow^{-1} day^{-1})	3.00	15.00	7.11	2.39
Total daily milk yield (L day^{-1})	8.00	320.00	68.85	49.75
Mean milk yield per cow (L cow^{-1} year^{-1})	915	4575	2168.55	727.85
Mean annual yield per area (L year^{-1} ha^{-1})	472.35	7019.20	1716.84	1153.80
Age of farm operator (years)	22.00	77.00	50.96	11.42
Dairy farming experience (years)	1.00	55.00	20.23	10.85

Agroecological variables are presented in Table 3. In general, the mean scores were low, particularly those on waste management, forage species, source of supplementary feed, soil management, and medicine use. On the other hand, water supply, fertilizer use, and pesticide use had the highest means.

Table 3. Agroecological scores of dairy farms (n = 100) analyzed in the study.

Variable	Min	Max	Mean	Standard deviation
Waste management	2	8	3.94	0.722
Forage species	2	8	3.66	1.208
Source of supplementary feed	2	8	3.94	1.347
Soil management	2	8	3.96	0.634
Pasture management	2	8	5.12	1.373
Winter/dry season strategy	2	10	5.74	1.813
Pasture afforestation	2	8	5.36	1.630
Water supply	4	10	7.76	1.640
Fertilizer use	2	10	6.60	3.345
Pesticide use	2	10	6.58	2.075
Medicine use	2	8	3.58	1.490

The agroecological variables that formed the most consistent groups were waste management, forage species, source of supplementary feed, soil management, and pasture management. Dairy farms with similar characteristics with regard to these agroecological practices were grouped, differing from farms of the other group.

Hierarchical cluster analysis generated two groups. Group 1 was composed of 59 dairy farms (59%) and group 2 comprised 41 dairy farms (41%) (Table 3). Groups 1 and 2 differed (p < 0.05) in the following agroecological variables: waste management, forage species, source of supplementary feed, soil management, and pasture management. Nevertheless, both groups had low mean scores for agroecological variables, indicating little use of ecologically based practices (Table 4).

Table 4. Agroecological scores of dairy farm groups identified by hierarchical cluster analysis.

Variable	Group	*n*	Mean	Standard deviation	*p*-value
Waste management	TE	59	3.76^{b}	0.652	0.003
	MS	41	4.20^{a}	0.749	
Forage species	TE	59	3.08^{b}	1.005	<0.001
	MS	41	4.49^{a}	0.978	
Source of supplementary feed	TE	59	3.63^{b}	1.202	0.008
	MS	41	4.39^{a}	1.430	
Soil management	TE	59	3.83^{b}	0.562	0.013
	MS	41	4.15^{a}	0.691	
Pasture management	TE	59	5.54^{b}	1.222	<0.001
	MS	41	5.95^{a}	1.139	

TE, Traditional extensive dairy farms; MS, Modern sustainable dairy farms. [a,b] For each variable, means followed by different letters are significantly different at p < 0.05.

Group 2, consisting of 41% of the dairy farms, obtained higher scores on agroecological variables, indicating that these farmers adopt such practices more intensively, with a higher degree of sustainability. Therefore, the group was called Modern sustainable dairy farms. Group 1, consisting of 59% of the dairy farms, obtained lower mean scores on agroecological variables, thus being called Traditional extensive dairy farms.

No dairy farm performed adequate waste treatment, but, in 90% of cases, farms used solid waste for fertilization of forage crops and vegetable gardens. Almost all dairy farms (98%) performed soil tillage, even if sporadically.

Typological Indicators

The KMO value was 0.688 and Bartlett's test was significant ($p < 0.05$), indicating that the 10 variables used in this study were adequate for exploratory factor analysis [38]. Three factors had an eigenvalue greater than 1.0 and explained 67.3% of the variance in the dataset (Table 5).

Table 5. Variance explained.

Factor	Eigenvalue	% of variance	Cumulative %
Production scale	3.49	34.9	34.9
Socioeconomic level	1.75	17.5	52.4
Cow health, reproduction, and milking practices	1.49	14.9	67.3

Production scale includes the variables milk production area, herd size, farm size, number of cows in milk. Socioeconomic level includes the variables age, level of education, and dairy farming experience of farm operators. Cow health, reproduction, and milking practices includes the variables milking hygiene, health and reproductive management, and milking process.

Each factor was labeled according to the variables composing it. The factor labeled Production scale explained the largest amount of variance between dairy farms (34%). The factor was composed of the variables milk production area, herd size, farm size, and number of cows in milk (Table 5). These variables represent production capacity and may directly influence the success of the activity, associated with increased revenue and investment power.

The factor labeled Socioeconomic level, accounting for 17.5% of the variance in the dataset, was defined by age, education level, and dairy farming experience of the farm operator (Table 5). These variables define the knowledge, experience, and disposition of farmers, which may influence the actions and management practices adopted.

The factor labeled Cow health, reproduction, and milking practices was defined by the variables milking hygiene, health and reproductive management, and milking process (Table 5). This factor accounted for 14.69% of the variation in the dataset. The variables are associated with herd health, yield, and milk quality. Table 6 shows the factors, variables, and respective factor loadings.

Table 6. Factor loadings and variables included in each factor.

Variable	Production scale	Socioeconomic level	Cow health, reproduction, and milking practices
Milk production area	0.911		
Herd size	0.896		
Farm size	0.874		
Number of cows in milk	0.869		
Age of farm operator		0.901	
Level of education of farm operator		−0.722	
Dairy farming experience		0.621	
Milking hygiene			0.827
Health and reproductive management			0.666
Milking process			0.532

* Variables with factor loading > 0.5 were retained.

Typology of Dairy Farm Groups

Typological analysis of dairy farm groups revealed that groups Traditional extensive and Modern sustainable did not differ ($p < 0.05$) in socioeconomic level or cow health, reproduction, and milking practices. This result is an indication that we should reject hypotheses h2 and h3 of this research.

Group Modern sustainable obtained a higher score ($p < 0.05$) on production scale (Table 6). This result allows us to accept the hypothesis h1 defined in this research. Modern sustainable dairy farms, characterized by systems adopting agroecological practices more intensively, had greater production scale, whereas Traditional extensive farms were characterized by reduced production capacity and income generation, possibly resulting in lower investments in production area and herd (Table 7).

Table 7. Factor scores of dairy farm groups identified by hierarchical cluster analysis.

Factor	Group	Mean	Standard error	*p*-value
Production scale	TE	−0.1015[b]	0.138	0.038
	MS	0.146[a]	0.141	
Socioeconomic level	TE	0.0863[a]	0.124	0.664
	MS	−0.124[a]	0.167	
Cow health, reproduction, and milking practices	TE	−0.0744[a]	0.138	0.080
	MS	0.107[a]	0.142	

TE, Traditional extensive dairy farms; MS, Modern sustainable dairy farms. [a,b] For each factor, means followed by different letters are significantly different at $p < 0.05$.

Although groups did not differ significantly in socioeconomic level or cow health, reproduction, and milking practices, in general, the level of application of adequate management practices, technological resources, and education was low. Regarding level of education, 55% of farm operators had completed only elementary school.

DISCUSSION

The diversity in production characteristics among the dairy farms analyzed here indicates that farms are heterogeneous with regard to management practices, resulting in different production scales. Such differences were observed despite the fact that all participating farms were located in rural settlements and therefore had to comply with maximum area requirements. Heterogeneity is commonly observed in Brazilian dairy systems, as reported in several studies assessing farms with different production scales and sizes [7,40,41].

In the current study, dairy farms had a maximum total area of 50 ha and were family-run, with a predominance of family labor, being therefore classified as family farms. According to Brazilian legislation [42], a family farmer or family entrepreneur is someone who practices activities on a rural property with an area smaller than four tax modules, whose activity is family-run, with a predominance of family labor and a given percentage of the household income derived from the rural enterprise. The tax module [43] is expressed in hectares and varies according to municipality. It is determined by taking into account the type and income of the predominant agricultural activity of the locality, as well as the concept of “family property”. In the municipality of Euclides da Cunha Paulista, São Paulo State, the tax module is 30 ha. Therefore, all dairy farms analyzed in the current study are classified as small rural properties [44].

Although family farming in Brazil is associated with food and nutritional security, given the close link between household and production environments, the limited production area may be seen as a structural problem, compromising the economic viability of dairy activity. Family farmers, in general, have low technology adoption, given the limited access to information, small workforce, inadequate infrastructure, and type of social organization. Therefore, it is crucial to seek alternatives to improve their production capacity and negotiating power [45]. Our results confirmed the low technological level of rural dairy farms.

Dairy farms had a mean total daily milk yield of 320 L day^{-1}, and 97% of farms did not exceed 200 L day^{-1}. As stated by Ferazza and Castellani [46], 92.6% of Brazilian dairy farms are small-scale, with a total milk yield of 200 L day^{-1}. The findings are in agreement with the typical herd characteristics of the study region, as analyzed by Pagani et al. [47]. The authors found that dairy farms of western São Paulo State generally have crossbred cattle with poor milk performance. Beef bulls are used for reproduction to allow complementary income from calf sales. Herds generally comprise up to 50 cows, as observed in 85% of dairy farms. A study analyzing 143 dairy farms in another microregion of western São Paulo State reported a total farm area of 0.50 to 171.00 ha, daily milk production of 8.00 to 700.00 L, and mean daily yield of 132.59 L day^{-1} [48].

Dairy production is directly influenced by production efficiency. Birth rate, animal longevity, number of replacement heifers, and genetic progress of the herd directly affect the productivity and profitability of the dairy activity. Thus, it is essential to monitor the reproductive and production characteristics of the herd and perform sanitary examinations to identify any reproductive problems and create strategies and interventions [49]. Dairy farms with better animal performance indices are associated with practices that promote production and reproductive potential, greater physical structure, increased feed autonomy, and higher production volumes [50]. Several studies on Brazilian dairy farms indicated that a larger production scale may translate into greater sustainability. High daily yield, yield per cow, yield per area, and herd size were associated with dairy systems that adopt practices to increase economic, social, and environmental sustainability, regardless of total farm size [7,21].

Group Modern sustainable (n = 41) scored higher on waste management, indicating that these farms apply solid waste for grass forage and pasture fertilization. According to Pegoraro [51], this practice is a critical point of internal biosecurity, as inadequate use of solid waste may lead to contamination of water, pasture, and hay. Other waste management alternatives include biogas and biofertilizer production, waste stabilization pond, composting, and manure processing.

Soil management is carried out more sustainably by group Modern sustainable. These farms till soil sporadically, whereas group Traditional extensive farms perform tillage intensively. Tillage practices, such as plowing, harrowing, and subsoiling, as well as pasture burning and continuous grazing, destroy soil structure and reduce organic matter content, causing compaction, compromising soil fauna, and leading to erosion and reduced fertility. These factors may generate dependence on agrochemicals [15].

Pasture management was performed more adequately by group Modern sustainable, indicating that they have a greater number of pasture divisions, affording better grazing control and higher forage yield and quality. However, none of the farms adopted Voisin rational grazing. According to Machado [52], Voisin rational grazing maximizes production by optimizing the pasture-animal-rotation interaction. This efficient method does not compromise environmental quality and improves soil fertility, reducing the need for machines, inputs, and labor, being essential for sustainable and ecologically friendly agriculture.

The extensive territory of Brazil and its tropical climate are favorable for the cultivation of grassy forages and legumes. Pastures are widely used as cattle feed, providing benefits from economic and environmental points of view. Pastures have low cost and high capacity to fix atmospheric carbon, provided that they are managed properly [53]. In this context, Voisin rational grazing is a viable management technique that meets current technical and environmental standards. It contributes to the regular, profitable production of fodder and enhances the generation of ecosystem services, such as soil carbon fixation, water retention, increased water quality and soil health, and stimulation of species biodiversity [12].

Non-adoption of Voisin rational grazing in the systems analyzed here, as well as in other regions of the country, is likely related to farm operators' resistance to changes and/or new techniques, difficulties in understanding and applying Voisin rational grazing laws, and perceptions of high costs and labor. Furthermore, farmers may consider conventional methods to be easier and methods that require low use of external inputs to be unfeasible, preferring conserved forage and refusing to build knowledge. Another factor may be the lack of specialized professionals for technical assistance and marketing strategies that encourage input acquisition and use [54].

Forage diversification was higher in group Modern sustainable. These farms likely intercrop forage species or plant different species in separate areas. In monoculture pastures, animal health may be negatively affected by low nutritional diversity. It is recommended to offer a mixture of tropical pastures or use paddocks with different forages and a variety of herbs. Short grasses are more suitable for dairy cattle, but legumes may be offered at a ratio of up to 30% [16].

English farmers reported that investments in pasture division, diversification of forage species, afforestation of grazing areas, and crop-livestock integration afforded higher forage yield and quality, increased animal performance, and improved health and soil fertility, among other production and environmental gains. Some of the reported disadvantages were the need for initial investments in infrastructure, machinery, equipment, and inputs and negative reception of farmers according to their perspectives and values [55].

Group Modern sustainable scored higher on source of supplementary feed. This parameter is related to the adoption of feed strategies for the winter and drought periods, indicating reduced dependence on external feed. The most efficient way to overcome pasture deficit is to process and store surplus forage as hay or silage. Other options include direct grazing or harvest of grass forage and use of alternative feed free of contaminants [52]. Dairy farms that invest in nutritional management, making the most of strategic moments and pasture scarcity, are characterized by a greater production structure (production scale), with greater farm size, production area, herd size, and milk yield. Such practices, when associated with milking management and herd control, contribute to positive production results [56].

Typological analysis revealed that group Modern sustainable had greater production capacity, larger production area, and greater number of cows in milk. These farms were characterized by a more intensive use of sustainable management practices. Several studies showed that variables related to production scale can differentiate dairy systems in Brazil [41,57]. Factors promoting socioenvironmental and economic sustainability contribute to meeting institutional requirements for milk quality, enhancing bargaining power, autonomy, and production control, thereby contributing to long-term permanence in the activity [7,22,21].

Dairy farms with greater production capacity have good milking practices, higher milk quality, increased farmer knowledge, adequacy with environmental laws, and higher levels of social sustainability [7]. Dairy farms with greater production capacity also have more efficient financial management, with greater autonomy and production control [22]. These characteristics may contribute to increasing product volume and quality. Dairy farms that achieve high production volumes and yields are associated with environmental sustainability, being in accordance with Brazilian environmental legislation. These farms generally have adequate waste management; adopt practices that promote the preservation of water resources, flora, and fauna; use organic fertilizers; and maintain high soil and pasture quality [21].

Production gains and farm sustainability are influenced by farm operators' experience in the dairy activity and training. Older age and low education level can be barriers to the adoption of new technologies. Younger farmers tend to have greater control over financial management, as evidenced by the use of software [57]. Age group and education level may influence the decisions made by farm operators, reflecting on farm performance. Farmers with older age and low education levels tend to not meet current market and institutional requirements and are less likely to adopt production technologies [22,57–59].

A low education level may negatively affect milk volume and quality. Farmers who adopt adequate milking management and hygiene practices, such as individual registration of cows, produce higher-quality milk, complying with sanitary laws and promoting greater financial return [22,60]. Farmers who do not comply with sanitary laws have low chances of remaining in the dairy activity in the medium and long terms [40]. Therefore, participation in training programs to improve milk quality may contribute to increased production structure and scale, more knowledge about quality parameters, and adoption of adequate management techniques. Farms that meet such requirements often receive price bonuses for high milk quality [61].

Meeting institutional and market demands for milk production volume and quality results in a higher price paid per liter of milk. This factor may encourage farmers to invest in production capacity, workforce, and other related aspects [61], contributing to permanence in the activity [8,48]. Such investments may include training and education for agroecological transition toward more sustainable production systems. However, transformation of dairy farms into more resilient and sustainable systems does not depend solely on investment capacity; it is necessary to stimulate the replacement of inputs and adoption of more adequate management practices. According to Caporal [62], in light of current socioenvironmental and economic challenges, changes are necessary to guide and facilitate such a transition toward ecological and social sustainability. Rural outreach, particularly public outreach, efforts are fundamental for family farmers, who must reinvent themselves and participate actively aiming at agroecological practices.

Overall, group Modern sustainable dairy farms had greater feeding autonomy, with more effective pasture management and less external dependence on supplementary feed. These farms also adopted more adequate practices regarding solid waste and soil management. These characteristics are associated with greater investments in production structure, such as in total farm size and production area. This group of farmers may increase sustainability by intensifying and implementing new agroecological practices, such as Voisin rational grazing, forage diversification and intercropping, internal production of supplementary feed, and waste treatment/reuse, further reducing their external dependence on inputs. Group Traditional extensive farms should invest in production scale, production structure, and milk quality to increase their production and investment capacity, allowing progress in other aspects of the production system.

CONCLUSIONS

Dairy farms from rural settlements in Euclides Da Cunha Paulista, Pontal do Paranapanema, São Paulo State, Brazil, are characterized by low adoption of agroecological management practices. Nevertheless, dairy farms were found to be heterogeneous, differing in factors related to production scale.

Dairy farms with higher production capacity had greater adoption of agroecological practices. This finding indicates that a greater production volume, achieved via investments in more technically appropriate practices, is directly linked to sustainability, increasing the likelihood of permanence in the activity in the long term.

Actions are necessary for the studied dairy farms to enhance their production capacity, particularly those comprising group Traditional extensive (59%), thereby maximizing their investment power and promoting the adoption of more sustainable management practices. These necessary transformations, however, must be participatory and guided by agroecological principles, with the action of rural outreach efforts to facilitate and encourage transition.

As future research, we suggest adding questions about the genetic standard of the animals, animal welfare, the type of production system—extensive, semi-extensive or intensive, information and data on nutritional aspects, among others—to the studies on sustainability in dairy production.

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study. Farmers agreed to participate in the survey on a voluntary basis. Data and information were anonymized and the farmers were not identified.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

MSSG, FIB and AAS designed the study. MSSG performed the data collection. FIB analyzed the data. MSSG wrote the paper with input from all authors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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