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RESEARCH ARTICLE

Diversification supports farm income and improved working conditions during agroecological transitions in southern Brazil

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Abstract

Management of crop diversity for improved agroecosystem functioning can provide economic co-benefits to farmers. Yet, there remain critical gaps in understanding how farm management practices evolve through agroecological transitions and how agroecological practices affect socioeconomic outcomes such as income and working conditions. We conducted a case study of farms transitioning from conventional tobacco production to diversified agroecological management in a participatory certification network in southern Brazil. We purposively sampled farms along a transition gradient and conducted crop diversity and management surveys and semi-structured, in-depth interviews with household members. Using these data, we assessed indicators of ecological management, income, and working conditions across three transition stages—conventional, transitioning, and agroecological. We found that ecological management indicators increased in magnitude and evenness by transition stage, as transitioning farmers increasingly used practices to support ecological complexity. Agroecological farmers utilized system redesign, a transformative approach to agroecosystem management, rather than efficiency-based or substitution-oriented practices adopted by conventional and transitioning farmers. While farms in transition reported more difficult working conditions and lower incomes, agroecological farmers had similar per capita working hours and improved work quality and occupational safety relative to conventional farmers in the region. On a per capita basis, experienced agroecological farmers earned similar net agricultural incomes and higher net household incomes than conventional farmers, by reducing agricultural expenses and diversifying their markets and livelihoods. Our study is the first to our knowledge to use a transition gradient approach to examine how agroecological transition stage affects both ecological and socioeconomic indicators on farms, providing insights into the processes and pathways by which farmers overcome challenges during transitions. Results highlight the potential for stable profits and improved working conditions on farms following agroecological transitions, within a supportive policy and market context.

Keywords Agroecology · Diversified farming systems · Ecological management · Financial independence · Market access · Participatory certification · Income · Sustainability transitions · Working hours · Work quality

1 Introduction

The United Nations Sustainable Development Goals demonstrate rising global acknowledgement that in order to feed a growing population through 2030 and beyond, agriculture must become more sustainable and equitable (Blesh et al. 2019). Agricultural shifts toward more biodiverse and biologically mediated models of food production are called "agroecological transitions" (Ollivier et al. 2018). While the phenomenon is well-recognized, the scientific community is only beginning to understand the processes and pathways that enable successful agroecological transitions, in part because there are few contexts in which policy and market conditions support them (Miles et al. 2017). Here, we conducted an integrated ecological and socioeconomic assessment of farms transitioning from conventional tobacco monocultures to agroecological management of horticultural crops and livestock in southern Brazil. Our study is the first to show how farm management practices affect income and working conditions on farms at different stages of agroecological transition, in the

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context of a farmer network and supportive institutional environment in southern Brazil.

Theoretical frameworks of agroecological transitions have now existed for multiple decades (e.g., Hill and MacRae 1996). A large body of work summarized by Gliessman (2014) conceptualizes agroecological transitions as processes with five stages: (1) input efficiency, (2) input substitution, (3) system redesign, (4) formation of alternative food networks, and (5) construction of a new global food system. The first three of these occur at the agroecosystem level, the primary focus of the present study, whereas the final two stages necessarily include the entire food system. Input substitution and efficiency are considered "incremental" but necessary shifts toward sustainable food systems, while system redesign, alternative food networks, and developing a new food system are "transformational" (HLPE 2019).

Practically, studying agroecological transitions requires the operationalization of concepts and indicators that encompass the management practices, social dynamics, and ecological innovations that together represent the field of agroecology (Wezel et al. 2009, 2020). As a science, agroecology applies ecological principles to agricultural systems to enhance biodiversity and ecosystem functions, with potential long-term benefits for soil fertility and productivity (Kremen et al. 2012; Gliessman 2014). Increasing crop diversity on farms supports multiple ecological functions such as nutrient cycling and beneficial species interactions that contribute to the success of agroecological transitions (Isbell et al. 2017; Dainese et al. 2019). The effects of diversification on ecosystem services tend to be magnified when multiple practices are combined, such as integrating mixed crop-livestock systems and cover cropping on a farm (Beillouin et al. 2019; Rosa-Schleich et al. 2019). Diverse crop rotations may also improve resilience on farms with adverse environmental conditions by increasing agroecosystem functioning, reducing reliance on a few staple crops, and balancing food availability throughout the year and over multiple growing seasons (Lin 2011; Bowles et al. 2020).

In addition to ecological processes, agroecology emphasizes social transitions (e.g., through changing practices, farmer learning networks, and supportive social movements) that must also occur for long-term changes to agricultural sustainability to take place (Mier et al. 2018; Ollivier et al. 2018). While no comprehensive list of socioeconomic indicators for agroecology has been developed, a recent review identified 13 main socioeconomic themes relevant to agroecology, including environmental equity, financial independence, market access and autonomy, sustainability and adaptability, and partnership between producers and consumers, among others (Dumont et al. 2016). Each theme reflects agroecology's valuation of self-governance and collective mechanisms for change, distinguishing agroecology from other agricultural paradigms that focus on profitability as a sole measure of socioeconomic success. More recently, Wezel et al. (2020) defined 13 agroecological principles that encompass ecological, social, and economic aspects of food systems and their importance for agroecological transitions, complementing the 10 elements of agroecology recently defined by the Food and Agriculture Organization (FAO) of the United Nations (Barrios et al. 2020). While both Dumont et al.'s themes and Wezel et al.'s social and economic principles apply at multiple levels of the food system, many of them have yet to be operationalized in agroecology research (D'Annolfo et al. 2017).

Only recently have empirical tests of processes and outcomes of agroecological transitions begun to emerge. The majority of studies comparing farms as they transition to sustainable agriculture tend to use a typologies approach based on level of market orientation (Kansiime et al. 2018) or specific farmer values (Teixeira et al. 2018), rather than ecologically relevant indicators of farm management practices (Petit and Aubry 2016; Dupré et al. 2017). However, process-based and mechanistic approaches to analyzing farm transitions may complement larger-scale studies and provide in-depth understanding about how specific practices, phases, and pathways influence ecological and socioeconomic outcomes (Lamine and Bellon 2009; Mawois et al. 2019). A focus on the mechanisms and rate of change is also needed to understand the short-term, often negative, "transition effect" on productivity and profitability, which can discourage farmers from beginning or continuing to transition without adequate support (Martini et al. 2004; Lamine and Bellon 2009).

Indeed, social and economic support systems for agroecology remain the exception rather than the rule. Agroecological farms receive less public and private financial support and investment than their conventional counterparts (Miles et al. 2017), demonstrating that the current agricultural technological regime has a high degree of lock-in (Geels 2002; Vanloqueren and Baret 2009). Without access to stable markets, knowledge, financial incentives, and other resources, agroecological transitions can be unattainable for many farmers (Blesh and Wittman 2015; Guerra et al. 2017; Valencia et al. 2019). Agroecological transitions also face the challenge of structural changes in farms' ecological and livelihood complexity, which are necessary to shift from a simplified production system to one with increased crop diversity (Vanloqueren and Baret 2009).

When farmers have access to institutional supports, agroecological transitions may also be more likely to provide economic benefits, for example, through price premiums for certified produce and reduced input costs (Bowman and Zilberman 2013; Valencia et al. 2019). Numerous global studies have compared the ecological and economic outcomes of organic and conventional agriculture, but most focus on simplified metrics of economic success, such as yield, and many find a "yield gap" between organic and conventional managements (Seufert et al. 2012; Smith et al. 2020). Still, other metaanalyses have found positive relationships between farm diversification practices and yield (Ponisio et al. 2015; Dainese et al. 2019). Such global comparisons tend to capture a wide range of practices on organic farms, not all of which are necessarily agroecological, which may contribute to their variable results. Furthermore, they neglect the mechanisms by which diversification and agroecological transitions specifically occur. For these reasons, farm-level indicators of ecological management that reflect changes in important ecosystem processes over time are needed to better understand both social and ecological outcomes of agroecological transitions.

In addition to the need for precise indicators of ecological management practices, we also know relatively little about relationships between ecological management and socioeconomic outcomes in cases where markets, incentives, and farmer networks support diversified agriculture (D'Annolfo et al. 2017; Valencia et al. 2019). Recent frameworks have been developed to summarize socioeconomic themes important to agroecological transitions (Dumont et al. 2016; Wezel et al. 2020) and to assess the sustainability of working conditions in agriculture (Dumont and Baret 2017). However, such indicators are rarely evaluated in agroecology and other sustainable agriculture studies (D'Annolfo et al. 2017; Malanski et al. 2019); even fewer studies test socioeconomic outcomes on working farms (as opposed to experimental stations) or consider farmer perspectives on agroecological transitions (D'Annolfo et al. 2017).

Our study examines how farm management practices and socioeconomic conditions differ across a purposively selected gradient of farms transitioning from conventional tobacco to diversified agroecological production. We operationalize theoretical principles from prior frameworks (Dumont et al. 2016; Dumont and Baret 2017; Wezel et al. 2020) to understand how farm income and working conditions, both important socioeconomic outcomes, vary across stages of agroecological transition, under enabling conditions of strong institutional and market support (Table 1). We specifically sought to study agroecological transitions in a region where farmers have access to knowledge, resources, and diverse markets to support their transitions, motivating our extreme case sampling approach (Patton 2014). In-depth interviews across a gradient of transitioning farms enable increased understanding of how different stages of transition influence socioeconomic outcomes, as well as ecological ones, based on farmers' experiences. When analyzed through the lens of qualitative causal explanation (Maxwell 2004, 2012), case studies are valuable for suggesting causal processes and mechanisms of change in a specific social-ecological context (Magliocca et al. 2018). Results of our case study could support farmer decision-making and provide incentives for more risk-averse farms to undertake agroecological transitions under similar social and environmental conditions. Identifying key contextual factors or farm-level leverage points that support transitions could also aid policymakers in designing appropriate programs and incentives to support farmers as they transition.

Using an in-depth case study of farms transitioning from conventional tobacco production to agroecological management in southern Brazil (Fig. 1), we asked the following research questions: (1) To what extent do farms' management practices at different stages of transition align with specific ecological indicators? And (2) how does transition stage influence income and working conditions on farms undergoing agroecological transitions?

2 Materials and methods

2.1 Study area, site selection, and sampling approach

2.1.1 The state of agroecology in Santa Catarina, Brazil

Diversified family farms predominate in the agricultural landscapes of Santa Catarina, a state in southern Brazil (Fig. 2). Agriculture in the region is highly influenced by its history of family farmer immigration from Europe and its steeply sloping terrain (Wildner et al. 2004; Wolford 2010). Both erosion from agricultural land uses and continued deforestation of the native Atlantic Forest biome have historically reduced the state's soil fertility. Despite its difficult agricultural conditions, Santa Catarina farms are highly productive, yielding 13% of Brazil's national agricultural output on just 1% of its total land area (Wildner et al. 2004). Family farmers in the region produce horticultural and staple crops for both home consumption and sale to local, regional, and export markets. Due to steep topography and heavy rainfall in the region, the use of heavy machinery, frequent tilling, and high agrochemical inputs typical of conventional agriculture contribute to soil erosion, acidification, nutrient loss, and losses of soil organic matter (SOM) on short time scales (Primavesi 1979). In the past several decades, declining soil fertility and crop yields have driven the state's agricultural extension organization, EPAGRI, along with scientists and other stakeholders, to prioritize research on sustainable management alternatives (da Costa et al. 2017).

Santa Catarina is a stronghold for the field of agroecology as a practice, a movement, and a science (Wezel et al. 2009). The state has a high prevalence of farmer networks, social movements, non-profits, and research and other public institutions dedicated to advancing agroecological management. Farmers in Santa Catarina can also access two government-mediated markets with price premiums for organic or agroecologically certified produce: PNAE, the federal school lunch program, and PAA, the now-defunded federal food acquisition program. Though certified organic and agroecological farmers make up only 1% of all farms in the state, the number of certified farms has tripled over the past decade

Table 1 Indicators of ecological management, financial independence, and working conditions on farms

Indicator	Definition	Measure
Ecological management		
(1) Crop and livestock diversity	Number of crop and livestock species (including fish) produced on a farm, weighted by area in production	Simpson's diversity (1−*D*, where $D = \sum p_i^2$ and p_i is the proportional abundance of species *i*)
(2) Continuous soil cover	Presence of permanent or semi-permanent vegetative cover on agricultural lands to stabilize soil, reduce nutrient losses, and build organic matter	Proportion of managed farm area in perennials or annuals with cover crops during fallow period
(3) Ecological nutrient management	Farm management that increases internal nutrient cycling and maintains soil nutrient pools with organic matter inputs to achieve optimal yields	Proportion of farm under ecological soil fertility management (e.g., application of compost, manure, cover crop biomass)
(4) Ecological pest management	Farm management that increases biodiversity and stability of pest populations; prevention or use of biological control for outbreaks	Proportion of farm under ecological weed, insect, and disease management
Financial independence		
(1) Net agricultural income (per capita)	Agricultural income exceeding operating costs (e.g., farm gross value added), on a per person basis	Annual gross agricultural income minus production costs divided by the number of household members
(2) Net off-farm income (per capita)	Off-farm income exceeding expenses, on a per person basis	Annual gross off-farm income minus expenses divided by the number of household members
(3) Net total income (per capita)	Combined agricultural and off-farm income exceeding operating costs, on a per person basis	Annual gross household income minus expenses divided by the number of household members
(4) Market access	Number of different types of marketing channels accessed	Number of market types that contribute to farm annual income (out of 8 types)
Working conditions		
(1) Agricultural labor hours (per capita)	Total time spent on agricultural activities (e.g., field-based, processing, marketing) on a per worker basis	Number of hours spent on agricultural activities per week or year divided by the number of workers
(2) Off-farm labor hours (per capita)	Total time spent on off-farm activities on a per worker basis	Number of off-farm working hours per week or year divided by the number of workers
(3) Total labor hours (per capita)	Total time spent on agricultural and off-farm activities on a per worker basis	Number of working hours per week or year divided by the number of workers
(4) Occupational health	Farmer-reported safety of agricultural work and associated health conditions	Qualitative description
(5) Work quality	Farmer-reported level of satisfaction with work, including mental, emotional, and physical well-being	Qualitative description

(Marcondes 2018). In 2019, certified agroecological and organic farmers in Santa Catarina numbered 1,275, with 700 more in transition (EPAGRI 2019); both figures are likely underestimates, as farmers commonly employ agroecological practices without certification. Certification in Brazil can occur in one of two ways—through third-party audits or through participatory guarantee systems.

Participatory guarantee systems offer a lower-cost option than third-party certification for farms transitioning to organic management. In this model, farmers do the work of certifying one another, and the network offers built-in opportunities for knowledge and resource-sharing related to agroecological management (Guerra et al. 2017). The main cost of the process is time, as participation in meetings and farm verification events is mandatory and enables the continued functioning of the system. While there are numerous participatory guarantee systems for farmers in different regions of Brazil, the predominant system in southern Brazil is Rede Ecovida [EcoLife Network], an agroecological network made up of farmers, consumers, and supporting institutions (Rede Ecovida de Agroecologia 2004). Rede Ecovida spans three Brazilian states—Paraná, Santa Catarina, and Rio Grande do Sul—and partners with other farming organizations

Fig. 1 Representative fields from farms at different stages of agroecological transition. Top: Agroecological farms use transformative practices such as intercropping and agroforestry, pictured here. Middle: This farm in transition still plants mostly monoculture staple crops (such as yams, pictured here) but is adding perennials like banana to diversify its cropping system. Bottom: Farmers prepare to plant this steep, conventional tobacco field following a fallow

across Brazil. The network is composed of 340 farmer groups totaling about 4,500 family farms and 20 NGOs across southern Brazil. Approximately 1,000 farms in Santa Catarina are certified through Rede Ecovida. To retain their certification, farmers must use organic nutrient sources and other ecological management practices—avoiding synthetic fertilizers and pesticides—to maintain or improve their soil fertility and crop yields (Rede Ecovida de Agroecologia 2004).

2.1.2 Farm selection and sampling approach

We conducted 13 months of intensive, interdisciplinary fieldwork in Santa Catarina between 2017 and 2019, combining qualitative and quantitative data collection methods. We worked with the agroecology non-profit CEPAGRO (Center for the Study and Promotion of Group Agriculture), a Rede Ecovida partner organization based in Florianópolis, Santa Catarina, to identify farms interested in participating in a

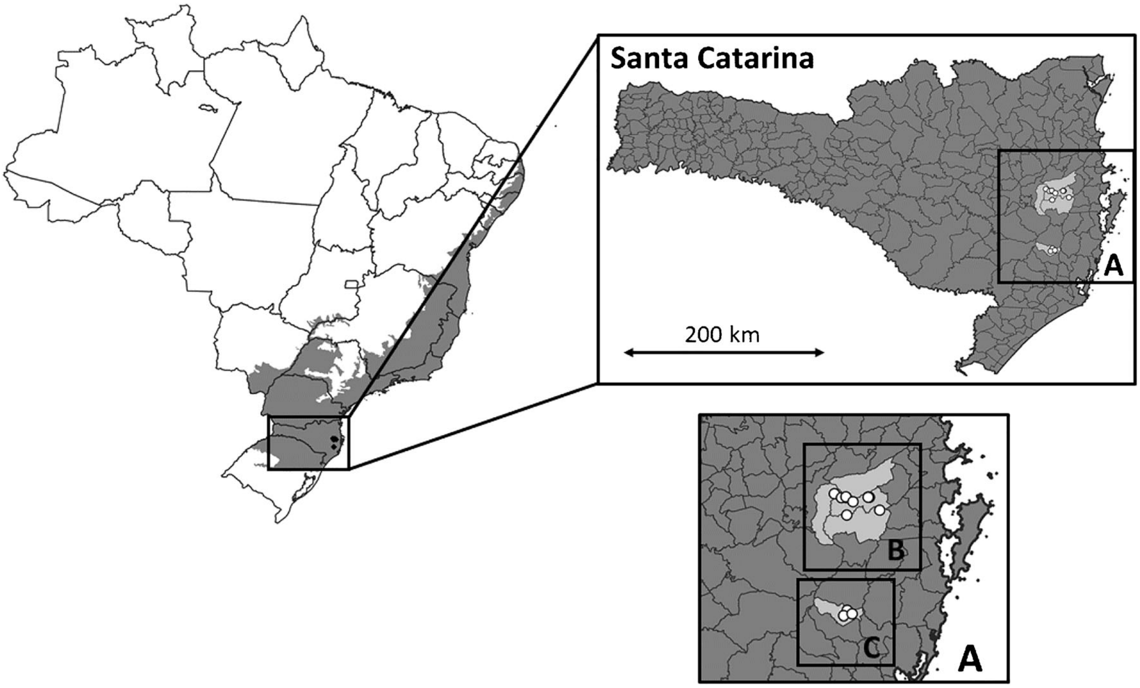


Fig. 2 Brazil with the state of Santa Catarina (inset). A: Study region in eastern Santa Catarina. B: Major Gercino region. C: Santa Rosa de Lima region. Shading denotes the prior extent of the Atlantic Forest biome, much of which has now been deforested for agricultural land uses

multi-year, integrated social-ecological study on diversification practices. The case study sample was selected from a group of farm households participating in a 2-year field experiment testing effects of crop diversification on soil fertility, yields, and crop quality (Stratton et al. In Prep). Farmers in our sample represent ecological innovators within their local agricultural context, and all of them have experience with the agroecological participatory certification network Rede Ecovida, the agroecology non-profit and member organization CEPAGRO, or both. We used a purposive sampling approach to understand the processes and mechanisms of transitioning to agroecological management in a context in which farmers have access to knowledge and resources to support their transitions (Patton 2014).

Descriptive, place-based narratives can be used to understand how social and environmental contexts interact with specific decisions or mechanisms to generate the observed effects (Maxwell 2012; Magliocca et al. 2018). To analyze our interview data, we used a qualitative causal explanation approach (Maxwell 2004) with extreme case sampling of innovative farm households, all of which had years of institutional support and exposure to ecological management techniques (Patton 2014). Our study design aimed for in-depth analysis, including multiple years of contact between researchers and each participating household, exhaustive farm management surveys paired with semi-structured qualitative interviews, and informal conversations with dozens of additional transitioning farmers. This rich qualitative data, paired with purposive sampling of farms across three stages of transition, provided the means to study how farmers perceived the causal mechanisms and effects of agroecological transitions.

After conducting preliminary management interviews and analyzing soil samples collected from 20 farms in eastern Santa Catarina, we selected 14 farms to participate in our study, which ran from February 2018 to June 2020. A sample size of 14 households within this methodological approach was sufficient to reach “saturation” or the point in qualitative interview analysis at which no new information or themes are garnered from additional data (Guest et al. 2006). Our approach to qualitative causal explanation was comparative: all of the farms had similar management histories in conventional tobacco production, similar climate and soil types, and access to similar resources through agroecology institutions, but they had distinct transition stages and years of experience with agroecological management (Maxwell 2004). Comparison between transition stages (conventional, transition, and agroecological) generated a counterfactual for what agroecological farms could look like if they were still conventional. We also analyzed individual farmer interviews to understand how each farming household viewed the evolution of their management practices and socioeconomic outcomes over time and at different stages of transition.

All farms were located in the same climatic region, with semitropical weather patterns and rainfall averaging 3500–4000 mm per year (Wrege et al. 2012; Marinho et al. 2020). Similarly, farms were selected in a single soil microregion, meaning soil types share parent materials and physiochemical characteristics. Soils throughout the region are associations of alic cambisols and red-yellow alic podzols (EMBRAPA 2004). Both soil types have low pH, low nutrient availability, and moderate to low moisture availability. Phosphorus deficiency and aluminum toxicity are common agricultural problems in the region. Within this environmental context, farms were chosen to represent a gradient of transition stages, with four *conventional* farms, five farms in *transition* to agroecological management (0–5 years certified organic through Rede Ecovida), and five established *agroecological* farms (>5 years certified). We used survey and interview data from farms at each of these transition stages to assess ecological management practices and socioeconomic outcomes.

2.2 Data collection

Our ecological field experiment examined the effects of cover cropping and intercropping on soil nutrient cycling, crop yields, and crop quality on farms across three transition stages (Stratton et al. In Prep). Over the course of the ecological experiment, we collected interview data and field observations on farmers' management practices, socioeconomic outcomes, and experiences with the process of transitioning to agroecological management. We conducted household surveys at the beginning, mid-point, and end of the study, which we paired with semi-structured interviews at two time-points to complement quantitative information with rich, descriptive data about the transition process (Maxwell 2004). The main period of data collection took place in May 2019 and combined structured surveys and semi-structured interviews with farm households, which together lasted 2 to 3 h.

Management and socioeconomic surveys included the following sub-sections: (a) farm characteristics and demographics, (b) farm land use and field characteristics, (c) crop rotations by field, (d) management and inputs by crop type, (e) farm labor patterns by worker, (f) household earnings (markets, yields and prices of principal crops, agricultural and non-agricultural household income and expenses), and (g) farmers' evaluation of the ecological experiment. Semi-structured interviews focused on the concept of transition, asking farmers what changes in crop selection, inputs, income and expenses, yields, and work quantity and quality had occurred since officially beginning the "organic" transition process or in the last 10 years, if conventional. We also asked farmers what key sources of information or learning experiences they relied on during the transition. Questions were designed to be open-ended to elicit novel responses. To corroborate original information on household earnings and labor collected in May 2019 and reduce recall decay (Beegle et al. 2011), we collected additional socioeconomic data from each farm in October 2019.

Participant observation was a mainstay of our study. The lead author cohabitated with farmers and shared agricultural and domestic work during four field campaigns over 2 years, each of which involved four or more day-long visits to experimental plots on each farm. We also performed agricultural tasks with farmers as participant observation for 1 day per farm. In addition to work in the field with farmers, we participated actively in local, regional, and network-wide meetings for Rede Ecovida. To triangulate our results and account for researcher bias, we regularly held "member checks" with farmers and employees at CEPAGRO, enabling us to adapt our theorized relationships based on the perspectives of the group of study (Maxwell 2004).

We completed two rounds of thematic coding of interview transcripts using NVivo text coding software (QSR International). Qualitative observations and experiences of farmers were used to understand the mechanisms driving quantitative results. All interviews were conducted in Portuguese by the lead author, and direct quotes used in the text were translated to English following thematic coding.

2.3 Indicator framework for agroecological transitions

2.3.1 Ecological management indicators

The 14 farms in our study spanned a wide diversity of practices, both within and across the three stages of transition (i.e., conventional, transition, and agroecological). To more precisely characterize ecological management on farms, we developed four indicators to measure on all farms in the sample based on known links between agroecosystem management or structure and ecosystem functions across transitions (Shennan 2008; Wezel et al. 2014): (1) crop and livestock diversity (Hill 1973; Jackson et al. 2007), (2) continuous soil cover (Tonitto et al. 2006; King and Blesh 2018), (3) ecological nutrient management (Drinkwater and Snapp 2007b; Drinkwater et al. 2008), and (4) ecological pest management (Letourneau et al. 2011; Kremen and Miles 2012) (Table 1). In addition to overall crop diversity, the specific addition of perennials and other forms of continuous living soil cover is known to exert proportionally large effects on soil fertility (King and Blesh 2018) and is of particular importance in regions vulnerable to erosion. Complementing continuous soil cover, ecological nutrient management consists of a suite of practices that reduce use of external nutrient inputs, manage crop and livestock diversity to cycle and retain nutrients, and build soil organic matter. Ecological pest management employs intentional management of crop and livestock diversity and other methods of biological control to modulate disease and pest populations. Each of our indicators aligns with broader ecological knowledge and also corresponds with one or more agroecological principles from the recent literature, including biodiversity, soil health, recycling, and input reduction (Wezel et al. 2020). Indicators were quantified using data from management interviews and field observations. Detailed information about indicator quantification can be found in *Supplemental Methods*.

2.3.2 Socioeconomic outcome indicators

Drawing on recent work highlighting emerging socioeconomic themes relevant to agroecology by Dumont and others (2016, 2017), we evaluated four indicators of *financial independence* and five indicators of *working conditions* across stages of agroecological transitions (Table 1). We conceptualize *financial independence* as a function of both income and level of perceived control over farm economic and technical decision-making. To assess each farm's *financial independence* (Dumont et al. 2016), we measured net income from agricultural and off-farm work (using three indicators, described below), as well as access to diverse markets to sell produce (Dumont et al. 2016; Roest et al. 2018; Valencia et al. 2019). Net agricultural income was calculated as earnings from agricultural activities minus farm operating costs and was divided by the number of household members for the per capita value. Net off-farm income was calculated as the difference between gross off-farm income and associated expenses, also on a per capita basis. Net total income was calculated as the sum of gross household income from all agricultural and off-farm sources, minus the sum of all agricultural and non-agricultural household expenses (e.g., gasoline for car travel, electricity costs, cell phone use, etc.) per capita. We use the term "net agricultural income" with several caveats; namely, we do not account for depreciation of agricultural equipment or for in-kind contributions from home consumption of agricultural products (Grosh and Glewwe 2000).

Based on the family farming context and primary themes farmers emphasized in interviews, we operationalized five indicators of working conditions: occupational health, time at work (per capita labor hours, divided into agricultural, off-farm, and total hours), and the intrinsic benefits of work (work quality/job satisfaction). Occupational health refers to the level of physical and mental well-being at work (Dumont and Baret 2017). Total time at work includes all working hours associated with farming, including production, processing, marketing and sales (including agritourism), and paperwork (agricultural working hours), in addition to any paid off-farm labor hours. Work quality is a measure of worker-reported well-being, here representing farmers' interest in work and expressions of satisfaction or contentment in their day-to-day activities (Harrison and Getz 2015; Timmermann and Felix 2015; Dumont and Baret 2017). Each of our socioeconomic indicators relates to overarching agroecological principles, with financial independence tied to economic diversification and sustainable land and natural resource governance, and working conditions related to concepts of social values, fairness, and participation (Wezel et al. 2020). Additional information regarding the quantification of socioeconomic indicators is included in *Supplemental Methods.*

3 Results and discussion

3.1 Farm characteristics

Participating farms were located in two municipalities with similar climatic and soil conditions—Major Gercino and Santa Rosa de Lima (Fig. 2) (EMBRAPA 2004). Across the state, 13% of farms produce conventional tobacco (Marcondes 2018). While tobacco remains an important crop in Major Gercino and surrounding municipalities, Santa Rosa de Lima has a higher proportion of agroecological farms, an organic food processing and marketing cooperative (AGRECO), and an agritourism organization, Alcolhida da Colônia (EPAGRI 2019). Across the sample, farm size ranged from 12 to 76 ha and cultivated area ranged from 3 to 48 ha (Table 2). Agroecological farms (mean=14 ha) tended to be slightly smaller than conventional farms (mean=30 ha), but there was substantial variation within groups. Principal marketed crops followed regional patterns, including notable production of tobacco (on conventional farms), grapes, banana, and honey in Major Gercino and diversified fruit and vegetable products in Santa Rosa de Lima (Marcondes 2018). None of the transitioning or agroecological farms continued to grow tobacco after joining Rede Ecovida; farmers perceived that nicotine poisoning from harvesting green tobacco ("green tobacco sickness"; Fodetar and Fodetar 2017) was even more severe in organic tobacco production, and they preferred to avoid it. All farmers in our sample had at least a decade of experience in agriculture (mean=29 years) and came from farming backgrounds, and all farms except one had a history of chemical-intensive tobacco farming. The remaining farm had a history of low-input subsistence agriculture, primarily producing staples such as cassava, beans, yams, and maize. The three farmers in our sample from Santa Rosa de Lima participated in value-added food processing through AGRECO and agritourism through Acolhida da Colônia.

All farms had access to multiple sources of knowledge and technical training around agroecology. Over the last decade, farmers participated in trainings from multiple institutions, including our partner organization CEPAGRO (Major Gercino), the state agricultural extension agency EPAGRI (Major Gercino and Santa Rosa de Lima), tobacco companies such as Souza Cruz (Major Gercino), and university researchers (Santa Rosa de Lima). CEPAGRO staff, who have worked with many farmers in these regions for the past 30

Table 2 Descriptive characteristics of conventional, transitioning, and established agroecological farms in the case study in Santa Catarina, Brazil

Farm ID	Transition stage	Region	Number of household members	Mean age in household (years ± SD)	Mean educational level in household (years ± SD)	Years of farming experience (heads of household)	Years certified organic	Highest earning crop	Annual production, primary crop (kg)	Farm size (ha)	Cultivated area (ha)
1	Conventional	Major Gercino	6	39 ± 17	9 ± 4	18	0	Tobacco (dried)	11,250	57	28
2	Conventional	Major Gercino	6	44 ± 18	5 ± 3	15	0	Tobacco (dried)	10,500	36	22
3	Conventional	Major Gercino	6	53 ± 13	7 ± 4	35	0	Green bean (canned)	10,300	61	48
4	Conventional	Major Gercino	5	25 ± 15	9 ± 3	35	0	Tobacco (dried)	8,000	32	21
5	Transition	Major Gercino	5	54 ± 25	7 ± 6	22	0	Banana	4,000	45	29
6	Transition	Major Gercino	2	38 ± 6	10 ± 0	16	3	Banana	9,000	68	29
7	Transition	Major Gercino	7	34 ± 14	9 ± 4	33	3	Tomato	5,500	31	19
8	Transition	Major Gercino	4	48 ± 24	10 ± 4	60	5	Honey	1,000	60	30
9	Transition	Major Gercino	5	40 ± 24	8 ± 4	32	5	Grape	12,000	76	28
10	Agroecological	Major Gercino	3	36 ± 21	8 ± 1	38	7	Banana	12,000	25	16
11	Agroecological	Santa Rosa de Lima	2	38 ± 18	14 ± 3	24	8	Honey	2,000	12	3
12	Agroecological	Santa Rosa de Lima	4	35 ± 15	15 ± 2	14	9	Blackberry	1,000	19	4
13	Agroecological	Major Gercino	5	27± 20	6 ± 2	29	12	Grape	30,000	28	25
14	Agroecological	Santa Rosa de Lima	3	43 ± 25	9 ± 1	35	20	Cassava (flour)	700	42	23

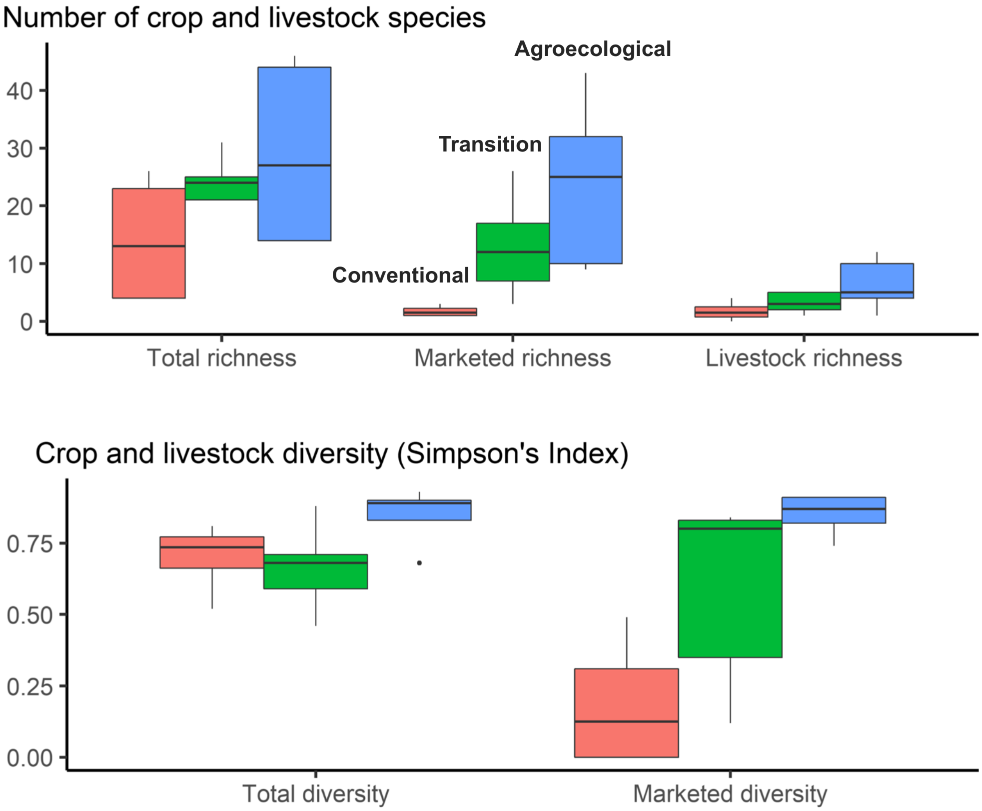
years, consider the farmers in this study to be leaders and conservation innovators in their respective transition stages. Farmers' support networks, however, differed between conventional farmers and the two agroecological stages. Tobacco producers received most of their crop advising from tobacco company representatives, whereas transitioning and agroecological farmers relied on regular support from other farmers and organizations in Rede Ecovida. Established and transitioning agroecological farmers attended monthly Rede Ecovida group meetings in their respective municipal regions, both of which were part of the Coastal Santa Catarina Nucleus, which holds bi-annual meetings open to all participating farmers.

Family participation in agriculture is a prominent feature of farming culture in Santa Catarina and has been cited as one factor that promoted strong social movements in the region, such as the *Movimento dos Trabalhadores Sem Terra* (MST) and Rede Ecovida. This tendency held true for farms in our case study. Farm household size ranged from two to seven, with a median value of five. Although five farmers shared narratives of local youth migrating to urban centers, four of these cases involved young people moving to the city for higher education or to seek employment and then returning to support and build the family farm. This trend opposes Santa Catarina's increasing emigration from rural areas; the state's farming population reached its peak in 1985 and has since fallen by 56% (Marcondes 2018). Agroecological farmers expressed the hope that their diverse crop and market structures and youth involvement in Rede Ecovida could reverse this trend and keep their children and relatives on the farm.

3.2 Ecological management across transition stages

Indicators of ecological management tended to increase from conventional to agroecological farms, as expected. Though 12 of the 14 farms in the sample had diversified home gardens for household consumption, both total and marketed crop richness increased from conventional to agroecological farms (Figs. 3 and 4). Mean livestock richness was also higher on agroecological farms than that on conventional or transitioning farms. These results are perhaps unsurprising, given the tenets of agroecology required for participatory certification through Rede Ecovida. Recommendations go beyond typical organic certifications by requiring not only elimination of synthetic fertilizers and pesticides but also increased crop diversity, crop-livestock integration, use of perennials, organic nutrient sources, and ecological pest control methods, such as biocontrol and push-pull techniques (Rede Ecovida de Agroecologia 2004; Cook et al. 2007). It is important to note the higher variability in ecological management practices on farms in transition, which includes farms with up to 5 years of organic certification.

Fig. 3 Farm-level crop and livestock diversity across agroecological transition stages shown as species richness (top) and Simpson's diversity index (bottom). Total crop and livestock species produced per farm are shown on the left and marketed species are shown on the right



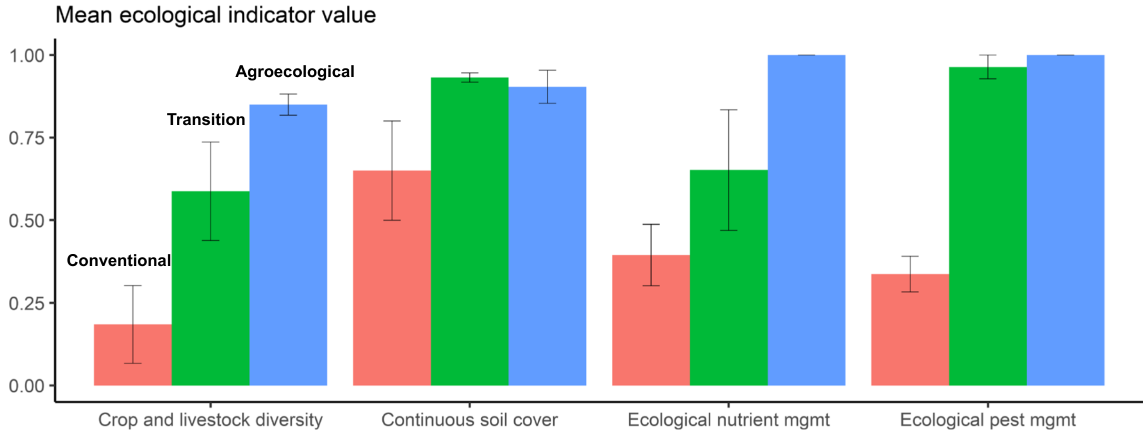


Fig. 4 Farm ecological management indicators at different stages of agroecological transition (mean values with standard error). Four indicators of ecological management are shown: (1) marketed crop and livestock diversity (Simpson's diversity index), (2) proportion of farm under continuous soil cover, (3) proportion of farm under ecological nutrient management, and (4) proportion of farm under ecological pest management. All indicators were calculated on a scale from 0 to 1, with 1 representing greatest alignment with agroecological principles and 0 representing least alignment

Farmers' management practices are mapped closely onto agroecological transition stages of input efficiency, input substitution, and system redesign (Gliessman, 2014). Conventional farmers diversified their crop rotations to increase the efficiency of synthetic input use; farmers in transition and in the early years of organic certification (0–5 years certified) relied on input substitution, substituting purchased organic inputs for synthetic pesticides and fertilizers; and established agroecological farmers (>5 years certified) used transformative practices such as mixed crop-livestock systems and agroforestry to redesign their systems and reduce labor and input costs.

3.2.1 Crop and livestock diversity

Marketed crop and livestock diversity was highest on agroecological farms (mean=24 crops, sd=15), followed by farms in transition (mean=13, sd=9) and finally conventional farms (mean=2, sd=1) (Fig. 3). While half of the conventional farmers in our sample were "diversified" tobacco producers, planting rotations of tobacco, maize, and arracacha (*Arracacia xanthorrhiza*, a biennial root vegetable in the carrot family) cash crops with grass-legume cover crop mixtures in between, the other half planted fewer crops in rotation and irregularly cover cropped with black oat (*Avena strigosa*). Conventional farmers cited tobacco companies as a main influence in their decision to increase their crop rotational diversity from what were previously tobacco monocultures. Farmer 1 asserted:

> Today even the tobacco companies have changed their point of view. They want a well-diversified farmer, too. They prefer a farmer that can stay on the land – that's an advantage for them. They don't really want some broke farmer depending on them because it ends up generating a loss for them at the end of the day. [The farmers] won't be able to invest in the equipment [the companies] require.

Farms in the early stages of agroecological production had the most variation in marketed crop and livestock diversity, as well as other ecological management indicators (Fig. 4). Marketed crop richness ranged from 3 to 26 crops on transition farms, depending on their management histories. These farmers managed the agroecological transition with an input substitution approach—substituting a conventional input for an organic one, without changing the structure or function of the agroecosystem (Rosset and Altieri 1997; Duru et al. 2015)—and several established agroecological farmers described going through a similar phase during their transitions. For example, one agroecological farmer reflected on all the products they used to purchase in the early years of the transition, explaining:

> We bought chicken litter, even sawdust, … for soil cover. We would plant a row of turmeric and leave that bare space in between. Then we weeded that area and left it all exposed, so we had to buy sawdust to put between the crops. Later, we started to put beans and other crops between rows, so the rain wouldn't compact the soil so much. … So, that helped and we didn't need to do so much anymore, since the bean leaves fell there and covered the soil, helping out the situation.

Marketed crop richness was high on established agroecological farms (9–43 species) (Fig. 3). Farmers in this group relied on several forms of agroecosystem redesign, including use of diversified agroforestry systems (*n*=3 farms), integrated crop-livestock systems (*n*=3), and intercropping with annuals and perennials (*n*=5, 100%), as well as livelihood or market diversification (*n*=5). Nearly all agroecological farmers described this transformation of their farming systems from monoculture tobacco with a few subsistence crops to diversified, complex agroecological cropping systems as a learning process with various phases. Similar to prior findings (Lin 2011; Blesh and Wolf 2014), farmers in our study described a gradual shift from reliance on input substitution toward their realization that crop and livestock diversity could be used as a tool to reduce agricultural expenses and labor while also increasing the resilience of their farm to market and biophysical shocks. For example, one agroecological farmer spent 17 years farming tobacco before transitioning to diversified vegetable production and has now been certified in Rede Ecovida for 12 years. The farm has a crop-livestock system with dairy cows grazed under perennial grapevines, annual intercropping, and consistent use of grass-legume cover crop mixtures during fallows. Explaining the farm's change in approach over the transition, this participant said:

> [Our input use] changed a ton because in the beginning we thought that the cost [of transitioning] would be high because you had to buy organic fungicides and insecticides, let's say, but today we can see that we no longer need those things on our farm. In reality, you have to diversify. Good soil keeps the plants strong, so you don't need to be dumping on insecticide and those things.

3.2.2 Continuous soil cover

Due to the importance of erosion prevention in this hilly region of Santa Catarina, soil cover was high across all stages of transition (Fig. 4), although agroecological and transitioning farms had slightly higher proportions of their farms under perennials and cover crops than conventional farmers. Conventional farms maintained 65% of managed farmland under continuous soil cover on average. Responding to falling yields and growing farmer indebtedness (according to farmers across transition stages who had grown tobacco), tobacco companies now recommend that farmers rotate their cash crops with cover crops to reduce soil erosion and disease pressure, build soil organic matter, and maintain tobacco yields over time. Conventional farmer 4, who had the lowest marketed crop and livestock diversity (a simple tobacco-silage corn rotation and several beef cattle) of any farm in the case study, had just begun using cover crops in an effort to rebuild his soil, as he reported he had been increasing his chemical inputs with diminishing returns, and it was time to make a change to increase his input use efficiency.

Most farms in transition had high levels of continuous soil cover (mean=94%, sd=4), but this number represents a high proportion of monoculture eucalyptus plantations (mean=27% of perennials, sd=27), which are grown as "reforestation projects" supported by government incentives and are also used to heat tobacco-drying ovens. Conventional farmers also had comparably high proportions of eucalyptus (26% of perennials), whereas agroecological farms had fewer areas dedicated to tree plantations (10% of perennials). Agroecological farms had a high proportion of their farms under continuous soil cover (mean=90%, sd=11), with large areas of diverse perennial agroforests and extensive use of cover cropping.

3.2.3 Ecological nutrient management

While conventional farms in the sample managed cover crops to recycle and supply nutrients on 40% (sd=40) of their land on average, transitioning (mean=73%, sd=35) and established agroecological farms (100%, sd=0) had higher mean proportions of their farms under ecological nutrient management, recycling organic residues into soil to build fertility, including use of on-farm sources of composted food scraps, manure, and cover crop biomass (Fig. 4). Conventional farmers in the study stated that adding cover crops in rotation provided benefits for fertilizer input efficiency, building soil organic matter and soil nutrient-holding capacity over time, which follows from broader understandings of ecological nutrient management (Drinkwater and Snapp 2007a). Tobacco farmers in our sample thereby reported reducing their synthetic nitrogen fertilizer use by 15–50% with cover crops.

The wide variability in ecological nutrient management strategies among farms transitioning to agroecological methods provides evidence that agroecological transitions are a process with distinct trajectories and timelines (Fig. 4). This variation results from the tendency of transitioning farms to maintain distinct sections of their farm under conventional management, applying synthetic fertilizer to conventional areas that are not yet in transition to agroecological certification. Similarly, some farms in transition continued to apply herbicides, although because occupational health was a principal motivation for many farmers to transition, continued pesticide use during transitions was less common (see Sect. 3.3.2).

Because established agroecological farms had completely shifted production over to certified organic, they were obligated to rely solely on ecological fertilizer and pest control methods; as such, 100% of all agroecological farms' fields were under ecological management for both of those indicators. Agroecological farmers also emphasized the use of inputs from inside their farms, including taking advantage of manure, kitchen scraps, forest litter, and processing waste from value-added products (e.g., liquid extracted from cassava flour, grape peels from juice production) to make compost for their crops—all examples of ecological nutrient management.

3.2.4 Ecological pest management

Weed and insect pest pressure can increase during agroecological transitions, due to reduced tilling and sudden restrictions on chemical pesticide use. Conventional farmers still scored lower than other transition stages in ecological pest management, with 20–50% of their cultivated area managed without use of synthetic pesticides (mean=34%, sd=11) (Fig. 4). In fact, conventional farmers stated that cover cropping increased their reliance on the herbicide glyphosate, which was used to kill cover crops prior to planting cash crops. Farms in transition (mean=96%, sd=8) and agroecological farms (100%, sd=0) used ecological pest control methods on nearly all of their managed land.

Farmers in the transition group regularly cited increases in labor due to the need to use manual rather than chemical forms of weed control, as has been shown in other systems reliant on hand-hoeing (Nyamangara et al. 2013). Some farmers in transition lamented the loss of herbicides as a tool to reduce labor difficulty and working hours. When asked if he had observed any environmental changes during the transition, one transitioning farmer commented jokingly that “the weeds are taller and there are more leaf-cutter ants!”, indicating that pest pressure had increased, along with his household’s workload. One older farming couple (transition farm 8) expressed a more complex understanding of herbicide use during the transition process:

> Husband: We maybe spent more on inputs [as conventional farmers], but the herbicide was easier. It was a little less work because you just put it on and it lasts much longer before the weeds come back.
> Wife: Except the land thins out – because it doesn’t produce [biomass].
> Husband: That’s the part where people are losing a lot, because people aren’t careful, because what’s an advantage in [herbicide use] also has its downsides. Because the land starts degrading. In a few years it won’t give anything anymore.

By killing emerging weeds with herbicide and keeping the soil bare, the farmers limited the living biomass on their fields and increased chances of soil erosion. Their quote reflects an ecological understanding of agriculture—that a farm field without soil cover and biomass inputs will lose fertility over time—but the farming couple did not go so far as to suggest alternatives to manual weeding or weed whipping as a substitute for herbicide, in keeping with the input substitution ideology. This pattern distinguished farms in transition from established agroecological farms, which focused on increased use of intercropping, diversified perennial systems, and animal integration as strategies to reduce weed and insect pressure and provision nutrients inside the farm.

Past research has found that farmers’ management and labor outcomes can change as they develop skills with ecological methods for weed suppression, including techniques using crop competition (Mhlanga et al. 2016) and cover crops (Kruidhof et al. 2010; Navarro-Miró et al. 2019), which can reduce the need for hand-weeding and longer working hours. Many agroecological farmers saw increased biodiversity and practices like intercropping as less work-intensive ways to control pests and produce more, as agroecological farmer 11 described:

> The main motivation [to diversify] was to control diseases because I noticed that we get great production in intercrops. It is easier; we don't have to do so much work. The thing I’ve observed the most is that when one plant “likes” the other, it seems like it produces much more.

3.3 Socioeconomic outcomes across transition stages

As one conventional farmer stated, it is not enough for agriculture to be diversified; it must also make ends meet for the household. Prior studies have emphasized approaches to minimize tradeoffs between profitability and ecological functions on farms, primarily through price premiums and increased input efficiency (Crowder and Reganold 2015; van der Ploeg et al. 2019). Our case study results indicated that over the course of agroecological transitions, use of system redesign approaches rather than input substitution contributed to improved socioeconomic outcomes. Using our indicator framework, we identified two overall socioeconomic benefits related to ecological management changes during agroecological transitions in the case study: increased *financial independence* and improved *working conditions* (Table 3, Fig. 4).

3.3.1 Financial independence

Income Agroecological farms demonstrated increased financial independence relative to conventional and transitioning farms (Fig. 5). Net total income was highest on agroecological farms, moderate on transitioning farms, and lowest on conventional farms on a per capita basis (Table 3), while net household income overall (e.g., not accounting for household size) was lowest on transitioning farms (Table S1). Net agricultural income (per capita) was similar between agroecological and conventional farms but lower on farms in transition. Transitioning and agroecological farms received 38 and 41% of their gross annual income from off-farm sources on average, representing livelihood diversification beyond agriculture, whereas conventional farmers received only 1%. Net agricultural income per cultivated hectare was also nearly 2.5 times higher on agroecological farms than on conventional farms due to similar earnings from smaller cropped areas. Our results align with the “transition effect” commonly observed

Table 3 Mean values and standard deviations (SD) for each indicator of financial independence and working conditions by agroecological transition stage

Indicator type	Indicator	Conventional		Transition		Agroecological	
		Mean	SD	Mean	SD	Mean	SD
Financial independence	(1) Net agricultural income (per capita)	$1,964	$1,351	$1,241	$1,403	$2,102	$1,874
Financial independence	(2) Net off-farm income (per capita)	$375	$750	$1,521	$1,461	$3,183	$2,247
Financial independence	(3) Net total income (per capita)	$2,339	$1,491	$2,762	$902	$5,284	$3,459
Financial independence	(4) Market access	2	1	3	2	3	1
Working conditions	(1a) Annual agricultural labor hours (per capita)	2830	684	2150	252	2234	590
Working conditions	(1b) Weekly agricultural labor hours (per capita)	54	13	41	5	43	11
Working conditions	(2a) Annual off-farm labor hours (per capita)	0	0	210	254	339	503
Working conditions	(2b) Weekly off-farm labor hours (per capita)	0	0	4	5	7	10
Working conditions	(3a) Annual total labor hours (per capita)	2830	684	2360	296	2573	920
Working conditions	(3b) Weekly total labor hours (per capita)	54	13	45	6	49	18
Working conditions	Number of workers	6	1	4	3	4	2
Working conditions	Number of household members	6	1	5	2	3	1

Net agricultural and total incomes exclude monetary contributions from household self-provisioning and losses due to depreciation. Additional socio-economic indicators can be found in Table S1

on certified organic farms (Martini et al. 2004; Lamine and Bellon 2009), as agricultural income tended to be lower on farms in the first 5 years of the transition. This analysis also demonstrates that established agroecological farms were able to achieve comparable levels of net agricultural income as conventional farms—along with additional socioeconomic benefits, described below—following a transition period.

According to interview data, the mechanisms behind these outcomes at different transition stages related primarily to two changes in management on established agroecological farms: reduced synthetic input intensity (and corresponding savings on input costs) and increased diversity of marketed products. Diversification in agriculture has long been known to reduce variability in income and labor (Heady 1952), supporting farmer livelihoods throughout the year. Reduced input intensity affected net agricultural income, whereas increased diversity affected the consistency of income and labor patterns, but both relate to the idea of "farming economically" by reducing input costs per output (van der Ploeg et al. 2019).

Conventional tobacco farms in our sample tended to have high gross annual agricultural incomes (mean=$66,248) but also high agricultural expenses (mean=$55,129), whereas both farms in transition and agroecological farms had much lower gross agricultural incomes (means=$10,078 and $12,975, respectively) but even lower farm expenses (means=$5,156 and $6,483) (Table S1). This extreme difference results in part from the high levels of investment and inputs required for tobacco production for export, but it aligns with broader trends in global input-intensive agriculture, in which rising input costs and falling prices due to overproduction lead to a cost-price squeeze on farm incomes (Goodman and Redclift 1991; Rosset and Altieri 1997; Crews and Peoples 2004). Tobacco farmers in the sample participated in a contract scheme with export-oriented tobacco companies, in which they purchased inputs (fertilizer, agrichemicals, and seeds) annually based on their total planted area and received a payout at the end of the season in line with the quantity and quality of tobacco produced. Major investments required by the company included infrastructure for growing tobacco seedlings, tractors for shaping tobacco terraces in the steep hillsides, and drying ovens for the harvested tobacco. Agroecological farmers, on the other hand, said they were able to lower input costs even as they increased production by utilizing more resources internal to the farm, such as reusing waste streams (e.g., composted household food scraps and cow manure) as fertilizer, and relying on ecological pest management, as one agroecological farmer describes below:

> Our agricultural expenses fell by 90% because we don't use anything defensive [against pests], and from there we kept adapting based on the merits of the farm. We take advantage of manure to make the compost, using the leftovers that would have been garbage–that's fertilizer, right?
> Even four years ago we thought we would have to apply some treatments to the grapes because there was a lot of mold. Then while we were still thinking over the situation, our neighbor bought the fungicide, the treatment to apply to the grapes, and he produced even less than us that harvest. We just pruned and mowed [under the grapes] and we got a good harvest.

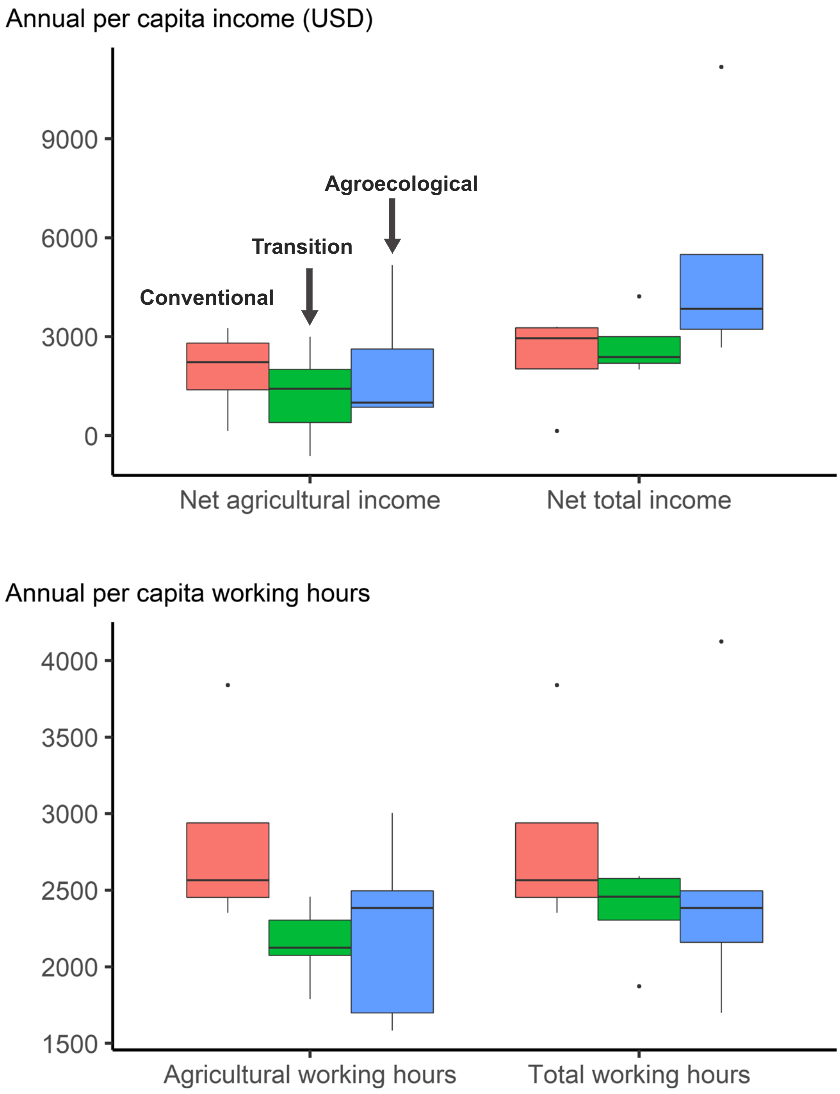


Fig. 5 Boxplots of farm indicators of financial independence and working conditions at different stages of agroecological transition. Horizontal lines represent median values by transition stage. Two measures for each indicator are shown on the x-axes. Financial independence is shown as (1) annual per capita net agricultural income and (2) annual per capita net total income from agriculture and off-farm activities. Working conditions are shown with (1) annual per capita agricultural working hours and (2) annual per capita total working hours from agricultural and off-farm work. Per capita values were calculated as the average annual value for the household divided by the number of household members for income and by the number of workers for labor hours. Net income values represent cash flows and do not include the estimated value of depreciation or household self-provisioning of agricultural products

An agroecological banana and palm farmer concurred with this perspective, stating that relative to tobacco, "income isn't very high, but expenses are low. We don't have to make all those investments in fertilizer and 'agrotoxics.'"

In contrast to prior studies that have assessed profitability on organic and diversified farms (Iles and Marsh 2012; Crowder and Reganold 2015), agroecological farmers in our case study rarely cited price premiums as a main incentive for transitioning or a critical source of income. In fact, agroecological farmer 13 explicitly stated that it was increased marketed crop diversity, and not price premiums for certified agroecological products, that led to his profits, explaining:

> It's not the increased price of organics, it's the diversity. Because money comes in every week, which is an advantage. If you have diversity, you make money every week; if you have a monoculture, just one crop, you make money just in one harvest.

Farmers regularly discussed livelihood diversification through agritourism and increased market access and stability through their networks in Rede Ecovida as important factors in their socioeconomic transition. Through monthly group meetings, learning exchanges, and resource sharing for economic diversification, the Rede Ecovida farmer network embodies many agroecological principles that support transitions, including co-creation of knowledge, social values and diverse diets, participation, fairness, and sustainable land and natural resource governance (Rede Ecovida de Agroecologia 2004; Wezel et al. 2020). Pluriactivity, a form of rural livelihood diversification in which farmers have both on- and off-farm sources of income (van der Ploeg 2008), supported both transitioning and agroecological farmers in the case study. As agroecological farmer 11 from Santa Rosa de Lima, who had the smallest cropped area in the study (3 ha), stated:

> It's also worth saying that tourism is super important for us to be here [on the farm]. If it wasn't for tourism, our small-scale production definitely wouldn't maintain us. That valorization of seeing, having people coming and recognizing that it is important for us to stay here and continue the work [keeps us going].

Diversifying income sources through pluriactivity is an important mechanism for rural people worldwide to stay on the farm while also building other skills (van der Ploeg 2008; Schneider and Niederle 2010). By supporting farms' financial independence, pluriactivity may also support agroecological transitions and rural transformation (Meek 2014).

Access to diverse markets Economic diversification is a fundamental principle of agroecology (Wezel et al. 2020). While conventional farmers earned 59% of their gross annual agricultural income on average from their primary crop, illustrating their high degree of single-market dependence, transitioning and established agroecological farmers earned only a third of their annual agricultural incomes from their highest-earning crop (mean=33% for both). Many farmers in our sample began their transitions by selling smaller volumes of horticultural crops for school lunches in their municipalities through PNAE (*n*=8). In Brazil, PNAE provides a mediated market for agroecological produce that is supported by federal law, and it can provide a pathway toward increased farm autonomy and diversification, especially for smaller farms (Wittman and Blesh 2015; Valencia et al. 2019). However, over time, most established agroecological farms in our sample increased the number of sales outlets as their production expanded.

When beginning their transitions, farmers described attending "seminars, get-togethers, and presentations from groups that already worked in agroecology and were incentivizing it, like CEPAGRO," the partner organization for this case study, often traveling as far as the state capital of Florianópolis (3–4 h) to participate. The cluster of institutions and social movements supporting agroecological transitions in the region provides a platform for change, enhancing access to ecological and marketing knowledge through public events and to sales opportunities through hundreds of farmers markets. Farmers in the Rede Ecovida network directly coordinate the transport and supply chains of diverse agroecological products through the tri-state Southern Circuit of Circulation and Commercialization of Foods (Magnanti 2008).

Prior research has also found that diversification can stabilize incomes as farmers develop marketing skills to sell their diverse products (Roest et al. 2018). Both transitioning and agroecological farmers discussed the benefits of growing "a little bit of everything," which was helpful for both household consumption and stable incomes throughout the year. Farmer 9 explained that, to his household, having a diversified farm meant "more healthy food on the table without spending money."

Re-establishing direct-to-consumer markets and economic partnerships with other farms may increase profitability for smaller farms seeking to diversify (Roest et al. 2018). Farmers involved in agritourism extolled the high value they were able to acquire from direct sales to consumers, relative to selling to wholesalers or other intermediaries who took a cut of the profit. Through the farmer network Rede Ecovida, several transitioning and agroecological farmers in our study joined efforts to create a multi-farm vegetable basket sold weekly to consumers in the state capital of Florianópolis. One transitioning farmer (7) said that joining Rede Ecovida had opened up a host of new opportunities, such as participating in an international event through the Slow Food movement, which partners with Rede Ecovida in Santa Catarina. Not only that, but the Rede Ecovida network had validated the quality of her farm products, as she said emphatically:

> Before, I didn't have the courage to say, "My product is worth this much, so pay me this much." I didn't know before how much my things were worth. Now, I have the courage to get to the farmers market and say, "my cassava flour is worth R$8"… and I end up making that much.

Although some studies have found that the benefits of community-supported agriculture can be reduced as competition increases and the market becomes saturated (Brown and Miller 2008; Dumont and Baret 2017), the market for organic produce continues to grow in southern Brazil (EPAGRI 2019), offering further opportunities for agroecological farmers to diversify their marketing channels and increase their financial independence. While median net agricultural income (per capita) was slightly lower and more variable on agroecological than on conventional farms, agroecological farms had higher total net incomes per capita due to economic diversification through off-farm work (Fig. 5). Our novel findings highlight the possibility of higher net household income on established agroecological farms when peer networks and stable markets enable redesign and transformation of agricultural systems.

3.3.2 Working conditions

Working hours Working conditions are a critical consideration in farmers' minds as they ponder whether and how to undertake agroecological transitions (Dumont and Baret 2017). We found no evidence of increased annual working hours during or following agroecological transitions in our sample (Fig. 5). On the contrary, time devoted to agricultural labor was highest on conventional farms, with similar total (on- and off-farm) working hours across transition stages (Table 3). However, on a per-hectare basis, agroecological farmers worked nearly 3.5 times as many agricultural labor hours per capita as conventional farmers and earned about $1022 USD (239%) more profit (net agricultural income) per hectare. This relationship was primarily driven by smaller cultivated areas of higher-value horticultural crops on agroecological farms. This finding epitomizes increased land productivity, in which cultivated area is reduced and labor is concentrated in smaller areas, maximizing profit on the fewer acres in production while maintaining a higher proportion of natural vegetation on remaining land (Chappell and LaValle 2011). Transitioning farmers, however, worked on average 25% fewer hours per person per hectare relative to conventional farmers but also made only 50% of the profit per hectare. This result related to higher proportions of low-labor perennial crops such as eucalyptus and banana on transitioning farms, which farmers were still learning how to manage productively.

Other work comparing agroecological and organic farming systems to conventional systems generally finds increased intensity of agricultural labor in more diversified systems due to fewer possibilities for mechanization and increased complexity in rotations (Galt 2013; Dumont and Baret 2017). In our case study, we found the opposite to be true for per-capita working hours, in part due to the labor-intensive nature of tobacco production—from tobacco in the field, to post-harvest drying (using wood-burning stoves), and in the sorting of leaves by quality prior to sale. In addition, both conventional and agroecological farming in eastern Santa Catarina are done with minimal mechanization because of the steepness of fields; fifty percent of farms in the sample owned tractors or rototillers, but farmers used them almost exclusively for tillage, as most crop maintenance and harvesting are done by hand. This case study demonstrates that in the case of tobacco, with mechanization held constant for most tasks, physical work can be more intensive on conventional than on established agroecological farms.

Work quality Farmers reported that quality of work, or job satisfaction, was an important driver of difference in working conditions across agroecological transitions. Similar to findings from other contexts (Bacon et al. 2012; Dupre et al. 2017), both farmers in transition and agroecological farmers described greater labor and income stability throughout the year due to diversified crop rotations as a benefit to farm operations and worker well-being. Farmers also expressed the enjoyment that agroecological farming brought to even a long workday, demonstrating the intrinsic value of their work for their quality of life (Dumont and Baret 2017). As one farmer (14) with a thriving agritourism business said:

> It's more fun. Sometimes when we are feeling a bit worn out from being out there [in the field] weeding, we come and see a group has made a reservation – every day there is something to look forward to.

Other transitioning and agroecological farmers expressed that their work was better simply because it was "clean, without chemicals" and they could "work in a good mood … with love and with good health."

On the contrary, conventional tobacco farmers framed pesticides as an agricultural tool that drastically reduced the difficulty of their workload and increased their productive capacity. Because tobacco farming in Santa Catarina tends to be labor-limited rather than land-limited, using chemical rather than mechanical weed and pest management can enable farmers to plant more acreage and increase their agricultural income with less physical effort. Conventional farmer 4 described this as a major change over the last several decades, when the state agricultural agency EPAGRI and tobacco companies began promoting chemical pest control in the region, stating:

> Here at our house you won't find any hoes or scythes. Now we have a weed whipper and a chainsaw … Back in the day it was all by hand! We used an ax to cut wood [for the tobacco ovens]. Now we use a chainsaw. In the tobacco, with the pre-emergent herbicides, you don't need to hoe anymore. All of this reduced our labor by 70%.

While herbicides improved the quality of work for this conventional farmer, many agroecological and transitioning farmers emphasized that agrichemical application had severely reduced their quality of life as tobacco growers.

As other studies have theorized, while agroecological farming can be more labor-intensive (which was not the case in our study), farmers often say the work is more meaningful and enables skill-building and self-determination, also appealing to younger generations (Timmermann and Felix 2015). This concept has also been called "dignified rural livelihoods" in Global South contexts (Blesh and Wittman 2015) or "active work" in the Global North (Dupre et al. 2017). For small farmers with minimal hired labor who are accustomed to the day-and-night labor of tobacco production, however, agroecological farming, once established, was "about the same" or less work in our case study (Table 3).

Occupational health In 80% of cases, farmers cited occupational health as a main motivation for transitioning to agroecological production in our study. Over the last decade, Brazil has maintained its position as the world's top importer and third largest consumer of pesticides (after China and the USA), as well as the top global exporter of tobacco (FAOSTAT 2019). Tobacco cultivation is known for its high agrochemical use, as well as its propensity to cause moderate-to-severe symptoms due to nicotine poisoning ("green tobacco sickness") when hand-harvested, as it is throughout Santa Catarina (Frois 2015). On small-scale, remote farms in the Global South, where there is little promotion of or access to personal protective equipment for pesticide application, agroecological work is perceived as safer by farmers. Transitioning and agroecological farmers alike described how the intensive use of agrochemicals affected their daily lives and health. Transitioning farmers (9) who previously grew conventional tobacco and grapes said:

> There's always more to improve… but even just having that one thing that is no longer weighing on us—those "agrotoxics," messing with them and getting headaches, nausea—it's already wonderful. Our health is much better.

For these farmers, a desire to free themselves from the chemical-intensive agricultural model of conventional tobacco played a key role in their decision to transition to agroecological management in spite of known transition costs.

Occupational health also incorporates mental well-being, which can be strained through risk-taking (Dumont and Baret 2017). Farmers in the case study discussed the risks and costs associated with transitioning from conventional tobacco to diversified agroecological production, though none of the transitioning or established agroecological farmers spoke of their transitions with regret. By creating a social safety net, farmer-driven agroecology movements such as Rede Ecovida can reduce risk for individual farmers to shift their management practices (Hassanein 1999; Blesh and Wolf 2014). Even with support from Rede Ecovida, agroecological and transitioning farmers acknowledged that the transition process can take 5 or more years, especially when starting with former tobacco land. As one agroecological farmer (12) phrased it:

> I always say that the hardest part is to convert… but if you say, I am just going to convert to grow organic and commercialize, you won't last very long, you're going back to conventional right away. There can be crises in organics, as you don't have a guaranteed sale, and if you're far from the city, like us, you can't sell products as quickly. Now we've moved away from [third-party certified] organic to agroecological, but it's a slow process. Sometimes I say that we worked five or six years just to get a piece of land that we can grow on, because when we started there wasn't any life in the soil.

Agroecological farmers in the case study were able to take this risk and overcome the opportunity costs of transitioning in part because they were economically diversified, had off-farm sources of income, or both. On average, these farmers also had higher levels of education, smaller households, and more female-headed households than conventional or transitioning tobacco farms (Table 2). Each of these demographic characteristics has potential to influence farm decision-making, and prior work has found synergies between women's empowerment, control over household expenditures, and management decisions in agroecological transitions (Bezner Kerr et al. 2019).

3.4 Study limitations and future opportunities

Using an integrated social-ecological methodology along a gradient of agroecological transition stages, our study found that diversified agroecological farms can achieve comparable agricultural incomes to conventional tobacco farms, with improved working conditions. Due to the labor-intensive production systems for conventional tobacco in Santa Catarina, differences between agroecological and conventional farming in the case study may be magnified relative to regions with differing cropping systems. Compared to other global regions, agroecological farms in southern Brazil also have a historically beneficial policy environment (Medina et al. 2015), strong institutions, and movements, all of which likely contributed to our findings.

There remains much to learn about how farm management practices relate to socioeconomic outcomes for farms undergoing agroecological transitions. With our cross-sectional approach to quantitative data collection on a relatively small number of farms, we cannot determine causality using statistical methods. Instead, we used a purposive sampling approach across three agroecological transition stages combined with qualitative causal explanation to evaluate transition pathways and processes according to farmers' perspectives and experiences (Maxwell 2004). This detailed, descriptive approach to understanding causal mechanisms and effects can be used to learn deeply about the motivations for and challenges of transitioning, to generate hypotheses for case studies in other regional contexts, or to contribute explanations for findings from quantitative studies on agroecological transitions with larger sample sizes. To determine the applicability of these findings to other contexts, our transition gradient approach could be used to evaluate the environmental sustainability and economic viability of agroecological transitions in larger samples of farms and across distinct global regions. Further work is also needed to identify policy mechanisms that can support agroecological transitions in regional contexts where peer support networks such as participatory certification are not already active and where markets for agroecological products are nascent.

4 Conclusion

Using a case study of former tobacco farms transitioning to agroecological management in southern Brazil, we conducted a novel, integrated assessment of ecological and socioeconomic indicators relevant to agroecology. We took a critical realist approach combining qualitative data from interviews and quantitative data on farm management and land use for causal evaluation (Maxwell 2004). Our results provide initial evidence that moving from an input substitution paradigm to system transformation during agroecological transitions—using diversification, soil cover, and ecological nutrient and pest management—can lead to positive income and labor outcomes on farms with a strong peer support network and access to diverse markets. System redesign enabled agroecological farms in our case study to reduce their input costs and field labor, allowing more time for farmers to plan complex crop rotations, develop new value-added products, and diversify their marketing structures.

Established agroecological farms in our sample demonstrated the potential for win-win outcomes for ecological and socioeconomic indicators, including both net household income and working conditions. We also found evidence of increased land productivity on agroecological farms, as diversified farms had higher agricultural profits and working hours on a per-hectare basis relative to their conventional tobacco farming counterparts. This transformation was a lengthy process, however, and there were transition costs beyond the official certification period. Farms in transition (0–5 years certified) struggled to manage ecological complexity across the multiple dimensions of farm management, which led to increased work difficulty and reduced profits relative to both agroecological and conventional farms. Additional support for farmers in this early phase of transition could enable their establishment as agroecological farms with ecological, social, and economic advantages. Overall, our findings showcase the potential for income and labor parity between diversified agroecological and conventional farms when adequate support systems are in place. Our study demonstrates that local innovation, participatory certification through farmer networks, and stable markets can enable transformation of agricultural systems for ecological and social sustainability.

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Author contribution AES, HW, and JB conceptualized and designed the study. AES conducted case study fieldwork, surveys, and interviews and led data analysis, with support from all authors. AES wrote the original manuscript and created all figures, with substantial contributions and revisions from JB and HW. All authors read and approved the final version of the manuscript.

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Data Availability The datasets generated and analyzed during the study will be made available through the University of Michigan’s Deep Blue Repository upon publication.

Code availability Limited quantitative analyses were conducted in this study. However, R code for reproducing the figures for this manuscript is available from the corresponding author on reasonable request.

Declarations

Ethics approval This study was granted an exemption from ethics approval by the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board (Submission ID: HUM00142052) because the study focus was on agricultural practices and outcomes rather than on human behavior. While formal ethics approval was not required, study design and informed consent procedures conformed with ethical guidelines. All data was anonymized prior to analysis.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The authors confirm that all individual participants in the study provided informed consent to have their data published in a scientific journal article.

Competing interests The authors declare no competing interests.

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