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Review

Understanding farms trajectories methods to build sustainable futures on pioneer fronts: Lessons from a systematic literature review and a framework proposal

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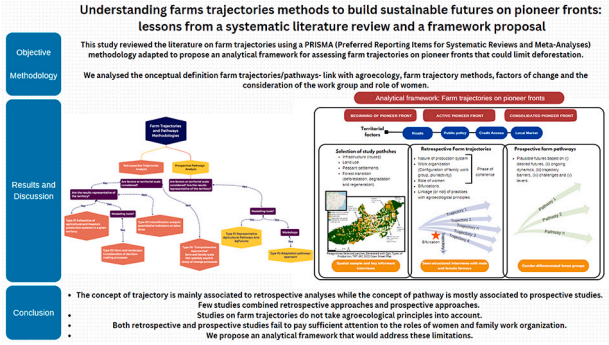
HIGHLIGHTS

- Analyzing farm trajectories may help to identify the most sustainable sequences of farm changes that could limit deforestation on pioneer fronts
- This review on fam trajectories is based on an adaptation of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method
- Existing studies overlooked agroecological principles, the effects of territorial factors, the contributions of women and family work organizations
- We propose an analytical framework that addresses the limitations found in existing studies and combine retrospective and prospective analyses
- This framework should help defining sustainable trajectories limiting deforestation in pioneer fronts

GRAPHICAL ABSTRACT



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ABSTRACT

Context: On pioneer fronts, the new spatial-temporal evolution of agriculture needs to be understood to help farmers find their way to conciliate food production and forest conservation. Analyzing farm trajectories is consequently critical for designing such futures and to assess their commitments with agroecology principles.
Objective: Based on the analysis of the literature on farm trajectories and pathways we proposed a renewed analytical framework to analyze farm trajectories in pioneer fronts and support the identification of desirable strategies for the future.
Methods: A systematic review adapted from the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was used. From an initial record of 246 papers, 81 were selected as eligible for the review. The articles were classified in six categories according to three criteria: i) the retrospective or prospective analysis of farm trajectories, ii) the consideration or not of the territorial scale (drawing lessons at territorial scale), iii) the use or not of modeling tools. We also explored whether off-farm factors (such as existing

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infrastructure at territorial scale or access to credit) and intra-farm factors (such as the organization of family work and the role of women within this organization) were considered since these factors affect farms trajectories in pioneer fronts.

Results and conclusions: Results indicate that the concept of trajectory is mainly associated with retrospective analyses while the concept of pathway is mostly associated with prospective studies generally using simulation tools for the design of future scenarios. The link between trajectories and agroecological principles also has been little explored in the literature. Both retrospective and prospective studies fail to pay sufficient attention to the roles of women and family organization. Lastly, most of the methodologies studied do not fully consider the effects of off-farm territorial factors and public policies on these trajectories.

We propose an analytical framework that would address these limitations.

Significance: This framework is currently used in Brazilian and Colombian Amazon and will help defining sustainable farm trajectories limiting deforestation. Such a framework is needed to support farm development on pioneer fronts and broadly in territories that must deal with highly critical environmental agendas.

1. Introduction

Pioneer fronts remain the focus of international attention since the conference of parties of the United Nations of 2008 regarding forest degradation and deforestation (Do and Van Noordwijk, 2023). Pioneer fronts in tropical forests are characterized by a process of colonization of landless migrant people who settle in sparsely populated lands, generally leading to advanced deforestation (Arnauld de Sartre, 2006; Théry, 2014; Thalès et al., 2021).

On pioneer fronts, farmers manage extreme tensions between economic development and environmental protection, leading to variable rates of forest deforestation (Pacheco and Poccard-Chapuis, 2012; Curtis et al., 2018; Córdoba et al., 2018; Solen et al., 2018; Knoke et al., 2022). Analyzing farm trajectories may help to identify the sequences of farm changes limiting deforestation that could be enhanced on pioneer fronts (Billard et al., 2014). Particularly, the 2000s marked a turning point in the Amazon, with the making of public and private commitments to limit deforestation and slash-and-burn practices (Stabile et al., 2020). Farmers are encouraged or instructed to modify their agricultural practices to avoid the use of fire and to stop cutting of the forest (Cialdella et al., 2015).

Farm trajectories help to understand mechanisms of their perennialization (Cialdella et al., 2009; Chantre and Cardona, 2014), and to identify moments of extreme tension that could be classified as bifurcations leading to radical changes. Bifurcations can be understood through trigger events (e.g., intergenerational succession, retirement, fluctuations in labour availability) (Sutherland et al., 2012). In general terms, bifurcations are important breaks or moments of redefinition of the trajectory that occur in a short time (Grossetti, 2006).

Agroecological transitions are presented as social-ecological reconfigurations of agroecosystems to produce following agroecological principles and improve the sustainability of farm and food systems (Duru et al., 2015; Ollivier et al., 2018; Tittonell, 2020; Polge and Pagès, 2022; Prost et al., 2023). Agroecological principles include biodiversity enhancement, biomass and nutrient recycling, soil and plant health, knowledge co-creation, and land and natural resource governance to create an enabling environment for farm and food systems transformation (Leippert et al., 2020; Barrios et al., 2020). Sustainable farm trajectories can consequently be described as sequences of changes in farms that limit deforestation and are aligned with one or various agroecological principles.

The specific biophysical and institutional configurations at territorial scale may affect farm trajectories (Tarsiguel et al., 2023). Farm location, existing infrastructure, and access to credit also affect farm trajectories (Obare et al., 2003; García-Martínez et al., 2009; Falconnier et al., 2015), especially the room of maneuver of farmers in pioneer fronts. A thorough understanding of these elements at territorial level is required to promote forest conservation.

Incremental or radical changes in the trajectory can emerge from changes in the organization of family work (Moulin et al., 2008; Terrier et al., 2012; Madelrieux et al., 2015) where women may play a key, if often invisible, role (Centrone et al., 2018).

Despite the recurrent use of farm trajectories in the analysis of agricultural systems (Wilson, 2008; Lamine, 2011; Sutherland et al., 2012; Ryschawy et al., 2017), no review has yet to be specifically dedicated to research on farm trajectories, meaning to the different methodological approaches used, their objectives, scope and limits.

The objective of this paper is to propose an analytical framework to characterize sustainable farm trajectories along pioneer fronts. For this aim, we conducted a systematic literature review of worldwide studies on farm trajectories. We assumed that this framework should take into consideration both off-farm factors at territorial scale and intra-farm factors particularly the organization of family work and the role of women, since these factors could be determinants of farm trajectories in pioneer fronts (Murphy, 2001; Ballon et al., 2016). In addition, the framework should consider agroecological principles in order to highlight sustainable trajectories.

The papers were analyzed according to five dimensions:i) complementarities or divergences between the concept of trajectory and the concept of pathway sometime used as synonymous (Chantre et al., 2015; Falconnier et al., 2015; Mawois et al., 2019), and the concept of agroecological transition, ii) the methodologies used for the analysis of farm trajectories, iii) the factors that affect farm trajectories and generate bifurcations, iv) with an emphasis on how family work organization and the role of women in trajectories are considered, and v) the specificity of studies conducted in pioneer fronts.

After describing the methodology applied for the systematic review (Petticrew and Roberts, 2006), we present the scope and methodologies used in the studies, and the factors affecting farm trajectories with their main limitations and strengths. We then propose an analytical framework based on the shortcomings found in the literature to specifically describe trajectories on pioneer fronts.

2. Method

2.1. Search strategy

A systematic literature review (SLR) based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method was conducted to have an exhaustive understanding of how agricultural changes at the farm level are analyzed (Page et al., 2021). We then focused on articles that used methodologies based on farm trajectories or/and pathways.

The search strategy consisted of consulting the CAB Abstracts, Web of Science Core Collection (WoS), Scopus, Springer (databases) and Cairn (provider). Our query ranged from 1975 to December 2023 for WoS, from 1960 to December 2023 for Scopus, from 1973 to December 2023 for CAB Abstracts and 1946 to December 2023 for Cairn. For each database and provider, the earliest possible year was selected.

Three key concepts were used for the search: trajectory, pathway and farmers.

The following equation was constructed to search results in titles,

abstracts and key words. TITLE-ABS-KEY ((“farm* trajec*” OR “farm* pathway*” OR “agric* trajector*” OR “agric* pathway*” OR “pathway* for agriculture”)).

Cairn was considered to include social sciences journals indexed journals. For the Cairn search tool, we focused the research equation on the entire document, and a specific equation was formulated in French:

- «trajectoires des exploitations agricoles» OU «parcours des exploitations agricoles» OU «trajectoires de l’agriculture»

2.2. Selection process

Using the equations and after removing duplicates, 246 documents were found. The first selection process, based on the screening of titles and abstracts, was done on the Rayyan platform (Rayyan, 2021), an online application for systematic reviews. The following selection criteria were used:

1. The core of the study is trajectories/pathways.
2. The trajectories are studied at the farm scale.
3. Peer reviewed articles.
4. Study cases articles.

After the screening process, 110 documents were included and 136 excluded (27 of these for not being a peer-reviewed article, 103 for not focusing on trajectories/pathways at farm scale and 6 not for not being a study case). In a second selection phase based on full-text reading, 36 articles were excluded (14 non-farm trajectories/pathways, 12 non-farm scale and 10 from unsubscribed journals by the research institution of the authors) and 74 articles that matched the selection criteria were included. In addition, we included 7 papers from the grey literature because we considered that they were at the heart of our farm trajectory/pathway topic. Consequently, 81 documents (supplementary material table a) were considered as eligible for the review. Fig. 1 summarizes the article selection process.

Fig. 2 presents the studies on farm trajectories and pathways per country. Interest in these concepts is worldwide, with nearly 22 research studies in Africa and 10 in South America. Various analyses were conducted in France. This may be linked to the use of the Cairn database that included mostly French studies.

For each of the 81 documents, we then analyzed: i) the conceptual definition used of farm trajectories and farm pathways and the potential link made with the concept of agroecology distinguishing cases where agroecology is included in the methodology (M) from cases where agroecology only appears in the discussion or conclusion (C), ii) the method used to describe farm trajectories/pathways, iii) the factors of change, iv) the consideration of the work group and role of women, and v) the focus made or not on pioneer fronts.

For the analysis of the method used to describe farm trajectories we classified the studies into types according to three variables:

- The retrospective or prospective analysis of farm trajectories.
- The consideration or not of the territorial scale (consideration of how the characteristics of the landscape or territory affect farm trajectories or having a representative sample in order to draw lessons at territorial scale).
- The use of modeling tools to simulate the effects of factors at landscape scale on farm trajectories.

Regarding the retrospective analyses, when they aimed to be representative at territorial scale, they were classified in TYPE R1. Articles that also used modeling tools to analyze the effects of off-farms factors at landscape or territorial scale on farm trajectories (e.g. public policies, demographic factors or markets accessibility) were classified as TYPE R2. Studies that considered how the characteristics of the territory affect farm trajectories but that do not aim to draw lessons at territorial scale were classified as TYPE R3. The ones that only focused on the farm history were classified as TYPE R4. For the prospective analyses, all of them aimed to draw lessons at territorial scale. Those that used models were classified as type P1, and those that relied on mixed methods (modeling + workshops) as type P2.

For these types, we also described the time scale (the entire time frame over which the trajectory is analyzed), and the time step (the division of the time scale into periods where the changes to be studied

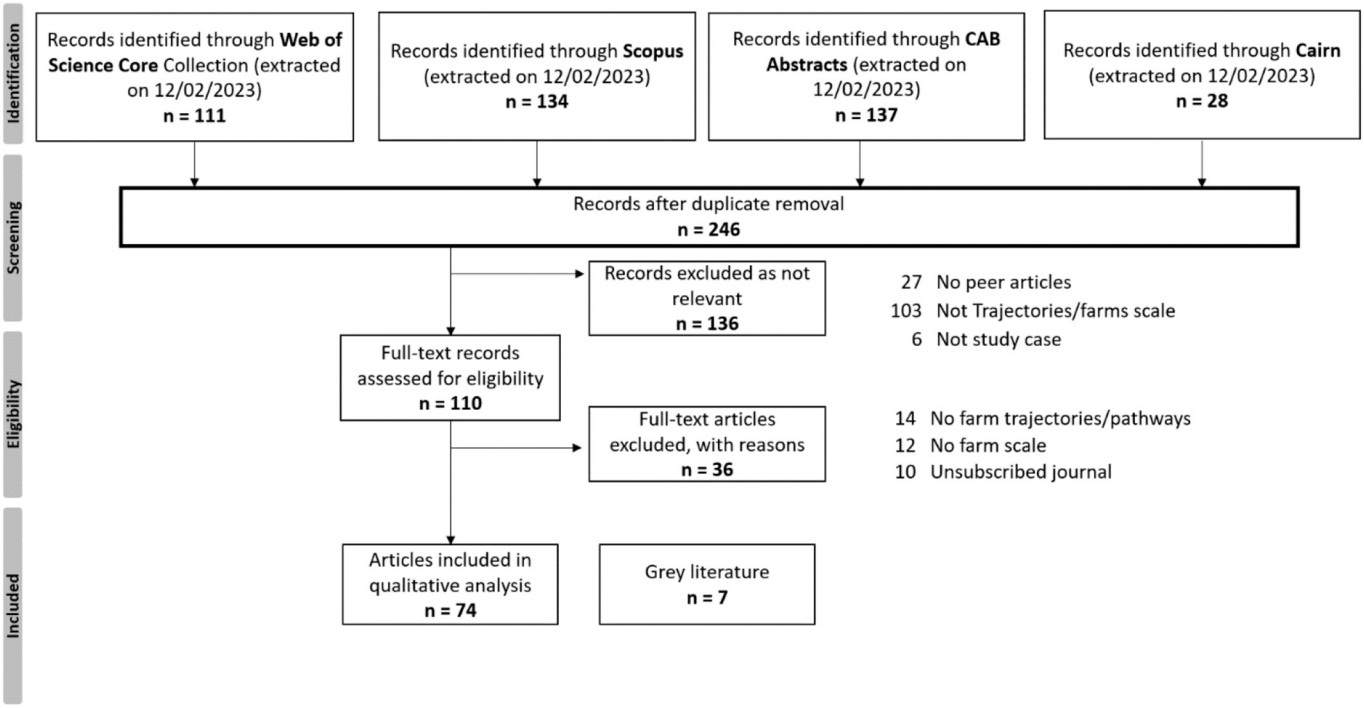

Fig. 1. PRISMA flow diagram showing the complete article selection process (adapted from Page et al., 2021).

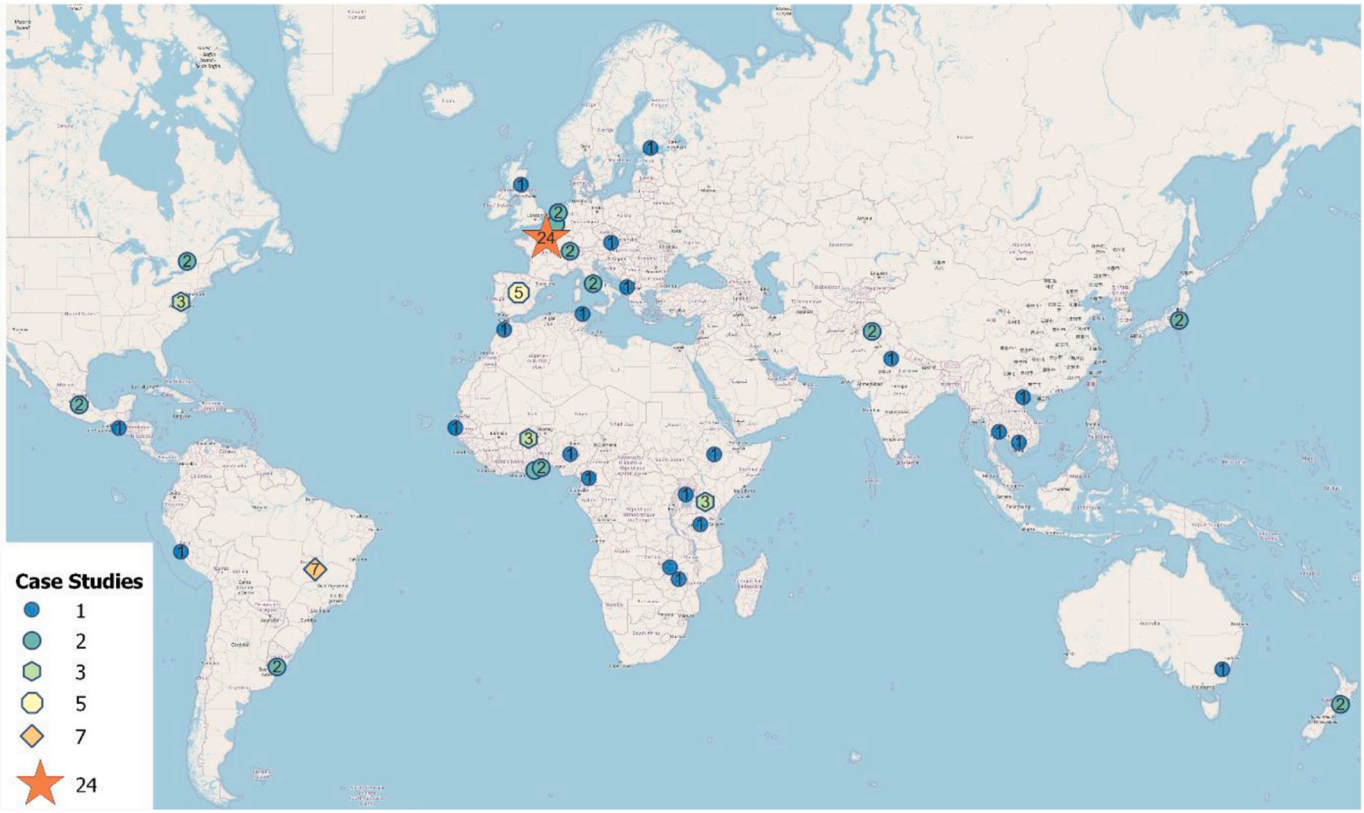

Fig. 2. Case studies of farm trajectories and pathways by country. France: 24, Brazil: 7, Spain: 5, Kenya, Burkina Faso, USA: 3, Ghana, Belgium, Pakistan, Togo, Mexico, Uruguay, Canada, Italy, Japan, New Zealand, Netherlands, Switzerland:2. Nigeria, Ethiopia, Thailand, Australia, Senegal, Tanzania, Scotland, Guatemala, Zimbabwe, Finland, Uganda, Peru, Zambia, Cambodia, Morocco, Albania, Cameroun, Mali, Tunisia, India, Vietnam, Austria:1.

take place) and the size of the samples of farms.

3. What are farm trajectories and pathways and how are they analyzed?

3.1. Farm trajectories, pathways and agroecological transitions

Only 7 of the 81 articles explicitly defined the concept of farm trajectory. Rueff et al. (2010) defined it as "a succession of chronological steps characterized by structural and/or organizational changes in the farm and farming system", which is in line with the definition proposed by Revoyron et al. (2018) and Mawois et al. (2019) of "successive phases separated by transition periods". Chantre and Cardona (2014) defined farm trajectory as a concept to analyze processes of change in farming practices. Bredart and Stassart (2017) defined trajectory as the changes in farms over the long term. Polge and Pagès (2022) defined trajectories as "set of events that have followed one another over a given period of time and that have led to one or more changes in practices". For Bakker et al. (2023) trajectories are "understood as a process or period of change, which can take form in a plurality of trajectories and endpoints".

Moreover, 6 out of the 81 documents used an explicit definition of farm pathways. Mawois et al. (2019) defined it as "the identification of mechanisms facilitating farmers' adoption of practices that can be used toward change", this definition was close to the one used by Quénon et al. (2020), "combinations of changes in farmers' herd management practices". Madelrieux et al. (2014) defined pathways as "the evolution of the family's on-farm and non-farm activities, production systems, retail outlets and labor arrangements". Pearson and Dare (2021) defined pathways as "potential routes to realize desired goals" while Valdivia et al. (2017) used the concept of "representative agricultural pathways", which are plausible qualitative narratives and quantitative trends in economic, social and technical aspects in agriculture, to generate and translate them into a model (i.e., scenarios) for climate impact assessment, giving a more prospective meaning to the term.

Twenty-two of the 81 articles selected used both concepts (trajectories and pathways). Twelve of the 22 used the two as synonyms, while 10 articles distinguished between the two concepts. In the 12 articles using them as synonyms, 9 used them to refer to retrospective analyses (Rueff et al., 2010; Moreno-Perez et al., 2011; Madelrieux et al., 2014; Terrier et al., 2012; Alavoine-Mornas et al., 2014; Gonzáleza et al., 2014; Kong et al., 2019; Rissing et al., 2021; Bakker et al., 2023), while 3 articles referred to prospective analyses. In the 10 studies distinguishing between trajectories and pathways, 6 defined pathways as the regrouping of individual trajectories (Ryschawy et al., 2014; Chantre et al., 2015; Mawois et al., 2019; Huttunen, 2019; Revoyron et al., 2018; Alary and Frija, 2022) while 4 defined pathways as an alternative way to existing trajectories (Navegantes-Alves et al., 2012; Vall et al., 2017; Bruce, 2019; Song et al., 2022).

Out of the 81 articles, 82% had a retrospective approach, generally associated with the trajectory concept, while 18% used a prospective analysis, which was mostly associated with the pathway concept. In most cases there was no combination of retrospective and prospective analyses.

Only 8 articles that used the concept of trajectory also considered the concept of agroecology (Table 1). Two of these used the efficiency-substitution-redesign (ESR) framework to analyze the transition of agricultural systems toward systems that included the principles of agroecology (Mawois et al., 2019; Bakker et al., 2021). It should be noted that 7 additional articles (Alavoine-Mornas et al., 2014; Chantre and Cardona, 2014; Revoyron et al., 2018; Zollet, 2018; Merot et al., 2019; Rouget et al., 2021; Alary and Frija, 2022) used the concept of trajectories to analyze the conversion to organic farming or to sustainable agriculture (2 used the ESR framework and 5 did not).

Table 1
Main characteristics of trajectory articles dealing with agroecology.

Main agroecology definition	Farm trajectory's purpose	Integration of agroecology in the study (Complementary or Methodological)	Study case	Author
Agroecology incorporates biodiversity into the agricultural management and aims to reduce input use by integrating ecological principles with agricultural production	Redesign the relationship between agricultural systems and biodiversity conservation	**C** The conclusion proposes agroecology as a mediating concept for collective action	Gaume (Belgium)	(Bredart et al., 2014)
Agronomic principles of agroecology	Analyzing agricultural practices and production system trajectory changes	**C** In the results section, agroecology is mentioned in comparison with intensive monoculture.	States of Amapa and Pará (Brazilian Amazon)	(Cialdella and Navegantes Alves, 2014)
Agroecology supports the long-term management of natural resources, food production, and ecosystem services in the face of climatic unpredictability	Analyze evolution of production systems and yields	**C** The conclusion describes agroecology as a strategy for adapting to rising energy costs and inputs.	France	(Veysset et al., 2015)
Agro-ecological conditions, input use (e.g., mineral and organic fertilizer)	Analyzing farmer diversity, link with farm resource endowment and government support	**C** Analysis agroecological conditions of farms particularly input use, land investment, access to information (extension services), services (credit). and market.	Koutiala, Southern Mali	(Falconnier et al., 2015)
Agroecological practices such as the introduction of legumes as diversification	Understanding how and why farmers have modified their practices and how can it let to legumes introduction	**M** Agroecology integrated in the methodology through the analysis of ESR proposed by Hill and MacRae (1996)	The Langrois Plateau in Burgundy and the region of Chateaubriant in Pays de la Loire (France)	(Mawois et al., 2019)
Agroecological principles rather than a set of predefined techniques	Analyze the change in farming practices in order to evaluate family farming schools	**M** analysis of gradual variations in the intensity of observed changes in practices and their potential to stimulate crops or farming system transformation using ESR	Northern Togo and western Burkina Faso	(Bakker et al., 2021)
Agroecology is a science, a social movement and a set of practices providing ecosystem services and including economic and social dimensions with application to the	identification of common phases within individual trajectories and typology of sequences To understand the dynamics of interactions of a social network who have adopted agroecological practices	**M** articulate trajectory and relational chain analysis to understand how they drive agroecological transitions	the Limagne plain of the Puy-de-Dome (France)	(Polge and Pagès, 2022)
Agroecology applies ecological concepts and principles to the design and management of sustainable agroecosystems, it is also a sustainable farming practice and a social movement	Describe the diversity of determinants and modalities of implementation of agroecology in farming system, including "outer" and "inner" dimensions	**M** Agroecological transition/ transformation analyzed from the interplay between zones of friction and traction across the personal, practical and political sphere and notion of "trigger-events"	Netherlands	(Bakker et al., 2023)

In other words, there was no real articulation between the concepts of trajectories and agroecology. In the analysis of agroecological transitions, longitudinal farm trajectories studies did not seem to be as common. The review of the literature on farm trajectories revealed that only four articles had fully integrated agroecology in their method, these studies mostly focused on practices rather than on agroecological principles.

3.2. Main trajectory and pathway characteristics and methods

The published articles used different tools for analyzing trajectories and pathways (Fig. 3). Most were qualitative analyses that described trajectories and pathways through a narrative approach using, for example, semi-structured interviews (62%). Various studies also used exploratory quantitative analyses (46%) based on statistical tools such

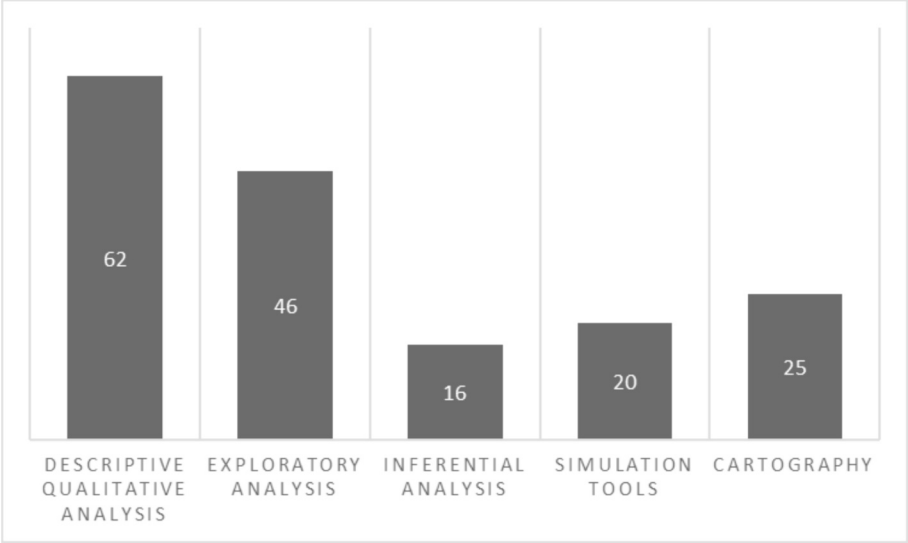

Fig. 3. Methodological tools used in farm trajectories and pathways per number of occurrences (% of $N = 81$).

as cluster and principal component analyses (PCA). Simulation tools, inferential analyses and cartography also were used, but less frequently (20%, 16%, 25%, respectively). It should be noted that these tools are not mutually exclusive and that, in most cases, they were complementary.

Fig. 4 highlights the six main types of methodological analyses.

Type R1 studies (22 articles) focus on a territorial approach, land use and a comprehensive view of production systems in a territory, with samples ranging from 40 to 3200 observations. A good example is the study conducted by Perrot et al. (1995), which proposed to analyze farm changes between two key dates. Type R1 studies generally represented well the diversity of farmers in a studied territory (Perrot et al., 1995). However, they did not fully analyze the links that may exist between farm types within a given territory. In addition, the typology may have excluded unusual farms - that do not fit any type - while these very special farms may be the ones that innovate and set a sustainable trajectory. R1 studies used time scale ranging from 4 to 34 years.

In the R2 type (4 articles), the integration of landscape and farm-scale dynamics in the analysis using simulation tools is characteristic of this methodological approach. The article by Plassin et al. (2015) illustrates this type. In this article, the authors studied the spatio-temporal process of intensification at the farm scale in the Brazilian Amazon, highlighting the interactions between farmers' decisions and natural resources, located in a landscape. R2 type studies based on modeling approaches may have simple parameters that are constrained by the data available and the challenges of data collection in remote rural areas. A considerable amount of information is needed to model the links between agricultural practices and their consequences on natural resources. The time scale of these studies ranged between 15 and 40 years.

Type R3 (18 articles) studies focus on the farm scale and consider factors at territorial scale without looking for territorial representativeness. For example, Navegantes-Alves et al. (2012) analyzed the factors of grassland degradation in eastern Amazonia between 2003 and 2008. The authors classified stable and changing farms, and one of their main results showed that under the same management practice, the invasion of undesirable plants was lower on the stable farms. This type of research was mostly based on medium-sized samples (from 24 up to 130). Type R3 studies can overcome the limit of static variables that characterizes type R1 studies and can collect longitudinal data on the evolution of farms. However, analyzing the effects of off-farm factors at territorial scale (such as roads, or markets) on farm trajectories is a challenge when trying to integrate different cropping and livestock systems due to i) the lack of data at the farm level, ii) the heterogeneity of the variables between production systems, and iii) the complexity of links between the territory factors and what happens on the farms. Type R3 studies that were based on interviews used time steps ranging from 6 to 10 years and time scales ranging from 4 to 66 years.

The type R4 studies (23 articles), which feature a comprehensive approach (family farm history and life cycles) at the farm and family scale, did not consider the effects of territorial factors on farm trajectories, except in the studies where a cross-case analysis of various case studies was done (Dedieu, 2009; Cialdella and Navegantes Alves, 2014). Articles in this type focus on change processes and in-depth family histories. Most do not analyze more than one production system. The production systems analyzed were mostly livestock, dairy cattle, wheat and maize systems. Samples generally ranged from 7 to 50 farmers. In type R4, which uses retrospective interviews, the interviews serve to merely recreate the history and evolution of the trajectory based on farmers' memories. Some authors attempted to corroborate the qualitative data collected during the interviews with events at the territorial level, but these events were often combined with events at the farm and family level (son becoming independent, family member illness, etc.). As for type R3 studies, type R4 used time steps ranging from 6 to 10 years.

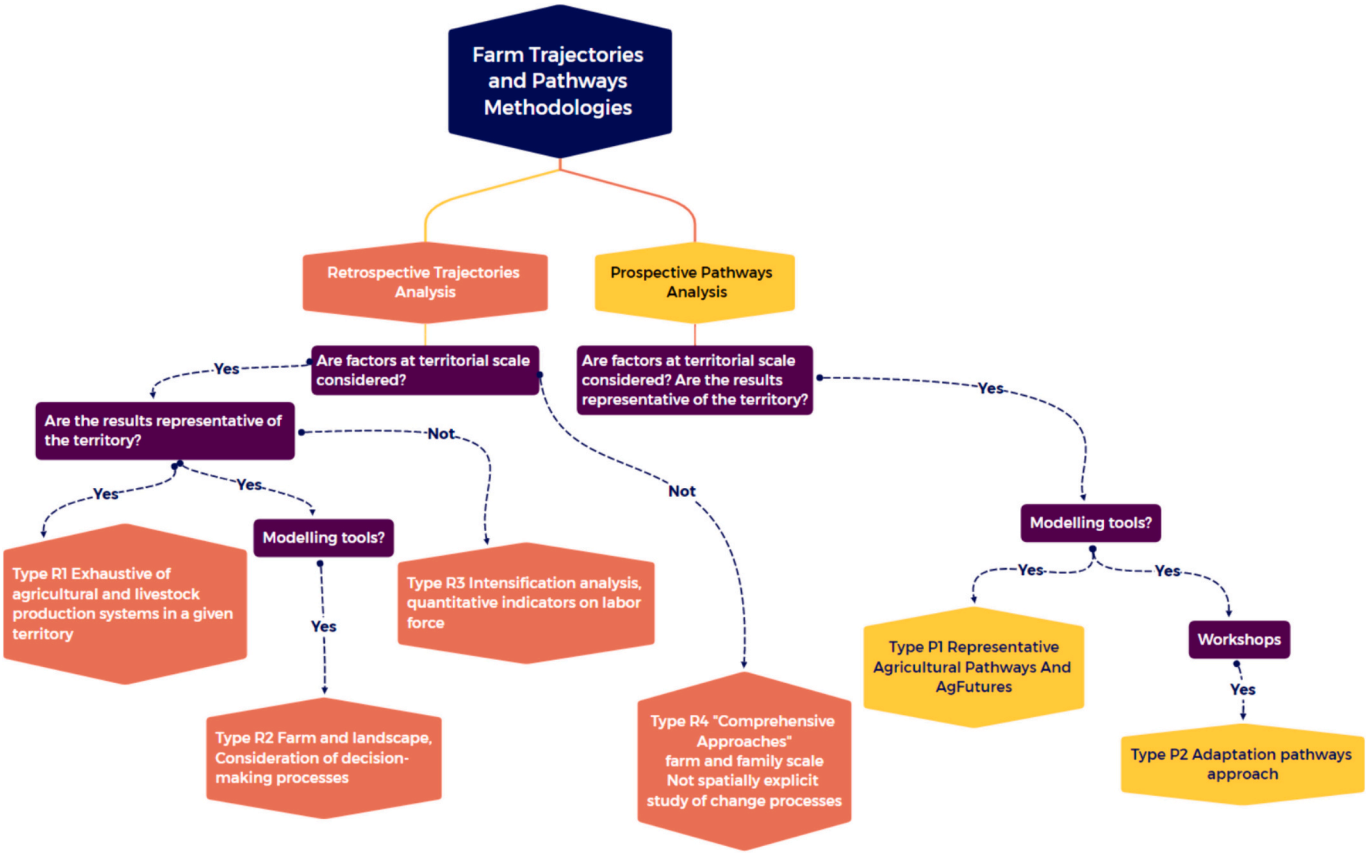

Fig. 4. Main farm trajectory and pathway methodologies, left side shows retrospective trajectory analysis, right side shows prospective pathway analysis.

In contrast, the prospective studies (14 articles) using a pathway approach mainly relied on models in their analyses.

In the P1 type (11 articles), which used exclusively simulation tools, 9 used the Representative Agricultural Pathways (RAP) model. This model projects biophysical and socio-economic data to provide regional agriculture information, generally for adaptation to climate change (Rosenzweig et al., 2013; Mulwa et al., 2016; Mu et al., 2019; Naqvi et al., 2019; Ahmad et al., 2020; Maccarthy et al., 2021; Tui et al., 2021; Valdivia et al., 2017). One study used the AgFutures model that explores sustainable agriculture futures using land use evolution and impact assessment on environmental and socio-economic systems (Sharma et al., 2006), Additionally one study developed and evaluated scenarios based on shared European agricultural socioeconomic and climate change pathways and land use modeling (Nishizawa et al., 2023). Time scales in type P1 ranged from 13 to 40 years. The studies focus on large databases, which leads to the loss of the comprehensive analysis that can be obtained by conducting semi-structured interviews.

In the P2 type, the 3 articles used pathways approaches to define adaptation strategies. Based on mixed methods, including modeling, workshops and interviews with farmers, financial service providers and the central government, they aimed to establish a multiple perspective on climate change adaptation at territorial scale (Kenny, 2011; Cradock-Henry et al., 2020; Egger et al., 2023). They used a time step of 10 years and a time scale of 100 years. In contrast to P1 studies, Cradock-Henry et al. (2020) conducted semi-structured interviews with agricultural experts (farmers, growers and consultants).

3.3. Factors influencing farm trajectories

Changes in farm trajectories can be the result of a set of factors that may be endogenous to the agricultural activity (family organization, agricultural practices) or exogenous (agricultural development policies, markets, migration dynamics, etc.).

Of the total number of articles addressing the issue of trajectories, 23 related the observed changes to variations in farmers' capital, farm size, farm technology, number of cattle heads, and economic performance and markets (Benoit and Laignel, 2011; Moreno-Perez et al., 2011; Malaquin et al., 2012; Huttunen, 2019; Veysset et al., 2015), they are retrospective studies from types R1 (9 articles), R3 (9 articles) and R4 (5 articles). Sixteen articles related these changes in farm trajectories to farmers' management practices, skills or strategies; for example, changes that expand, specialize, diversify or intensify the farm (Iraizoz et al., 2007; Cots-Folch et al., 2009; Navegantes-Alves et al., 2012; Bernard et al., 2014; Vall et al., 2017). These articles belong to restrospective types R1 (5 articles), R2 (1 article), R3 (3 articles) and R4 (7 articles). Seven retrospective articles (type R4–4 articles, and R3–3 articles) associated changes in trajectories to family farm organization (Terrier et al., 2012; Alavoine-Mornas et al., 2014; Madelrieux et al., 2014; de Carvalho et al., 2015; Kongmanee and Ahmed, 2019). Eight articles (type R1–2 articles, type R2–1 article, type R3–3 articles and type R4–2 articles) analyzed the effects of public policies such as the common agricultural policy, credit access, agrarian reforms, agri-environmental measures and transport development policies on farms' trajectories (Ryschawy et al., 2013; David et al., 2014; Vall et al., 2017). Four articles (type R1–2 articles, type R3–2 articles) focused on factors such as population growth and biophysical characteristics of the land, climate change (Mellisse et al., 2018; Greenville et al., 2019; Kong et al., 2019; Fischer et al., 2022; Le Trouher et al., 2023). Only 3 articles (type R4) analyzed bifurcations in farm trajectories. The authors stated that bifurcations may be caused by the lack of a successor, illness, professional identity changes, financial difficulties or public policies (Lamine, 2011; Bredart and Stassart, 2017).

3.4. Family work organization and the role of women

When studying farm trajectories and pathways, only 11 articles integrated the family work organization in their analysis. They are in types R3 and R4. Most analyzed family organization from the perspective of land inheritance (Valbuena et al., 2010) or the intention to continue with the activity (Malaquin et al., 2012), illness of family members (de Carvalho et al., 2015) or family engagement to new practices (Alavoine-Mornas et al., 2014).

Madelrieux et al. (2014) proposed a method based on three levers for analyzing family farm organization: the structure of the work group, the on-farm activities system and the pluriactivity of farmers and non-farm activities. This study focuses on changes in the structure of the work group (size, family-based or not) due to the specialization of the farm, diversification or organic farming. Changes in workload and the composition of the work group are described, but the role of family members was not studied. Rissing et al. (2021) highlighted that the specific needs of women farmers are often not met by official agricultural education and technical assistance.

Only one study proposed an in-depth analysis of the co-evolution of farms and family organization. Terrier et al. (2012) studied the long-term transfer of farms from one generation to the next and how farmer couples interact as well as their respective roles on and off-farm in relation to management and organization. This study questioned the effect of the collective farm transmission project on individual behaviors (logic of descent group). The family configuration was characterized regarding:

i) Inheritance on the farm and the role of the previous generation in the farm activity
ii) The professional career of the spouses
iii) The division of work by gender on and off-farm
iv) Balances of power by gender and generations
v) Time and space (at farm level) management.

In the studies analyzed, interviews were generally conducted only with household "heads", which can create a bias and underestimate women's work and roles when the household head is not a woman. Terrier et al. (2012) conducted interviews with each family member to overcome this bias. However, this kind of studies leads to more data being collected for each farm, reducing the possibility of large farm samples.

3.5. Specificity of farm trajectories on pioneer fronts

Only six of the selected articles refer to pioneer fronts, and most of these were in Brazil. According to Cialdella and Navegantes Alves (2014), the most widespread small farm settlements in the North Eastern Amazon can be modelized as a five-steps trajectory: i) settlement with a deforestation of about 5 ha on land that can range in size from 50 to 100 ha at the end of the process; the deforestation is done by hand, ii) planting of self-consumption crops, mainly plantains, cassava and maize through slash and burn practices, iii) introduction of pastures, and iv) livestock development.

Farm trajectories on the pioneer fronts are highly dynamic. Navegantes-Alves et al. (2012) points out that this is due to a sequential change in land use and production techniques, as well as changes in family, society and territorial organization. The stability of farm trajectories depends on financial access, technical assistance and road infrastructure. Similarly, de Carvalho et al. (2015) stated that the precariousness of infrastructure, energy and transportation make farm trajectories unstable. Raising livestock is one way to provide some security in such a context.

Plassin et al. (2015) combined the results of retrospective interviews to characterize the coherence of the farmer (reasoning) and the landscape (result of the farmer's actions). The conceptual model identified factors that are internal (such as farm household characteristics) and external (such as socio-economic, political, or regulatory contexts, or pedoclimatic conditions). External factors played an important role in

the farm trajectories on the pioneer fronts. Kong et al. (2019) described individual farm trajectories to analyze land use/cover changes (LUCC) with a conceptual framework based on proximate causes (eg. infrastructure development (roads), agriculture, resource exploitation) and underlying factors (eg. demographic, economic, technological, environmental and political factors) on pioneer fronts in Cambodia. Kong et al. (2019) described the farm trajectory as having four main stages: i) timber exploitation leading to cleared areas, ii) agricultural extension based on annual crops such as soybeans and peanuts, iii) start of intensive hybrid maize farming, and iv) agricultural diversification with paddle rice and tree crops such as mango, longan and rubber. In some circumstances, there is a fifth stage represented by livestock introduction.

4. Discussion

4.1. Limitations on farm trajectories analyses

The first limitation we found in existing studies was the lack of combination of retrospective and prospective analyses. Consequently, the lessons learned in retrospective analyses were not used to design desirable scenarios and strategies for the future. There was also a lack of consideration of the link between these trajectories and agroecological principles. Articulating the concepts of trajectory and agroecology could enable a better qualification of the trajectories. The biophysical (diversification, synergies, recycling, etc.) and socio-technical principles of agroecology (participatory governance, co-creation of knowledge) could be used to identify favorable trajectories over time.

Changes in farm retrospective trajectories were described in three main ways (i) as successive phases (Dedieu, 2009; de Carvalho et al., 2015; Chantre et al., 2015; Polge and Pagès, 2022), (ii) comparatively (Perrot et al., 1995; Paquette, 2007; Hirczak et al., 2013), and (iii) as perturbations or shocks (Lamine, 2011; Bredart and Stassart, 2017). In the various studies, different phases of capital accumulation, production improvement, technological advancement, intensification strategies, and changes to how family work is organized were identified. The study of progressive phases in farm trajectories can be related to changes in work organization and gender that was lacking in most studies. Analyzing work organization in farm trajectories can revel women's roles and farm strategic decisions.

Geography studies have highlighted the significance of pioneer fronts dynamics. The stages of evolution refer to i) the beginning of pioneer fronts, characterized by land ownership conflicts with scarce infrastructure and services, ii) the active pioneer fronts, when a major organization of land ownership emerges, but roads and services are still precarious, iii) the post pioneer fronts characterized by an expansion of production systems based on a model of intensification or diversification (Poccard-Chapuis et al., 2020; Thalês et al., 2021).

Diverse factors operating at different scales have been identified as influencing farm trajectories. Most of the studies focused on factors such as yields, input reduction (fertilizers, tillage, irrigation), farm size and public policies. In this last case, establishing a causal relationship between the effect of a public policy and a change in agricultural trajectory is difficult (Lefebvre et al., 2012). There are in effect methodological challenges since public policies can be designed at the regional or national scale, and their effects may be different on different trajectories, especially in terms of farm work organization. Existing studies failed to understand the localized impacts of public policies on farm trajectories. Territorial variations in infrastructure, market accessibility, and credit access can significantly alter the effectiveness of implemented strategies. Consequently, future research efforts must delve into these territorial factors to unravel the diversity of farm trajectories. Combining R2 and R4 farm trajectory approaches is interesting to articulate in-depth analysis of farm trajectories and to draw lessons at territorial scale in pioneer fronts. However, using modeling tools in these areas can be challenging given the amount of data that needs to be collected or the simplifications that need to be done. The use of anticipation methods based on focus groups as done in P2 studies can be a relevant option.

4.2. An analytical framework proposal for a renewed analysis of farm trajectories in pioneer fronts

An analysis of sustainable farm trajectories on pioneer fronts requires an evolution of existing methods, we propose an analytical framework that addresses the limitations we found in existing studies.

The first innovative feature of this framework is to relate the retrospective analysis with the pioneer fronts stages (the beginning of pioneer fronts, the active pioneer fronts, and the post-pioneer fronts) of the territory. Farm trajectories may depend on the stage of the pioneer front. This means selecting contrasted study sites (contrasted territories) where pioneer fronts are in different stages. It increases data collection effort; however, it is key to understand the link between forest transition (deforestation, degradation and regeneration) and farm trajectories.

The second innovative feature is to make a cross analysis between forest transition, farm trajectories, and territorial factors (e.g., public policies, changes in landscape, demographic or market accessibility factors) in specific sites of the territory presenting distinct spatial or organizational characteristics that we call "patch" (Fig. 5). Each patch would be identified with experts selected for their role in agricultural development of the territory (researchers, university, farmers' organizations, local government representative, local representative of the ministry of agriculture, input suppliers, bank). Relying on patches would avoid extensive data collection in the territory. Maps could be used as a support to the discussion and identification of such patches with experts. Additionally, semi-structured interviews with farmers and their families within each patch would help to identify the main public policies that, in one way or another, have affected their individual farm trajectories. In remote areas where census of farms may not be available, methods such as snowball sampling (Goodman, 1961) could be used to select farmers in patches by asking interviewed farmers to identify other farmers that followed distinct trajectories. The third innovative feature is the analysis of the evolution over time of farm organizational practices and their link with agroecological principles to identify sustainable trajectories (Wezel et al., 2020). Identifying how agroecological principles are addressed in long-term farm trajectories can be a complex task. The characterization of coherent phases in farm trajectories regarding the farm organization and activities (Moulin et al., 2008; Chantre et al., 2015) may help to identify how each phase of the farm trajectory is linked to one or various agroecological principles defined by Wezel et al. (2020) rather than each year of the trajectory. To limit the duration of farm surveys, only one proxy per agroecological principle could be considered (eg. active participation to a farmer group can be used as a proxy for co-creation of knowledge).

Selecting the correct time step to report patterns of change in farm trajectories remains a major challenge (Cialdella et al., 2009; Rueff et al., 2012), especially in the context of pioneer fronts where changes may occur more frequently. In our analytical framework, as a fourth innovation we propose to not define any time step to not miss changes that may occur suddenly (bifurcations), but to define a minimum time scale of 30 years to capture changes in forest transition (deforestation, degradation, regeneration). As suggested by Chantre et al. (2015), time scales need to be flexible in order to perceive the elements that cause changes; without defined fixed time steps, these could emerge from interviews. For example, separations of couples and illnesses of family members do not have a definite time step but may have important repercussions on a trajectory.

The fifth innovation is to link retrospective and prospective analyses based on the assumption that past farmer trajectories are the basis for constructing future analyses (Ryschawy et al., 2014). For the prospective analyses, as done in the P2 pathways group, we suggest using anticipation methods (Pereira et al., 2018; Miller et al., 2018; Minkkinen et al., 2019; Jahel et al., 2023) where the plausible future farm pathways

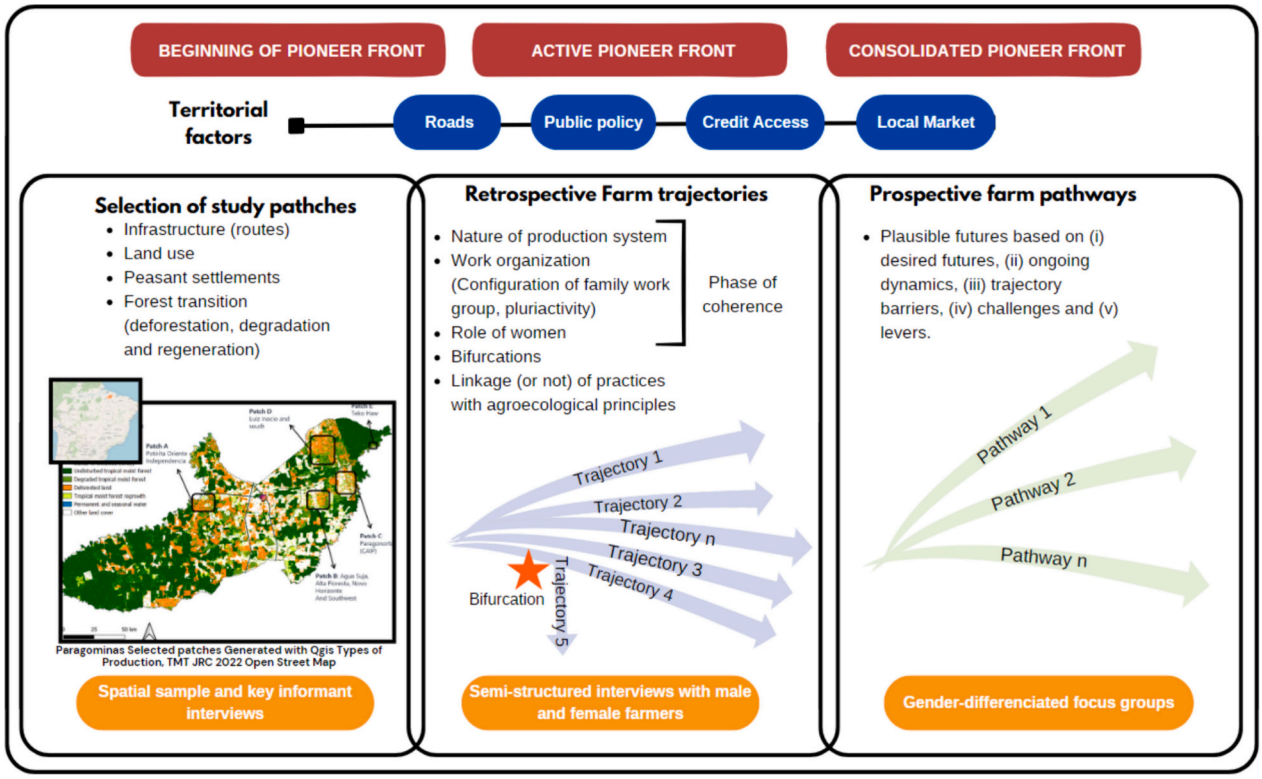

Fig. 5. Analytical framework in a pioneer front context. Farm trajectories depend on the stage of the pioneer front: Beginning, Active and Consolidated. The main territorial effects were identified: Public Policies, Infrastructure, Local Market, and Credit Access. The retrospective trajectories on the pioneer fronts are based on phases coherences, work organization and the role of women. The prospective analysis of pathways through workshops are based on retrospective trajectories.

on pioneer fronts are explored in focus groups. Over the last 10 years, there have been few works on trajectories on pioneer fronts, and these were specifically anchored to retrospective Brazilian dynamics. However, these studies and the related database will help us in the construction of sustainable (prospective) pathways.

In order to overcome the underrepresentation of women role in farm trajectories, conducting gender differentiated surveys is crucial. In addition to the data collected on public policies, or on the implementation of agroecological principles, specific data should be collected on the division of work by gender, power decision on the trajectory, invisible work performed by women, and their roles in bifurcations (Terrier et al., 2012). Furthermore, the focus groups conducted for the prospective analyses need to be divided by gender to better capture the distinct expectations of men and women.

We found that four out of six studies on farm trajectories on pioneer fronts were conducted in Brazil. The analytical framework we propose aims to capture the specific challenges that need to be explored in a diversity of contexts in the Amazon where the pioneer fronts are in different stages due to specific public policies, demographic pressure or social conflicts (Murillo-Sandoval et al., 2021). Furthermore, the framework is generic enough for analyzing trajectories in other pioneer fronts of the world such as the one described by Kong et al. (2019) in Cambodia bringing insights on the role of work organization and of women in bifurcations that could explain forest transition. Despite our emphasis on pioneer fronts, the methodological insights can be relevant in many cases that aim to explore endogenous and exogenous factors of changes in farm trajectories.

5. Conclusion

The systematic review allowed us to identify the types of methodologies used for describing farm trajectories and pathways. Two clear trends emerged in the results, namely that retrospective approaches have been used to study trajectories and prospective approaches for pathways. Both types have their own strengths and drawbacks for the study of farm changes, and neither has close links with the concept of agroecology. The diversity in methodologies highlighted some shortfalls: i) the articulation between retrospective and prospective analyses has not been explored at the farm scale, ii) the trade-off between conducting a general study with a large database and a diversity of variables, or studying in-depth the evolution of a few trajectories based on family and farm history, iii) the role of the family work organization in farm trajectories is scarcely studied, especially the role of women. Similarly, farm trajectories on pioneer fronts are scarcely studied. We proposed an analytical framework useful for future studies that would address these limitations. It considers agroecological principles in the analysis of farm trajectories to provide insights for limiting deforestation, particularly in the beginning and active pioneer front stages. It also considers bifurcations in trajectories to characterize tense moments and to better orient changes in agricultural systems. It combines retrospective and prospective analyses to identify plausible futures. This framework is currently used in Brazilian and Colombian Amazon and will help defining sustainable trajectories limiting deforestation. Future lines of research involve implementing and monitoring such pathways with specific attention on women's professional recognition, on the adoption of agroecological principles, and on local community well-being. This requires participatory research on the design of organizational and institutional changes such as new advisory services, markets and policies at territorial scale to better support sustainable trajectories.

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CRediT authorship contribution statement

Andrés Vega-Martinez: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Data curation, Conceptualization. **Nathalie Cialdella:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Nadine Andrieu:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

List of selected articles is available in the supplementary material. The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Appendix A. Supplementary data

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