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UMR Innovation

Building sustainable agriculture in the Amazon: a study of farms trajectories and farmers' visions of ideal farms in Brazil and Colombia

Présentée par Andrés VEGA-MARTINEZ
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Sous la direction de Nadine ANDRIEU
Et le co-encadrement de Nathalie CIALDELLA

Devant le jury composé de

Benoît DEDIEU, Directeur de Recherche, INRAE	Rapporteur
Xavier Arnauld DE SARTRE, Directeur de Recherche, CNRS	Rapporteur
Camille JAHEL, Chercheuse, CIRAD	Examinatrice
Gabriel RESQUE, Professeur, Universidade Federal Rural da Amazônia	Examinateur
Jean-Christophe CASTELLA, Directeur de Recherche, IRD	Président du jury
Nadine ANDRIEU, Chercheuse, CIRAD	Directrice de thèse
Nathalie CIALDELLA, Chercheuse, CIRAD	Invitée

Foreword

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Résumé étendu

1. Introduction : Complexité dans la transformation des territoires amazoniens

L'Amazonie couvre une superficie totale de 8 470 211 km² selon la *Red Amazónica de Información Socioambiental Georreferenciada* (RAISG) (RAISG 2025). Ce vaste territoire est réparti entre neuf pays, le Brésil occupant la plus grande superficie (61,80 %), suivi du Pérou (11,40 %), de la Bolivie (8,40 %), de la Colombie (6,00 %), du Venezuela (5,60 %), du Guyana (2,50 %), du Suriname (1. 70%), de l'Equateur (1,60%) et de la Guyane française (1,00%). On observe une diminution constante de la superficie forestière depuis 1985, estimée à 800 000 km², soit l'équivalent d'environ 1,47 fois la superficie de la France métropolitaine, selon le RAISG. Ce phénomène de déforestation, impulsé par une dynamique de colonisation à la fois spontanée et planifiée, a pour conséquences la dégradation des écosystèmes. Il provoque également l'érosion et la dégradation des sols, affectant leur fertilité, altérant les ressources en eau et les cycles hydrologiques. Cette déforestation se matérialise et se localise principalement sur des fronts pionniers.

Les fronts pionniers sont des processus d'expansion territoriale et d'occupation, caractérisés par l'avancée de la frontière agricole et la transformation de l'environnement naturel et de la société. Les politiques de colonisation, à travers les grands projets de construction de routes, ont constitué une étape importante dans le développement de fronts pionniers en Amazonie, à l’instar de la route Belém-Brasilia (BR-010), construite en 1962 au Brésil. Par la suite, le décret-loi brésilien 1106 de 1970, qui a établi le programme d'intégration nationale (PIN), a impulsé la construction de la route *transamazonienne,* tracée d’Est en Ouest de l'Amazonie brésilienne ainsi que la route traversant du Nord au Sud entre Santarém et Cuiabá (Ferreira 2001; Poccard-Chapuis 2004). Les grands projets routiers, ont également concerné les connexions transnationales, telles la “*via marginal de la selva*”, un projet ambitieux en 1963, visant à relier la Colombie, le Pérou, l'Équateur et la Bolivie. La jonction avec le Venezuela interviendra plus tard, en 1967 (Snyder 1967).

La particularité des fronts pionniers amazoniens, par rapport à d’autres fronts pionniers du monde, est que l'élevage de bétail est l'un des principaux moteurs de la déforestation. Il répond à la demande croissante de viande sur les marchés nationaux et internationaux, tout en favorisant l’appropriation foncière à travers des systèmes très extensifs, avec moins d’un animal par hectare. Au Brésil, ce processus a été soutenu par les politiques d’investissement mises en œuvre par le SUDAM (*Superintendência Para o Desenvolvimento da Amazônia*), qui a octroyé de vastes étendues de terre (entre 3 000 et 4 500 ha) à de grandes entreprises d'élevage de bétail (Poccard-Chapuis 2004).

- La complexité de l'agriculture en Amazonie, les défis de la durabilité Agricole

Le déploiement de l’agriculture sur par les fronts pionniers, basé sur la déforestation et l’exclusion ou l’assimilation des populations colonisées, pose un véritable défi au regard de la durabilité, en cherchant à reconstruire une conciliation entre cette agriculture "coloniale” avec la conservation des écosystèmes forestiers.

La durabilité de l'agriculture est définie par des dimensions économiques, environnementales et d'équité sociale, conformément aux objectifs de développement durable des Nations Unies (United Nations, 2015). Malgré les efforts déployés par les acteurs publics et privés (tels que le moratoire sur le soja, engagement pris par les grands acteurs de la filière à ne pas commercialiser le soja produit dans les zones qui proviennent de la déforestation dans le biome amazonien, ou la Déclaration de New York sur les forêts générée par le sommet du Secrétaire général de l'ONU sur le climat en septembre 2014 et visant à stopper la déforestation et régénérer la forêt en Amazonie), promouvoir une agriculture durable se heurte à des défis considérables, telles que développer l'agriculture et l'élevage en limitant la déforestation, favoriser l'accès aux ressources productives, et limiter l'insécurité foncière, limiter l’usage des pratiques agricoles dégradant les sols et les ressources en eau. Afin de comprendre et d’accompagner la dynamique de changements et les perspectives des agriculteur·rices en matière de durabilité, une approche intégrée articulant le passé, le présent et l'avenir des exploitations agricoles est cruciale.

Les études existantes sur les trajectoires des exploitations agricoles (Perrot et al. 1995; Madelrieux et al. 2015; Le Trouher et al. 2023), ne permettent pas toujours d'analyser de façon holistique leur durabilité. De plus, elles tendent à sous-estimer le rôle des femmes au sein de ces trajectoires. Par conséquent, pour favoriser une agriculture durable en Amazonie, il est essentiel de comprendre comment, influencées par leurs expériences passées, les agriculteur·rices envisagent l'avenir de leurs exploitations, et d'adopter une approche qui prenne en compte de façon holistique les différentes dimensions de la durabilité.

2. Questions de recherche

Cette thèse explore la question générale suivante :

Dans quelle mesure les trajectoires passées des exploitations agricoles permettent aux agriculteur·rices d'envisager des exploitations durables plausibles ?

Cette question a été divisée en trois questions de recherche spécifiques :

Q1 : Comment analyser l'évolution des exploitations agricoles dans les fronts pionniers et caractériser leur durabilité, en tenant compte de leur passé, de leur présent et de leur avenir ?

Q2 : Quelles trajectoires d'exploitations agricoles sont actuellement durables dans les territoires amazoniens ?

Q3 : Comment les agricultrices et les agriculteurs d'Amazonie envisagent-ils leurs exploitations agricoles idéales à moyen terme (2034) ?

Pour répondre à la question générale, j'ai développé une méthodologie originale (figure 1). La thèse est présentée sous forme de d'articles pouvant être lus indépendamment les uns des autres ; un des chapitres a été publié dans la revue Agricultural Systems les autres sont à soumettre.

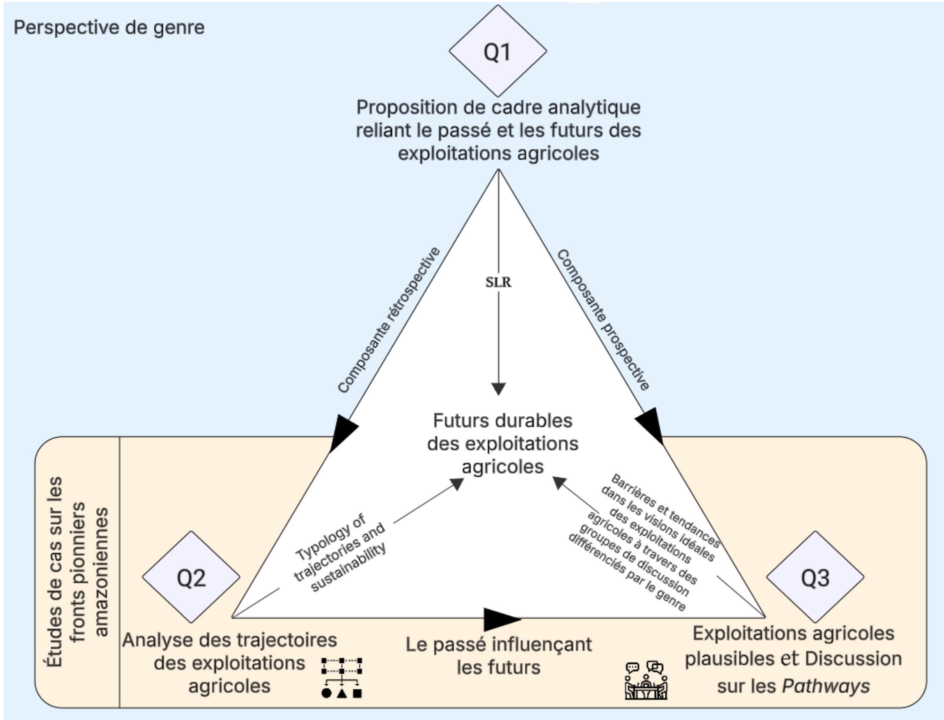

Figure 1 : Cadre méthodologique, adapté de Kong (2019)

3. La démarche méthodologique

La démarche méthodologique globale de la thèse était basée sur le développement d'un cadre analytique pour tenir compte du passé, présent et de l'avenir des exploitations et son application à deux études de cas sélectionnées pour correspondre à deux types de fronts pionniers : un front pionnier consolidé et un front pionnier actif.

La méthodologie a combiné trois étapes principales:

La première étape a consisté à explorer les concepts et les méthodes existantes pour analyser les changements dans les exploitations agricoles par le biais d'une revue systématique de la littérature. Cette étude visait à développer un cadre analytique pertinent pour la thèse, en articulant une analyse rétrospective et prospective des exploitations agricoles dans les fronts pionniers, en particulier en Amazonie. Cette étape visait à développer un cadre analytique permettant de définir le « comment » de la thèse dans les étapes suivantes.

La deuxième étape a consisté à mettre en œuvre de façon empiriquela composante rétrospective du cadre analytique. Elle s'est appuyée sur une analyse des trajectoires des exploitations agricoles et sur une évaluation de leur durabilité actuelle sur la base de principes agroécologiques. Cette étude a été appliquée à diverses exploitations agricoles dans les deux territoires différents d'Amazonie : (i) la municipalité de Paragominas, dans l'État du Pará, au Brésil, représentant un front pionnier consolidé, et (ii) le département de Guaviare en Colombie, correspondant à un front pionnier actif. Au sein de chacun de ces territoires, des zones spécifiques ont été sélectionnées, appelées *patches*, en tenant compte des caractéristiques géographiques, des types de production, des établissements paysans et des dynamiques forestières. A Paragominas, ces critères et les patches ont été validés via 15 entretiens avec des informateurs clés du secteur agricole (représentants d'instituts de recherche agricole, de l'université locale, de fournisseurs privés du secteur agricole, de l'institution financière agricole, d'associations d'agriculteur·rices et d'institutions gouvernementales locales). Dans le Guaviare, la sélection des *patches* a été faite en fonction des dynamiques forestières et des relations de confiance construites entre l'ONG partenaire et les groupes d'agriculteur·rices. La collecte des données a consisté en des entretiens semi-directifs rétrospectifs avec les agriculteur·rices afin de reconstituer les changements survenus dans leurs exploitations depuis leur création (Moulin et al., 2008), en se focalisant sur la combinaison d'activités ou de productions, la proportion de forêt sur l'exploitation et les pratiques d'utilisation des terres, ainsi qu'à l'abandon des exploitations. Quarante (40) agriculteur·rices ont été interviewé·es à Paragominas et quinze (15) à Guaviare. Les données ont traitées par une analyse des correspondances multiples (ACM) et d'une analyse ascendante hiérarchique afin d'identifier les types de trajectoires agricoles. Dix principes agroécologiques inspirés de la littérature mais adaptés au contexte amazonien ainsi qu'un système de notation de ces principes ont permis d'évaluer le niveau d'alignement de la phase actuelle de chaque trajectoire avec ces principes.

La troisième étape s'est concentrée sur la mise en œuvre de la composante prospective du cadre analytique. J'ai utilisé le Triangle des Futurs (Inayatullah 2008, 2023), outil d'anticipation permettant d'explorer et analyser la vision qu'ont les agriculteur·rices de leurs fermes idéales en 2034, ainsi que les facteurs favorables ou défavorables pouvant affecter le futur. Cette approche a été appliquée dans quatre « patches » (deux dans chaque territoire) sélectionnées sur la base de la collaboration d'associations d'agriculteur·rices. Des groupes de discussion (mixtes et non mixtes, composés uniquement de femmes) ont permis d'explorer de façon participative les visions portées par les agriculteur·rices sur leur ferme idéale. Au cours des groupes de discussion, trois éléments clés ont été analysés.

- L'attraction du futur : Visions des fermes idéales en 2034, où les agriculteur·rices ont décrit leurs systèmes de production souhaités, la répartition de l'utilisation des terres (y compris les zones de conservation des forêts) et du collectif du travail.
- La «poussée» du présent : les tendances et les forces actuelles qui facilitent la réalisation de ces visions.
- Le « poids » du passé : les barrières et obstacles historiques qui ont empêché de progresser vers des exploitations idéales.

L'analyse rétrospective des trajectoires a couvert la période entre 1989 et 2023, tandis que l'analyse prospective a été réalisée à moyen terme, sur une période allant de 2024 à 2034.

4. Résultats

4.1 Comprendre les méthodes d'analyse des trajectoires des exploitations agricoles pour construire des avenirs durables sur les fronts pionniers : Leçons tirées d'une revue systématique de la littérature et proposition d'un cadre analytique

Une revue systématique de la littérature sur les trajectoires et les chemins (*pathways en anglais)* des exploitations agricoles a été conduite, dans le but de proposer un cadre analytique renouvelé pour analyser ces trajectoires sur les fronts pionniers et appuyer l'identification des stratégies souhaitables pour l'avenir. En utilisant une méthodologie adaptée de PRISMA (Page et al., 2021), 81 articles ont été analysés, classés selon qu'ils étaient rétrospectifs ou prospectifs, qu'ils prenaient en compte l'échelle territoriale ou uniquement l'échelle de l'exploitation et qu'ils utilisaient ou non des outils de modélisation.

La revue systématique a mis en évidence une diversité de méthodologies utilisées pour analyser les changements des exploitations agricoles, classées en six types principaux : quatre types d'études rétrospectives (R1-R4) et deux types d'études prospectives (P1-P2) :

- R1 Analyse rétrospective tenant compte de l'ensemble des système de production agricole et d'élevage d'un territoire donné (22 articles).
- R2 Analyse rétrospective considérant l'exploitation agricole et le paysage, en mobilisant la modélisation (4 articles).
- R3 Analyse rétrospective et longitudinale des effets de facteurs du territoire sur les dynamiques d'exploitations (18 articles).
- R4 Analyse rétrospective basée sur une approche compréhensive, à l'échelle de l'exploitation et de la famille (23 articles).
- P1 Analyse prospective basée sur l'utilisation de modèles pour simuler des données biophysiques et socio-économiques à l'échelle régionale (11 articles).
- P2 Analyse prospective visant à définir des stratégies d'adaptation dans le futur et basée sur des approches mixtes combinant modélisation et ateliers multi-acteurs (3 articles).

La revue a montré que le concept de trajectoire est principalement associé à des analyses rétrospectives, tandis que celui de *pathway* est davantage lié à des études prospectives qui utilisent généralement des modèles pour concevoir des scénarios futurs. Elle a aussi montré un lien limité entre analyse des trajectoires et les principes agroécologiques, ainsi qu'une attention insuffisante du rôle des femmes et de l'organisation du travail familial dans l'évolution des exploitations agricoles. En outre, la plupart des méthodologies étudiées ne prennent pas pleinement en compte les facteurs externes, tels que les facteurs territoriaux affectant ces trajectoires.

Pour remédier à ces limites, un cadre analytique innovant a été proposé, qui combine l'analyse rétrospective et l'analyse prospective, il relie l'analyse rétrospective aux étapes du front pionnier (début du front pionnier, front pionnier actif, front pionnier consolidé) et propose d'utiliser des méthodes d'anticipation afin d'explorer les trajectoires plausibles à l'avenir dans des groupes de discussion avec les agriculteur·rices. En conclusion, il souligne la nécessité d'articuler les analyses rétrospectives et prospectives, de prendre en compte le rôle de l'organisation du travail familial (en particulier celui des femmes) pour mieux comprendre et accompagner les trajectoires d'exploitations dans les zones de fronts pionniers.

4.2 Durabilité des exploitations agricoles dans les fronts pionniers de l'Amazonie colombienne et brésilienne : combiner les trajectoires des exploitations et les principes agroécologiques.

Six types de trajectoires agricoles ont été identifiés : (1) intensification progressive de l'élevage avec pâturage en tournant, (2) élevage stable, (3) agroforesterie, (4) passage rapide à l'élevage avec pâturage tournant, (5) élevage extensif et (6) culture de soja associé à l'élevage. Les trajectoires d'agroforesterie et du passage rapide à l'élevage avec pâturage en rotation sont celles qui s'alignent le plus aux principes de l'agroécologie.

Chaque type de trajectoire est confronté à des défis particuliers et présente des opportunités spécifiques pour l'adoption de pratiques agroécologiques. Les caractéristiques territoriales, telles que l'accessibilité aux marchés et aux infrastructures, exercent une influence majeure sur le développement des trajectoires agricoles. Une prévalence de l'élevage comme activité principale a été observée dans la plupart des trajectoires analysées dans les deux fronts pionniers.

4.3 Exploration des visions des exploitations agricoles en Amazonie brésilienne et colombienne : une étude participative des futurs avec une perspective de genre

Cette étude a permis d'explorer les futurs des agriculteur·rices de petite échelle en Amazonie d'ici à 2034, en analysant les dynamiques actuelles et les obstacles passés dans la municipalité de Paragominas (Brésil) et dans le département de Guaviare (Colombie).

Cinq types d'exploitations idéales ont émergé, avec une tendance marquée à la diversification de la production et une forte préférence pour des systèmes d'élevage basés sur le pâturage tournant ou le sylvopastoralisme combinés avec des systèmes agroforestiers dans les deux territoires.

Des facteurs transversaux tels que l'adoption de nouvelles pratiques (élevage basé sur le pâturage tournant et systèmes sylvopastoraux), les connaissances et l'expérience locales, le soutien des ONG et des instituts de recherche et l'existence d'associations d'agriculteur·rices ont été identifiés.

Les poids du passé sont communs aux deux territoires : le manque d'accès au crédit et à une assistance technique adéquate, la dépendance aux intrants agricoles, l'absence de marchés équitables et les problèmes liés à la délivrance de titres fonciers ont été mentionnés. Dans le Guaviare, le conflit armé et la production de coca ont été des poids importants, rendant difficile toute projection dans l'avenir. Les questions de genre, telles que la surcharge de travail des femmes, ont également été identifiées comme des obstacles.

Les discussions ont révélé des tensions entre les poids du passé et les poussées du présent, mettant en évidence des défis persistants tels que le conflit à Guaviare, l'accès au crédit pour les femmes et les impacts de l'agro-industrie à Paragominas. Les participants ont également identifié des leviers pour surmonter les obstacles, tels que la négociation avec les institutions de crédit et le renforcement des associations.

Les trajectoires agricoles passées semblent influer sur la nature des futurs envisagés. Les agriculteur·rices ont tendance à imaginer des exploitations idéales basées sur leurs expériences antérieures et les systèmes de production qu'ils connaissent dans leur environnement local. En outre, des différences de vision entre femmes et hommes ont été mises en évidence, les femmes mettant souvent l'accent sur la diversification des activités et l'équité entre les sexes dans la gestion de l'exploitation.

Les agriculteur·rices de ces deux territoires Amazoniens envisagent un avenir agricole plus diversifié que leurs systèmes de production actuels, bien que ces visions semblent intrinsèquement liées à leurs expériences passées et conditionnées par les forces actuelles et les défis historiques. Ils soulignent l'importance de prendre en compte les perspectives de genre dans l'élaboration de *pathways* vers des futurs durables et inclusifs dans la région.

5. Discussion et Conclusion

L'originalité méthodologique de la thèse relève de l'articulation de l'analyse des trajectoires des exploitations agricoles avec l'évaluation des principes agroécologiques. Cette combinaison permet une évaluation de la durabilité des exploitations en tenant compte de leur trajectoire, dans les contextes amazoniens étudiés. La thèse souligne également l'importance d'intégrer des méthodes rétrospectives et prospectives pour comprendre comment les expériences passées des agriculteur·rices façonnent leurs aspirations futures. Cette articulation fournit une base solide pour le développement de *pathways* vers la durabilité à la fois à Paragominas et à Guaviare, et potentiellement dans d'autres régions pionnières de l'Amazonie.

L'un des principaux enseignements de cette recherche empirique est la présence persistante et significative du bétail dans les trajectoires des exploitations agricoles et, par conséquent, dans les visions qu'ont les agriculteur·rices de leurs exploitations agricoles idéales. Cette constatation indique que la promotion de la durabilité dans la région doit prendre en compte l'élevage comme pilier de l'agriculture. La transition de systèmes d'élevage extensifs vers des pratiques plus intensives, telles que les systèmes sylvopastoraux ou le pâturage tournant pour le bétail font partie de l'équation. Cependant, la thèse souligne que ces *pathways* vers la durabilité doivent tenir compte de l'hétérogénéité des trajectoires et des visions des exploitations agricoles afin d'être pertinentes et adaptées aux besoins et aspirations spécifiques des agriculteur·rices, augmentant ainsi les chances de construire un avenir agricole plus durable pour l'Amazonie. En outre, la recherche révèle la sous-représentation des femmes dans les dynamiques agricoles, malgré leur rôle fondamental, ce qui souligne la nécessité d'adopter une approche explicite au genre.

Envisager une durabilité basée sur les systèmes d'élevage de pâturage tournant ou le sylvopastoralisme peut être controversé en raison du risque d'utilisation du bétail comme moyen d'appropriation du foncier, y compris dans les aires protégées (dont celles dédiées aux populations autochtones).

Nos résultats montrent que, malgré un cadre réglementaire environnemental établissant à 80 % la surface forestière à conserver sur chaque propriété rurale en Amazonie brésilienne, l'idéal des agriculteur·rices est bien en dessous, avec une médiane de 20 % pour Paragominas et 19 % pour le Guaviare. Cette projection semble prendre en compte la flexibilité légale accordée aux exploitations familiales de moins de 220 hectares à Paragominas, dans le cadre du Code forestier de 2012.

Dans le Guaviare, la légalité de couper la forêt ne se détermine pas en fonction d'un pourcentage de la superficie totale de l'exploitation, mais dépend du zonage du terrain selon les réglementations environnementales et les plans d'aménagement municipaux.

La vision prédominante d'une ferme idéale combinant des systèmes d’élevage basés sur le sylvopastoralisme ou le pâturage tournant avec l'agroforesterie peut potentiellement améliorer la prise en compte des principes agroécologiques tels que le recyclage, la réduction des intrants synthétiques, la santé des sols et la biodiversité, ainsi que la diversification des revenus.

Malgré les avantages potentiels, l'adoption de cette vision idéale augmente la complexité technique, économique et sociale de l'exploitation, dont il faut tenir compte pour sa mise en œuvre effective.

En conclusion, la diversité des trajectoires des exploitations agricoles et leur durabilité du point de vue de l'agroécologie fournissent une base solide et contextualisée pour la conception de pathways vers la durabilité. Cette approche reconnaît la nécessité de construire des pathways qui permettent la transition vers des exploitations plus durables, en tenant compte des caractéristiques de chaque type de trajectoire et de sa durabilité actuelle. Ces informations sont précieuses pour l'élaboration des politiques publiques ainsi que pour les parties prenantes qui œuvrent en faveur d'une agriculture plus durable en Amazonie. En articulant les spécificités de chaque trajectoire avec la vision de l'exploitation agricole idéale, il est possible de concevoir des *pathways* plus précis et plus adaptés aux besoins et aux aspirations des agriculteur·rices, ce qui augmente les chances de pouvoir construire 'un avenir agricole plus durable pour la région.

Ce travail a également mis en évidence l'importance de prendre en compte les différences entre les genres dans les trajectoires agricoles et les visions des futurs. Les agricultrices, dont les rôles sont souvent invisibilisés dans les discours normatifs, jouent un rôle fondamental dans l'agriculture, avec un triple rôle, dans le travail agricole, le travail domestique et les soins de la famille. Leurs visions soulignent souvent l'importance de la diversification, allant au-delà des systèmes de production traditionnels pour inclure des activités telles que l'agroécotourisme. Elles envisagent également l'équité entre les sexes à travers la reconnaissance de leur statut de cheffes d'exploitation. Cette recherche offre un cadre analytique innovant pour étudier la dynamique du changement agricole dans la région pionnière de l'Amazonie, qui pourrait également s'appliquer à d'autres fronts pionniers. Ce cadre permet d'imbriquer le passé, le présent et l'avenir des exploitations agricoles dans une optique de durabilité, tout en intégrant des dimensions de genre et des facteurs territoriaux. Les résultats contribuent à une meilleure compréhension des aspirations et des défis auxquels sont confrontés les agricultrices·eurs dans cette région soumis à des enjeux majeurs.

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- ABIOVE (Brazilian Association of Vegetable Oil Companies)
- AFD (*Agence Française de Développement*)
- ANEC (Association of Grain Exporters)
- APP (Permanent Protection Area)
- ARL (Legal Reserve Area)
- BASA (Bank of Amazonia)
- CAR (Rural Environmental Cadastre)
- CDA (Corporation for Sustainable Development for Northern and Eastern Amazon)
- CIRAD (French Agricultural Research Centre for International Development)
- DANE (National Administrative Department of Statistics)
- ESR (Efficiency, Substitution and Redesign)
- EURD (European Regulation on Deforestation-free Products)
- CONTAG (National Confederation of Agricultural Workers)
- FARC-EP (*Fuerzas Armadas Revolucionarias de Colombia Ejército del Pueblo*)
- FETAEG (Federation of Agricultural Workers)
- FINAGRO (Fund for the financing of the agricultural and livestock sector)
- FNO (Northern Constitutional Financing Fund)
- HAC (Hierarchical Ascending Classification)
- IBGE (Brazilian Institute of Geography and Statistics)
- IDB (Inter-American Development Bank)
- IMAZON (Amazon Institute of People and the Environment)
- INCODER (Colombian Institute of Rural Development)
- INCORA (Colombian Institute of Agrarian Regulation)
- INCRA (National Institute for Colonization and Agrarian Reform)
- JRC (Joint Research Center)
- LUCC (Land Use/Cover Changes)
- MCA (Multiple Correspondence Analysis)
- NGO (Non-Governmental Organization)
- ONF-A (*Office National des Forêts Andina*)

- PCA (Principal Component Analyses)
- PES (Payments for environmental services)
- PIN (National Integration Program)
- PNAE (National School Food Program)
- PNIS (National Integral Program for the Substitution of Illicit Crops)
- PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)
- PRONAF (National Program to Strengthen Family Farming)
- RAISG (Amazonian Network of Georeferenced Socioenvironmental Information)
- RAP (Representative Agricultural Pathways)
- AFS (Agroforestry Systems)
- SDGs (Sustainable Development Goals)
- SENA (National Training Service)
- SENAR (National Rural Learning Service)
- SINCHI (Research Institute of the Colombian Amazon)
- SLR (Systematic Literature Review)
- SPS (Silvopastoral Systems)
- SUDAM (Superintendence of Amazon Development)
- UN (United Nations)
- UNODC (United Nations Office on Drugs and Crime)
- UPRA (Rural Agricultural Planning Unit)
- USAID (United States Agency for International Development)
- WoS (Web of Science)

Chapter one: Introduction, problematic and methodology

1.1 Introduction: Complexity in the transformation of Amazonian territories.

The Amazon covers a total area of 8,470,211 km², according to the boundaries established by the Amazonian Network of Georeferenced Socio-environmental Information (RAISG) (RAISG, 2025). This vast territory extends over nine countries, with Brazil occupying 61.80%, followed by Peru (11.40%), Bolivia (8.40%), Colombia (6.00%), Venezuela (5.60%), Guyana (2.50%), Suriname (1.70%), Ecuador (1.60%) and French Guiana (1.00%). According to RAISG, an area of 800,000 km² of forest has been lost since 1985, equivalent to approximately 1.47 times the area of metropolitan France.

This drastic deterioration of the Amazon is the cause of a growing international concern. In the international policy agenda, the Amazon is frequently presented as an extraordinary biodiversity reserve and a fundamental pillar in the global ecosystem equilibrium due to the role of its forests in climate regulation (Albert et al., 2023; Boulton et al., 2022). As a result, and since the 1990s, the Amazon is a priority on the international agenda. (European Union, 2024; United Nations Framework Convention on Climate Change [UNFCCC], 2014; Társia, 2024).

However, in this international agenda, while the aspirations of today's local populations is recognized, it is overlooked. It is crucial, indeed, to consider the reality of the populations who inhabit this region, and their socio-cultural diversity. The populations may be urban and rural; native, colons (melt-people), with their own logic built in their own context. The total population on the Amazon exceeds 45 million people with 400 indigenous groups, who speak more than 300 languages (ACTO, 2023). This population diversity is translated in varied processes of establishment, the clashing of ideas in the construction of territories, as well as in the way in which futures are envisioned (Palacio, 2025)

In the Amazonian Forest, there are various territorial expansion and occupation dynamics that lead to the transformation of the natural environment. Initially, this expansion was characterized by the exploitation of natural resources followed by the progress of the agricultural frontier. This process is known as pioneer fronts (Albaladejo & Tulet, 1996; Ferreira, 2001). Pioneer fronts involve the exploitation of resources, often in an unsustainable way (Piketty et al., 2002). Pioneer fronts are processes of colonization, migration and landscape transformation (Albaladejo, 2001; Poccard-Chapuis et al., 2020). In their first stages, pioneer fronts involve the establishment of people in a land, modifying the land use in a search of a social and territorial development (Poccard-Chapuis et al., 2024). Pioneer fronts may consequently be spaces of conflict given the interaction of different social actors.

Despite the diversity of expansion and occupation dynamics, the emergence of these territories follows a common socioeconomic pattern: their rapid demographic expansion driven by the migration of people searching for land and work (Hodel, 2023). In territories characterized by fragile institutions and precariousness of basic services, such as education and health, the speed of the population growth generally exceeds the management capacities of such institutions (Gudynas, 2007). This leads to the emergence of an informal economy, where the lack of agricultural development references and of support for the evolution of production systems hinders their development (Hostiou et al., 2004).

In this context, expansion and occupation dynamics lead to a degradation of ecosystems; it is estimated that 17% of the remaining forest in the Amazon has been degraded by human disturbances. The deforestation stands out as one of the main unfavorable impacts; it is estimated that the Amazon biome forest has lost 13% of its original forest (Flores et al., 2024). This is mainly driven by the expansion of agriculture and cattle raising (Ribeiro et al., 2025). The destruction of natural forest habitat reduces biodiversity, affecting both animal and plant species. Cumulated deforestation has a major impact on climate change, and it is estimated that exceeding the 20% deforestation threshold could trigger an acceleration of forest mortality and a significant reduction in rainfall at the regional level. (Flores et al., 2024). This deforestation also causes erosion and soil degradation, which in turn affects their fertility. Forest fragmentation makes water resources vulnerable and alters hydrological cycles, in addition to negative consequences on carbon sequestration and other ecosystem services (Huang et al., 2025).

These environmental changes occur within what is called the pioneer march, a concept which captures the process of advancement of the agricultural frontier and the transformation of the territory (Becker, 2005; Dollfus, 1981). The pioneer march has been analyzed from a constructivist perspective of stages that can be successive. Each stage is associated with specific land use patterns, environmental impacts, and socioeconomic dynamics, following an evolutionary logic. The process begins with the stage of a potential front, marked by the plan of colonization from an incipient population and forest areas are almost intact. Then, in the pioneer settlement stage, the basic infrastructure is developed, including roads and small settlements. At this stage, agriculture begins to play a key role in the configuration of the territory at the expense of forest.

Later, in the pioneer expansion stage, the agricultural area grows significantly considering its proportion in the total area of the territory. The spatial organization of the pioneer front begins to stabilize, structuring itself around a center with basic infrastructure (town, main roads, essential services such as health and education). This development facilitates the expansion of agriculture and resource exploitation to areas that are more distant and difficult to access. The process continues with a pioneer consolidation stage, where most of the space is occupied by agricultural production. However, there are still dynamics of land use change, which sometimes lead to deforestation. Finally, in the post pioneer stage, the territory is integrated into the national space. At this stage, deforestation is controlled, and agricultural production is based on an intensified models and diversified economic sectors (e.g. development of industry and service sectors) (Albaladejo & Tulet, 1996; Coy & Lucker, 1993; Poccard-Chapuis et al., 2020, 2024).

- The Amazon colonization

The Amazon attracted its first Spanish and Portuguese colonizers due to its natural wealth. However, its dense vegetation, adverse climatic conditions and rugged terrain made it difficult to access, which limited its integration into the emerging national entities on the continent (Sayago et al., 2010). The first economic activity in the Amazon was based on exploitation of natural resources. In Brazil, between the 16th and 18th centuries, exploitation was based on "*Drogas do Sertão*". They were native resources of the Amazon, highly valued in Europe for their exotic character. Among them were Brazilian pepper (*Schinus terebinthifolia)*, cinchona (*Genus Cinchona*) and cacao (*Theobroma cacao*), among others. However, its trade declined in the nineteenth century, with competition from crops in other regions, paving the way for the exploitation of rubber in the late 19th and early 20th centuries. It was not until the late 1950s and 1960s that a marked process of official colonization began, triggered by public policies.

Infrastructure policies played a key role in the Amazon colonization, one of the most significant milestones in the development of pioneer fronts was the process of territorial integration through the construction of highways. In Brazil, in 1962, the Belém Brasilia highway (BR-010) was a turning point in the incorporation of the Amazon into the national territory. To this hand, the Brazilian policy Decree-Law 1106, the National Integration Program (PIN), of 1970, based its main axis on the construction of the Trans-Amazonian highway, connecting the east and west of the Brazilian Amazon. Additionally, the BR-163 was also constructed, connecting the North to South from Santarém to Cuiaba (Ferreira, 2001; Poccard-Chapuis, 2004). At the same time, in 1963, the marginal jungle road configured an ambitious international project designed to connect Colombia, Peru, Ecuador and Bolivia, which Venezuela would join later (Snyder, 1967).

Agrarian and land distribution policies influenced the configuration of the Amazonian pioneer fronts, determining to a large extent the access to land, the tenure structure and the socio-economic dynamics in these territories. Agrarian policies can trigger the occupation of territories by offering incentives for access to land, a concrete example being Law 5.174 of 1966, which granted a 50% reduction in the tax on land for those who invested in the Brazilian Amazon (Ferreira, 2001). Some policies contributed to social inequity within pioneer fronts, where land allocation criteria favored some actors with specific characteristics, in this example favoring actors with capital to invest. However, governments also provided land plots to low-income populations, in Brazil this occurred under the policy of a land without men for men without land. In Colombia, the law 61 in 1874 encouraged the delivery of land to those who would cultivate it, under the idea of expanding the productive base in the Amazon and offering opportunities to low-income farmers (Ruiz, 2012). This was a strategic response by governments to avoid agrarian reforms.

The particularity of Amazonian pioneer fronts compared to other pioneer front areas of the world is that cattle ranching is one of the main divers of deforestation. Cattle ranching is driven by the demand for meat from both national and international markets. In Brazil, this process was promoted in the early stages of colonization through policies implemented by SUDAM (*Superintendência Para o Desenvolvimento da Amazônia*), which granted large areas of land (between 3000-4500 ha) to large cattle ranching companies (Poccard-Chapuis, 2004).

During the 1980s, the Brazilian Amazon continued to undergo processes of occupation and transformation. In southern Pará state, the gold rush attracted a massive influx of people and capital, profoundly altering the regional economy (Plassin, 2018). Cattle ranching has become a central economic activity due to its low labor costs and relative income security in a context of limited infrastructure and markets (Ferreira, 2001).

During the 1990s, changes in livestock dynamics occurred. Factors such as the 1994 Real Plan, new sanitary requirements and pasture degradation led to a trend of declining cattle numbers. In this context, some ranchers began to explore pasture alternatives as a response to degradation, anticipating a move towards intensification (Plassin, 2018). In the 2000s, the eastern Brazilian Amazon entered a phase of agrarian transition. Faced with limited access to new land and forest fertility, a movement towards land use diversification and livestock intensification emerged.

The expansion of agriculture, especially soybean cultivation, stands out as another important driver of deforestation in Brazil. In response to this situation, the soybean moratorium was established, based on a voluntary agreement signed in 2006 by the Brazilian Association of Vegetable Oil

Companies (ABIOVE) and the Association of Grain Exporters (ANEC) to prevent the purchase and sale of soybeans produced in deforested areas of the Amazon after that year. On the other hand, timber extraction and mining, both legal and illegal, were driving forces of the deforestation of the Amazonian pioneer fronts. Their impact varies according to the degree of regulation and integration with other economic activities mentioned above, such as agriculture and cattle ranching (Martins et al., 2022).

The colonization of the Colombian Amazon was linked with a transformation of the natural landscape, to develop agriculture and cattle ranching. In addition to cattle ranching, the colonists began to cultivate food crops (*pancoger*) such as yucca, plantain, corn and rice, mainly for self-consumption and incipient local markets. A determining factor in the 1970s was the coca cultivation as an economic survival strategy by the farmers. This activity generated a significant population increase and economic transformations in the region, attracting not only landless farmers, but also other groups in search of opportunities linked to the coca economy (Marin, 2002).

In the 1980s, the price of coca decreased due to factors such as overproduction and increased competition, which affected the profitability of the crop for farmers. In this same decade, there was a significant expansion of pastures for cattle ranching in the Amazon, with the transformation of hundreds of thousands of hectares of forest, specifically in Caqueta and Guaviare (Fajardo Montana, 2017). By the 1990s, coca cultivation remained an important economic factor within agriculture. In response to the fight against drug trafficking, the Colombian state implemented fumigation policies, most notably Plan Colombia in 1999, which affected both coca cultivation and farmers' livelihoods (Ruiz, 2012).

Since 2000, the colonization of the Colombian Amazon has been marked by the expansion of different production systems, mainly extensive cattle ranching. At the same time, agro-industrial projects centered on oil palm cultivation have emerged (Castiblanco et al., 2013). However, illicit crops, especially coca, continue to shape socioeconomic and territorial dynamics. As a response, the State has implemented crop substitution programs such as, the National Integral Program for the Substitution of Illicit Crops (PNIS), albeit limited in scope. Additionally, the peace agreement with the FARC-

EP (*Fuerzas Armadas Revolucionarias de Colombia Ejército del Pueblo in Spanish*) in 2019 has also had an impact on development in the region (Bravo Parra et al., 2018).

The development of pioneer front and its associated deforestation processes, is directly influenced by the productive logics that predominate in the region. They can be categorized in two types. On the one hand, the logic of family farming, which in some cases seeks food security and social reproduction of the family and in others, in addition to the above, seeks to generate surpluses to invest in expanding production. It has been a driving force for land occupation, where traditional farming techniques often require small extensions of land, but still contribute to agricultural expansion, and to deforestation. On the other hand, agro-industry is oriented to the production of commodities for export, although some may be destined to domestic consumption (Ferreira, 2001). It plays a central role in deforestation, since its large-scale production model requires vast land areas.

Amazonian pioneer fronts have facilitated the development of a diverse range of agricultural production systems typical to the region. Agroforestry systems, which are presented a sustainable alternative combining food production and limiting deforestation (Costa, 2024). Moreover, there is extensive cattle ranching, based on occupation of land with the objective of securing its possession and value, all while maintaining a low investment in infrastructure and management, leads to deforestation. In addition, typical systems include large-scale corporate production of grains, mainly soybeans, deeply associated to deforestation (de Azeredo Morgado et al., 2023; Song et al., 2021) .

1.2Research problem setting

1.2.1 The complexity of Amazonian agriculture, challenges for agricultural sustainability

Despite various definitions of sustainability (Brundtland, 1987; Daly, 1990), there is a consensus that agricultural sustainability encompass economic, environmental, and also social equity dimensions (Elkington &

Rowlands, 1999; Tilman et al., 2002). In September 2015, the 193 member states of the UN adopted the 2030 Agenda for Sustainable Development, identifying 17 SDGs (Sustainable Development Goals) (United Nations, 2015).

In that context, agricultural sustainability goes beyond maintaining the long-term productive capacity of food systems, it focuses on preserving the resource base on which agriculture depends. Such as soil fertility, economic viability of farms and farmers' knowledge, ensuring a balance between ecological, economic and social systems. Agroecology emerges as an approach that applies ecological, social, and economic principles and concepts to the design and management of food production systems to achieve sustainability (Gliessman, 2007). Agroecology is characterized as a scientific discipline, a set of practices and a social movement, thus providing a holistic approach (Gliessman, 2018a; Wezel et al., 2009). Agroecology provides basic principles on how to study, design and manage agroecosystems that reconcile productivity, conservation of natural resources, in addition to responding to cultural and socioeconomical challenges (Altieri, 2002). In essence, agroecological principles seek to balance food production with environmental protection and social welfare, promoting resilient and equitable food systems (Wezel et al., 2020).

Principles such as equity, sustainable governance of natural resources, recycling and synergies between the component of agro-ecosystems, reduced use of synthetic inputs are promoted (Wezel et al., 2019)

However, implementing agroecological principles in the Amazon is challenging. In addition to the deforestation caused by the development of agriculture, these systems implement unsustainable practices such as extensive grazing, exacerbating soil erosion, nutrient leaching and compaction, reducing its fertility and productive capacity (Feltran-Barbieri & Féres, 2021; Navegantes-Alves et al., 2012). The use of fertilizers and pesticides contaminating water, affecting human and ecosystem health (de Azeredo Morgado et al., 2023).

Additionally, in large-scale agriculture, the intensive use of synthetic inputs has triggered soil degradation, water pollution and biodiversity loss (de Azeredo Morgado et al., 2023; Hunke et al., 2015). The demand for land suitable for cultivation has led to a decrease in the length of fallow periods in slash-and-burn practices, a practice used mainly by smallholders. Short fallow periods (3 to 7 years) are depleting soil fertility and increasing weed pressure, which in turn demands more labor and reduces productivity (Abrell et al., 2024). Furthermore, slash and burn practices threaten forests with the risk of causing forest fires. It is estimated that slash and burn contribute to 15% of total deforestation in the Brazilian Amazon (Godar et al., 2014).

Agriculture in the Amazonian pioneer fronts also have limited access to credit, technical assistance and markets, which particularly affect family farming (Hostiou et al., 2004; S. Plassin, 2018). The externalization of environmental and social costs, combined with the volatility of agricultural commodities, is also a challenge for agribusiness (Sievert et al., 2024). The land tenure insecurity of Amazonian pioneer fronts has caused conflicts that in turn are an obstacle to the development of sustainable agriculture (Benatti & da Cunha Fischer, 2018).

The unsustainability of agriculture in the Amazon is the result of a complex interaction between environmental, socioeconomic challenges and limited room for maneuver for farmers. The agricultural activity in the region is facing an inherent complexity at different levels. At the technical level, soil management and land use within the farm stand out with the necessity to cut the forest to establish agriculture. At the social level, the organization of work within farms and the construction of knowledge networks among farmers. The lack of a stable base for farms in the pioneer front generates uncertainty and fragility in labor and social structures Finally, at the territorial level, agricultural activity is closely linked to spatial configuration, governance and land use dynamics (e.g. expansion of the agricultural frontier, land abandonment, etc.) that affect the evolution of the forest (deforestation, degradation and regeneration).

1.2.2 Sustainability for the Amazon, an integrated approach between the past, present and future of farms

The situation described above invites reflecting on how to address agricultural sustainability in the Amazon and what are the ways to achieve it. However, moving towards sustainable agriculture in the Amazon requires understanding how farmers envision the future of their farms, given that their decisions, strategies and agricultural practices depend on their perceptions, expectations and representations of the future of their farms. In turn, farmers' visions are shaped by their previous experiences built during their farm's trajectories and the historical context in which they are embedded. It is therefore essential to adopt a systemic approach that articulates the past, present and future to understand changes on farms, the sustainability of their current situation and the projections that farmers make about their farms.

Regarding the analysis of the past, the systemic agronomy approach to farm trajectories is an analytical tool for understanding farm changes (Le Trouher et al., 2023; Madelrieux et al., 2015; Perrot et al., 1995). These analyze the sequences of changes experienced by farms over time. These trajectories are influenced by factors that can be endogenous (farming practices, work organization) or exogenous (policies, climatic conditions, markets). Farm trajectories make it possible to identify patterns of change and turning points in the development of agricultural production systems (Bakker et al., 2021; Chantre et al., 2015).

The analysis of farm trajectories in the Amazon was first conducted in Brazil; these studies have addressed topics such as how migration patterns relate to agricultural systems and heritage transmission in family farming (Arnauld de Sartre, 2006). Other studies have focused on the relationship between cattle farming practices and pasture degradation, demonstrating that pasture sustainability is conditioned by the stability of farm trajectories (Navegantes-Alves et al., 2012). Other studies have explored the effects of the market on dairy producers, classifying trajectories as opportunistic or persistent based on their responses to market conditions (Carvalho et al., 2015). Additionally, the relationship between family trajectories and forest regeneration has been explored, considering various types of farmers and their impact on the state and function of secondary forests (*capoeiras*) on their land (Ballon et al., 2016). Plassin et al. (2017) developed trajectory types for landscape models of livestock systems, based on various land-use intensification strategies that led to contrasting spatial dynamics.

Trajectories approaches have provided valuable insights into sustainability in amazon farming. However, they often focus on reductionist aspects, such as sustainable ecological intensification practices, while overlooking other dimensions of sustainability that go beyond practices, such as gender equity. This literature shows that there is no clear connection between farm trajectories in the Amazon pioneer frontiers and an analysis of sustainability from a holistic perspective, such as the one offered by agroecology. Understanding this relationship is crucial for the study of sustainable agriculture in the Amazon.

Regarding the analysis of the present sustainability, agriculture on the pioneer fronts involves reconciling ecological, socioeconomic, cultural and political dimensions. For this, the use of agroecological principles as lens to understand sustainability can be relevant. Agroecology is diverse and adapted to its local environment through the creation of stakeholder knowledge. Specifically in the Amazon, how farms align with agroecological principles is poorly described. Pompeu et al. (2017) underscored the relevance of farmer cooperatives in Tomé-Açu, Brazil, with the aim of disseminating knowledge about agroecological farming practices. Resque et al. (2019) identified programs such as National School Food Program (PNAE acronym in Portuguese) and as promoters of agroecology, although they deemed them vulnerable due to political instability. Pizarro et al. (2025) examine the agroecological performance of small-scale dairy farms in the Peruvian Amazon, demonstrating that silvopastoral systems exhibit a more advanced agroecological transition compared to traditional systems. These studies provide important contributions to agroecology in the Amazon; however, they do not take into account the past dimension that can be analyzed from a farm trajectories perspective.

The above raises questions about what factors have limited or enabled alignment to agroecological principles in highly dynamic territories such as the Amazonian pioneer fronts. The absence of adequate methodological tools to retrospectively evaluate the alignment of each agroecological principle, specifically in a context of scarce information, hinders and impedes the feasibility of such an analysis. Combining an analysis of farm trajectories with the current evaluation of their alignment to agroecological principles could be feasible, although it raises methodological questions.

Additionally, we cannot talk about agricultural sustainability without considering the role of women in agriculture. Women play a key role, cultivating between 60% and 80% of the food consumed worldwide. However, they often face inequalities in access to resources and decision-making (Goli et al., 2025). Sustainable agricultural initiatives, whether political, academic or non-governmental organizations, that do not consider gender roles, differentiated access to resources and the specific needs of men and women farmers, may fail to achieve their sustainability objectives, particularly in the area of equity.

Understanding sustainability in Amazonian agriculture requires an approach that integrates a gender perspective, from both the retrospective and present analyses, considering the role of women in the evolution of farm dynamics. However, the role of women in Amazonian agriculture, their contribution to sustainability and their visions on the future of farms has historically been underestimated or little studied (Barrow et al., 2024; Hodel, 2023; Sonetti-González et al., 2023). This lack of recognition limits the design of inclusive and sustainable strategies for agricultural development in the region.

In relation to the future of sustainable agriculture, Diniz et al. (2015) examined future changes in livelihood security and environmental sustainability in the Brazilian Amazon from the point of view of smallholders. This research highlighted the presence of a significant trade-off between livelihood security and environmental sustainability. Folhes et al. (2015) conducted scenarios at various decision-making levels for territorial planning in Lago Grande, Brazilian amazon. Their approach focused on promoting dialogue between stakeholders, government entities and participating communities, with the objective to help to promote the empowering local communities. Furthermore, Garrett et al. (2021) identified key elements for achieving sustainable development in the Brazilian Amazon, such as innovations in agricultural management and improved forest governance. The study proposed pathways to a more sustainable future through the implementation of strategies such as sustainable intensification of cattle ranching and the promotion of a local forest economy.

If we look for the articulation between past and future, some studies on farm trajectories consider the future, exploring how the influence of new generations of farmers shapes long-term spatial configurations in a territory

(Arnauld de Sartre, 2006). Additionally, Carvalho et al. (2015) discusses scenarios for the evolution of milk production in the Amazon, emphasizing the uncertainty of dairy production in the region and various factors of instability, such as market access and its inherent volatility.

However, these studies lack a clear framework that links farm trajectory analysis with a prospective perspective. This absence limits the ability to anticipate the future of farms, hindering the construction of pathways toward sustainability. Additionally, the integration of a participatory approach with farmers remains insufficient, disconnecting the future of farms from the farmers themselves.

1.3Research questions

Given the contextual and scientific challenges described above we will explore the following question:

To what extent do past farm trajectories enable farmers to envision plausible sustainable farms?

Therefore, the object of this research is the role of past farm trajectories, their current sustainability, in enabling farmers to envision plausible sustainable farms, with a special focus on smallholders.

To explore this question, three specific research questions are formulated:

Q1: How can we analyze the evolution of farms in the pioneer fronts and characterize their sustainability, considering their past, present and future?

Through the first question, we aim to solve a methodological problem when understanding the changes occurring on farms in pioneer frontiers, taking into account territorial factors of pioneer fronts and the farm work organization, especially the role of women. In order to help farmers to reconcile food production with forest conservation and build sustainable futures. It is based on the hypothesis that the integration of retrospective and prospective analyses of farm changes can enable the design of an innovative analytical framework for building sustainable futures.

Q2: Which farm trajectories are currently sustainable in Amazonian territories?

The second question is related to the tension between past farms development and sustainability in Amazon pioneer fronts. The posited hypothesis is that, in the Amazonian pioneer fronts, farm trajectories affect the current alignment of the farm with agroecological principles.

Q3: How do women farmers and men farmers in the Amazon envision their ideal farms on the medium term (2034)?

The third question addresses one part of the challenge of building sustainable farms, where there is a recurrent marginalization of smallholder farmers, who play a fundamental role in food security and rural development. They face multiple sustainability challenges, including barriers in access to resources, limitations in the implementation of sustainable practices and structural inequalities, especially gender inequalities. As a step forward this process of building sustainable farms, it is essential to understand how farmers, particularly women, envision the futures of their farms. This question leads us to explore the plausible futures farms from the farmers' perspective. The hypothesis posited is that, in the Amazonian context, ideal visions of farms differ according to gender and shape their plausibility.

The conception of an innovative approach to evaluate the present sustainability of the trajectories, which allows identifying those that are sustainable and incorporating the farmers' visions in the construction of sustainable farms-constitutes the central axis of this thesis and represents a methodological contribution. This leads us to develop a research strategy oriented to deepen these aspects.

1.4 Methodology: Research Strategy

This section presents the overall thesis methodological framework. The location of the chosen case studies and their classification within the stages of the pioneer front is also presented. Each chapter of results was written as an article, published or to be submitted, and consequently provided a more detailed description of the method used.

In order to answer the research questions, and to support an integrated approach of the past, present, and future of the farms, three methodological steps were combined (Figure 1.1).

- ❖ The first step aims to explore the concepts and methods used for the analysis of farm changes based on a literature review. A systematic review of the existing scientific literature on farm trajectories and pathways was conducted with the objective of developing an analytical framework relevant for the thesis. This proposed analytical framework articulates a retrospective and prospective analysis of farms in pioneer fronts, specifically in Amazonia.
- ❖ The second step involved the empirical application of the retrospective component of the analytical framework. It was based on an analysis of farm trajectories and an assessment of their current sustainability based on agroecological principles. This approach was applied to diverse farms in two case studies chosen for corresponding to two distinct stages of pioneer fronts in the Amazon: (i) the municipality of Paragominas, in the Pará State, Brazil, representing a consolidated pioneer front, and (ii) the department of Guaviare in Colombia, corresponding to an active pioneer front.
- ❖ The third step focused on the application of the prospective component of the analytical framework. Using anticipation as a discipline, I employed a foresight approach based on a process that is participatory, which facilitates the exploration of medium futures (Jahel et al., 2023; Minkkinen et al., 2019). The methodological tool used was the Futures Triangle (Inayatullah, 2008, 2023) to explore and analyze plausible farms, considering the envisioning of ideal farms in the medium term (2034), as well as past constraining and present enabling factors for these ideal farms. This approach was applied in four study patches, selected from those used in the second step, and based on gender-differentiated focus groups with smallholder farmers.

The figure 1.2 presents empirical steps two and three, emphasizing that the retrospective analysis of trajectories covers the period between 1989 and 2023. The prospective analysis was performed on a time scale ranging from 2024 to 2034.

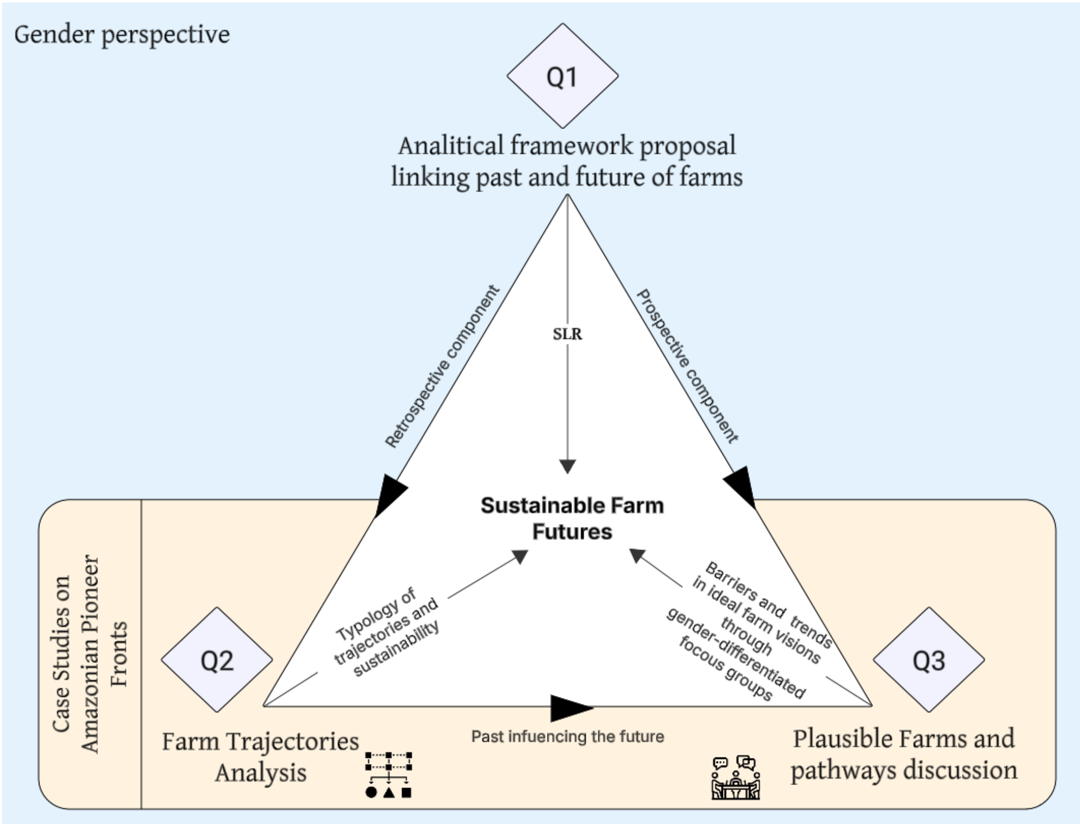

Figure 1.1 Methodological Framework inspired from (Kong, 2019)

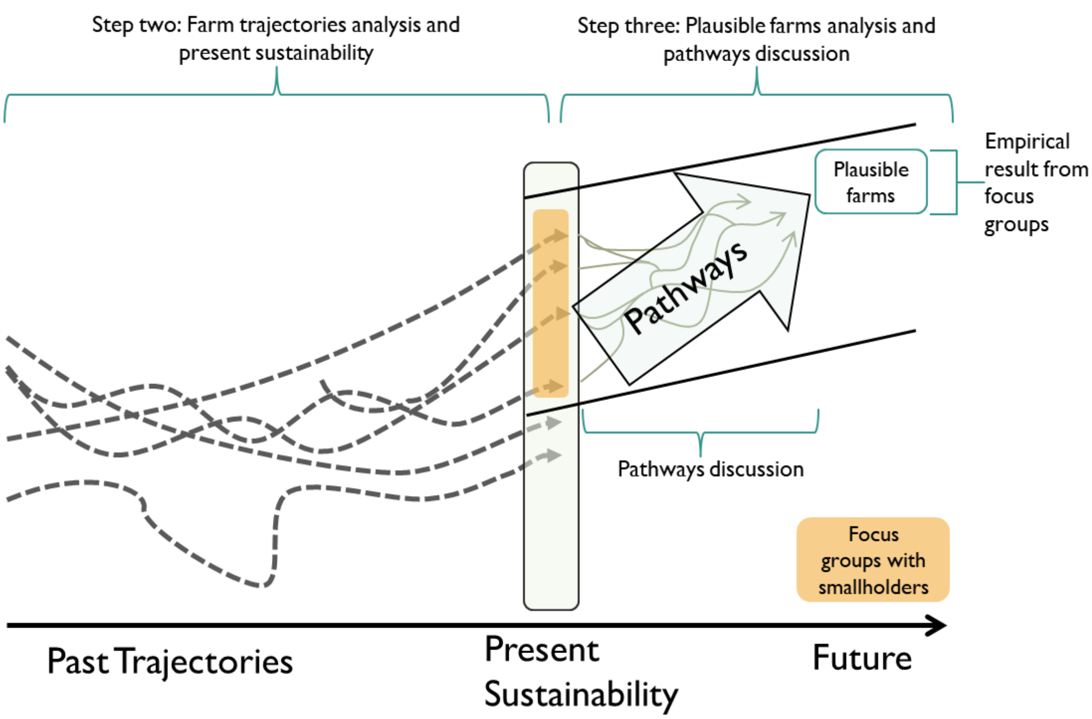

Figure 1.2 Empirical perimeter of the methodology

The following box describes the Terramaz project, this thesis was conducted in the third component of the project.

Terramaz project:

"In the current context of the continued deforestation and forest degradation in the Amazon, territories are developing innovative solutions based on the coordination and commitment of local stakeholders. They seek to harmonize sustainable agricultural transition, conservation and restoration of forest resources, as well as social inclusion. These initiatives offer new opportunities for the region. The TerrAmaz project, funded by the *Agence Française de Développement* (AFD), supports these initiatives. It is part of France's commitment to an International Partnership for Rainforest Conservation".

The primary objective of the Terramaz project is to assist Amazonian regions in executing their strategies to battle deforestation and transition to a development model that integrates low-carbon economic growth with ecosystem preservation.

"It is organized in 3 components. The first component aims at developing territorial engineering tools and methodologies allowing to improve territorial planning and management. The second component supports the implementation of concerted actions with farms, communities and local institutions of 5 pilot territories. The third component aims at producing scientific knowledge and capitalizing on relevant fields for the transition of territories towards a sustainable development free of deforestation: governance and public policy instruments, relevant and transparent indicators to certify sustainable landscapes, and the production of technical and economic references on sustainable agricultural, livestock and forestry systems."

Box 1 Terramaz Project

Additionally, this thesis employed artificial intelligence for English language translation using DeepL, Chatgpt and Quillbot.

1.4.1 Step 1 Systematic literature review and analytical framework proposal

This step employed a systematic literature review (SLR) adapted from the PRISMA method (Page et al., 2021) to comprehensively analyze existing studies on agricultural changes at the farm level. This systematic review of the literature allowed us first to analyze the methodologies used to study farm trajectories and pathways, with a focus on pioneer front. This gave us the basis for the construction of an original analytical framework.

The proposed analytical framework sought to overcome the methodological limitations found in existing studies on farm trajectories, especially in pioneer fronts areas. The originality of the framework lies first in the link made between retrospective analysis and the stages of pioneer fronts (active or consolidated pioneer fronts), selecting contrasting study sites. The second originality of the framework is to explore the link between forest transition (deforestation, degradation, regeneration), farm trajectories and territorial factors, identifying “patches” with distinct spatial or organizational characteristics, with the help of experts and interviews with farmers. The third originality of the framework is to link the analysis of the farm trajectory, their present phase and their alignment with agroecological principles to identify sustainable trajectories. The four originality is to link this retrospective analysis with a prospective analysis, using anticipatory methods in gender-differentiated focus groups to explore plausible futures capturing potential different expectations.

Thanks to the result of the SLR that is concretized in the analytical framework, I was able to solve the "how" in the thesis, which was needed to collect and analyze farm changes in steps 2 and 3.

1.4.2 Step 2 Implementing the retrospective component in two study cases

1.4.2.1 Study cases

The empirical part of the methods was implemented in two of the three case studies of the Terramaz project. These two case studies were selected for being at different stages of the pioneer march, which may influence the farm trajectories and visions and pathways. Some main pioneer fronts characteristics can be associated to active and consolidated stages (Becker, 2005; Dollfus, 1981; Katz-Asprilla, Phd in process; Poccard-Chapuis, 2004; Poccard-Chapuis et al., 2024; Thalês et al., 2021) and are summarized in table 1.1.

Table 1.1 Main characteristics of active and consolidated pioneer fronts

Criteria	Active Pioneer front	Consolidated Pioneer Front
Subnational Administrative Capacity (ability to perform administrative tasks such as infrastructure management and provision of public services)	• Road infrastructure connects the main population centers, it degrades drastically as it moves away from the central axis of the pioneer front, even being nonexistent in the periphery • Basic services are provided in urban areas, but water, health and electricity coverage are limited in rural areas and often absent • Unstable land use planning, although the rural cadaster process is advancing, it has limitations	• Road infrastructure connects the main population centers, it degrades drastically as it moves away from the central axis of the pioneer front, even being nonexistent in the periphery • High quality basic services are provided in urban areas; water, health and energy coverage reaches the rural periphery but is of limited quality • Advanced land use planning, most of the territory has a registered cadaster
Subnational Fiscal (ability to generate revenue through subnational fiscal revenue and manage those resources efficiently)	• It has a stable but limited tax base, often because sectors such as agriculture are informal or incipient	• It has a stable, in some cases diversified tax base. The formal economy predominates over the informal one, although the latter maintains a significant presence within the smallholders
Type of smallholder's settlements	• Some permanent settlements but also migratory	• Permanent settlements from a space perspective (in some cases may be disappearing given the dynamics with large landowners)
Integration of the Subnational territory at the national level	• The subnational level is relatively connected to the national level, although road infrastructures are not of high quality • Access to national or international markets is limited, although there is a link at the national level, this may depend on the value chains (meat, milk, non-timber forest products, etc.)	• High connectivity, transportation infrastructure between the subnational and national level is well developed. • Access to national and international markets is fluid and stable. However, the participation of small-scale agriculture is limited
Deforestation: Ratio of recent deforestation (4 years) to total deforestation	• Moderate: generally higher than 20% but with a tolerance in some cases starting at 15%	• Low: Generally, less than 8% but with a tolerance for some cases to be less than 14%

Poccard 2024		
Social conflicts	• Frequent; may be related to land disputes, concern different actors, settlers, indigenous communities, large landowners, illegal armed groups, etc.	• Rare, almost nonexistent, but may occur, mainly in litigation over land

- The municipality of Paragominas:

The municipality of Paragominas is located in the Pará state, in the Northern region of Brazil (figure 1.3). Paragominas is a consolidated pioneer front of 19.341 km². Paragominas pioneer front is characterized by a low recent deforestation with respect to the total land area of the municipality and its deforestation rates history, (95.7 km² in 2021 and 58.7 km² in 2022, with a low variation since 2016) (figure 1.4) suggesting that the process of agricultural expansion is slowing down. According to JRC data, between 1990 and 2022, 16% of the forest area has been deforested (figure 1.4) (Vancutsem et al., 2021). Now, rather than an expansion of the agricultural area, as observed in the past, a process of consolidation of these agricultural areas is taking place. This allows a regeneration of the forest in some areas of the territory. However, it does not mean that there is an absolute control of deforestation, which continues at a reduced rate. Instead, there is a transition towards a territory with a completely regulated deforestation (Poccard-Chapuis et al., 2024). The consolidated front is characterized by advanced land use planning, where most of the territory has a registered cadaster. In addition, the presence of infrastructures, mostly in central axis, facilitates access to water, electricity and health services.

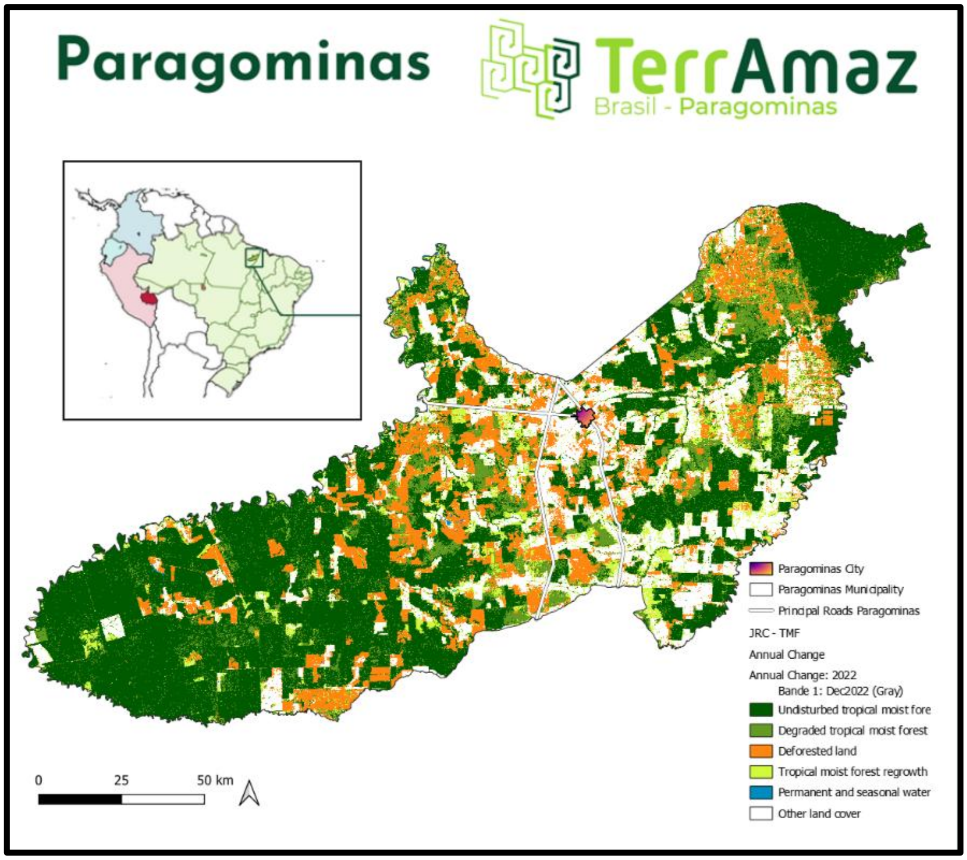

Figure 1.3 Location of the municipality of Paragominas, in the State of Para, in the State of Para, adapted from © C. Vautrin, CIRAD

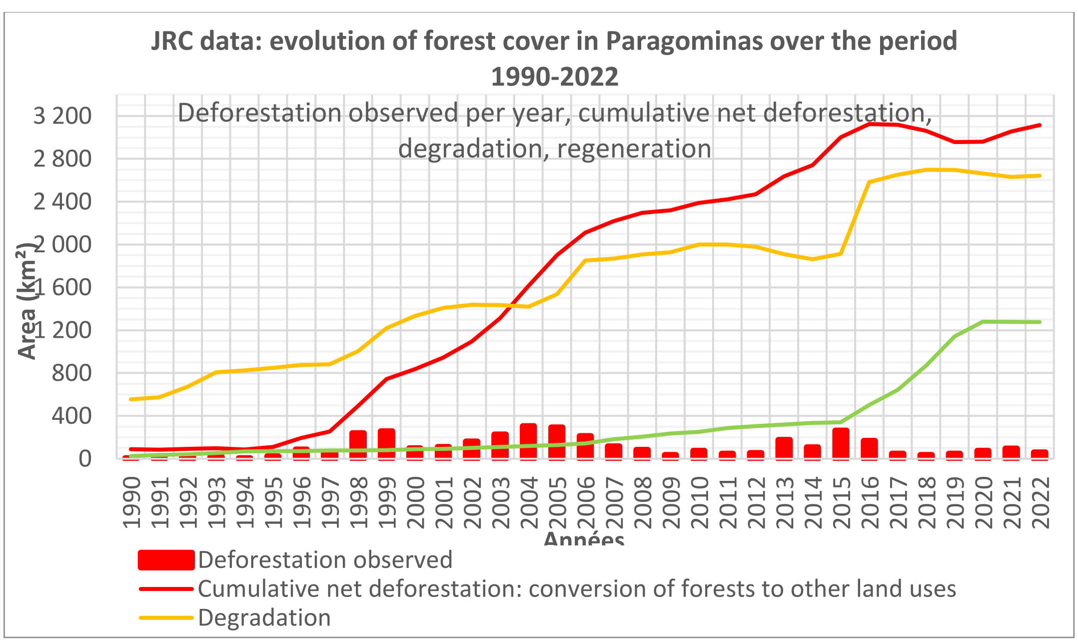

Figure 1.4 Evolution of forest cover in Paragominas over the period 1990-2022 (Area) JRC data.

JRC Tropical Moist Forests Annual change collection data:

The annual change collection depicts the extent and status of the TMF (degraded, deforested, regrowing) for each year between 1990 and 2022).

Undisturbed tropical moist forest: We define an undisturbed TMF as a closed evergreen or semi-evergreen forest without any disturbance (degradation or deforestation) observed on the Landsat valid observations up to the year of analysis. This class includes the mangroves and the bamboo-dominated forest.

Degraded tropical moist forest: A degraded forest is a closed evergreen or semi-evergreen forest (covered by existing or regrowing trees) that has been temporary disturbed during a period of maximum 2.5 years (900 days) and that started at the latest during the current year. It includes different types of degradation such as selective logging, fires, and unusual weather events (hurricane, drought, blowdown).

Deforested land: This class refers to the permanent conversion of forest into non-forested land that started at the latest the current year. Disturbances were observed over more than 2.5 years and no vegetative regrowth was detected. It includes three subcategories of converted land cover: (a) water bodies (new dams and river flow changes); (b) tree plantations; and (c) other land cover that includes infrastructure, agriculture and mining. It also includes deforestation areas that follow degradation.

Forest regrowth: This class refers to a pixel that has been deforested before the current year and that is currently regrowing. A minimum 3-years duration (2020-2022) of permanent moist forest cover presences needed to classify a pixel as forest regrowth (to avoid confusion with agriculture). It also includes in TMF-2022 afforestation of at least 3 years of regrowth (classes 92-94 from the Transition Map - Sub types).

Note: Although data from the JRC Tropical Moist Forest Product is available for 2023, I use data up to 2022, as it corresponds to the period when the interviews were conducted.

Box 2 JRC Tropical Moist Forests Annual change collection data

- The Department of Guaviare:

Guaviare is a department of Colombia, located in the southern central region of the country and covers an area of 53,460 km² (Figure 1.5). It shows the characteristics of an active pioneer front, with an increasing rate of deforestation. Its recent deforestation is particularly high, (Figure 1.6) with for example 299,9 km2 deforested in 2017 and 329,8 km² deforested in 2018, and an increased trend observed the subsequent years. According to JRC data, between 1990 and 2022, 6.9% of its surface has been deforested (Figure 67. This deforestation permitted to open large agricultural areas. The availability of large agricultural areas provides an opportunity for a transition to intensification, without the need to open new areas (Poccard-Chapuis et al., 2024). However, expansion into new lands may be driven by the lucrative pursuit of land appropriation. Indeed, the active pioneer fronts present a lack of cadastral information. This leads to conflicts and supports migrations. Although the central zone of the front has basic infrastructure that facilitates access to water, electricity and health services, the availability of these resources decreases notably as one moves away from the central axis, showing a marked absence of these services in peripheral areas.

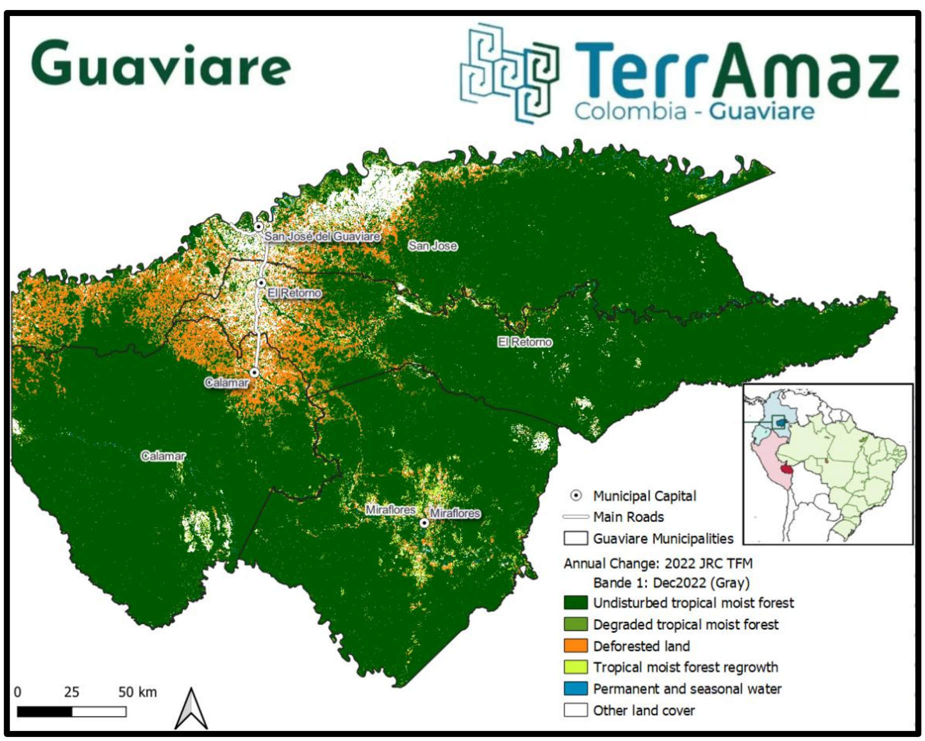

Figure 1.5 Location of the department of Guaviare in Colombia adapted from © C. Vautrin, Cirad

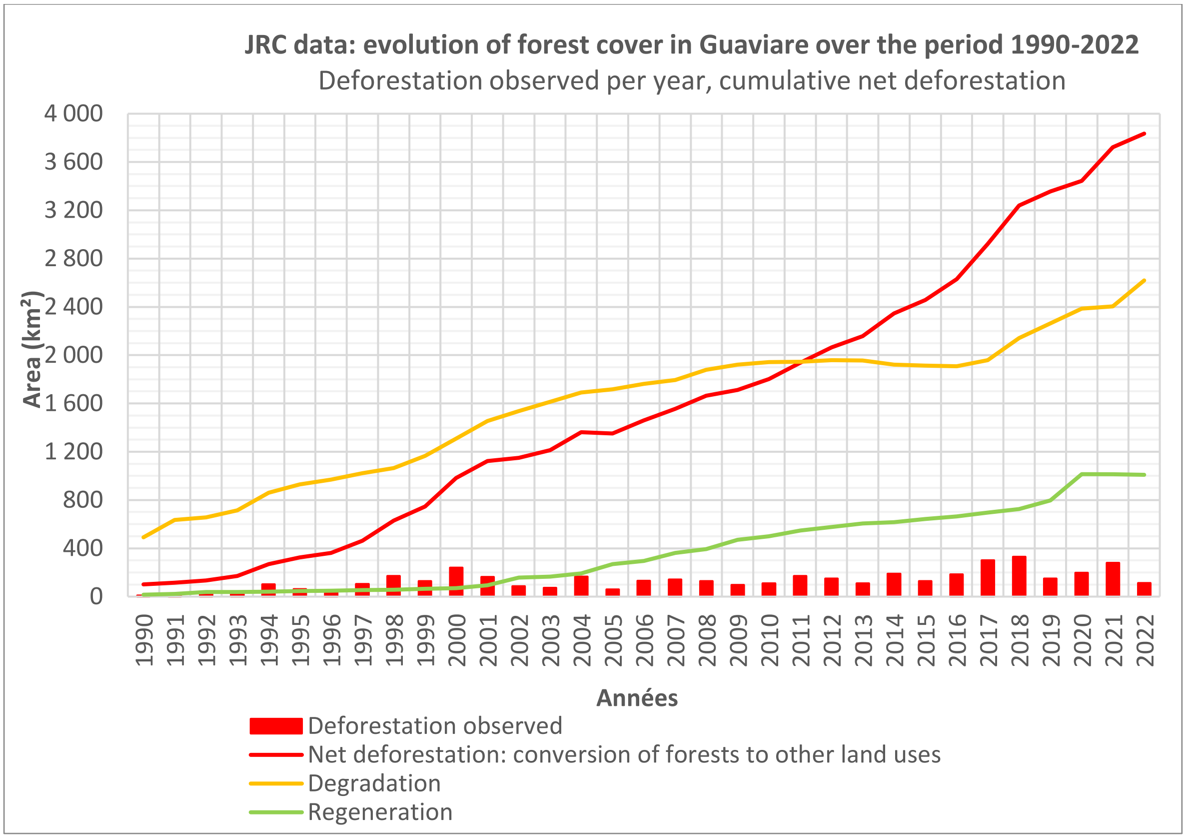

Figure 1.6 Evolution of forest cover in Guaviare over the period 1990-2022 (Area) JRC data

1.4.2.2 Past farm trajectories analysis and present assessment

The retrospective component of the analytical framework developed in step 1 was implemented in the two selected case studies. Step 2 was based on an inductive-deductive approach. My first objective was to analyze farm trajectories, but for this, I first need to understand them. I consequently described individual farm trajectories, in order to then classify their evolution in trajectory phases (Moulin et al., 2008). From this classification of trajectory phases, specific sequences of production systems (such as slash-and-burn to cattle ranching, followed by intensive rotational grazing for cattle) were identified, and a typology of trajectories was constructed. This process of going from the individual farm trajectory to a type, is characteristic of an inductive approach.

Additionally, I evaluated the alignment of the current phase of each type of trajectory with agroecological principles (Wezel et al., 2020). These agroecological principles, were translated into criteria adapted to the Amazonian context and used to evaluate the sustainability of the current phrase of each type. This is characteristic of a deductive approach.

For this step, I conducted semi-structured interviews with farmers to collect data on the farm trajectories but also with key informants in the agricultural sector (Agricultural research institutions, local University, financial institution, local government institutions, agricultural suppliers, farmers associations) to guide the selection of the study zones. The data collection was more extensive in the municipality of Paragominas, due to administrative requirements of CIRAD and the social context of the armed conflict in the department of Guaviare, which restricted both movement within the department and the time spent in the field.

I conducted 15 interviews with key informants from the agricultural sector in Paragominas in order to guide the selection of study zones within the territory, which I called patches, following three main criteria: (i) capture the diversity of agricultural systems in the territory, (ii) understand each key informant's definition of sustainability and (iii) the sustainability challenges of the patches. In Guaviare, given the mentioned security restrictions, it was not possible to extend the sampling to the whole department. Although the patches in Guaviare do not come from the results of key informant interviews, they captured the diversity of farming systems. This was made possible thanks to the support of the NGO, ONF-Andia, a partner in the Terramaz project, which guided the selection of patches.

In both case studies, a snowball sampling method (Goodman, 1961) was used to select farmers within patches. This consisted of interviewing a farmer and, at the end of the interview, asking him/her to identify another farmer who has had a different trajectory from his/her own. After receiving the answer, I asked if it was possible to have the contact of a woman farmer with such a trajectory. The sample of farmers is based on 55 semi-interviews, 35 women, 12 men and 8 couples. Of these 40 were conducted in Paragominas and 15 in Guaviare.

This step made emphasis on the past of the trajectories and their present sustainability. The third step permitted to explore the future of these trajectories.

1.4.3 Step 3 Implementing the prospective component: Plausible farms

The systematic review of the literature conducted in step 1 highlighted 14 prospective analyses of farm changes, 11 of which were based on simulation tools used to evaluate the effects of different socio-economic and climatic scenarios. However, using a similar approach was not feasible in the thesis, where socio-economic data are scarce, particularly in smallholder agriculture. For this reason, the strategy was to adopt the approach used on the three remaining studies, these were based on qualitative approaches and focus groups, enriched by additional literature on prospective studies of farms. I discovered anticipation studies, anticipation corresponding more to a discipline than to a method (Miller, 2018). Consequently, I developed an ad-hoc method that addresses both farmers' ideal farm visions and gender issues.

Within the discipline of anticipation there are different approaches, one of which is foresight. Foresight is defined as a process that is often participatory, oriented towards future intelligence, which facilitates the exploration of medium and long-term futures and the drivers of change (Jahel et al., 2023; Minkkinen et al., 2019). The research strategy in this step three, first seeks to position itself within the foresight frameworks (Minkkinen et al., 2019). Therefore, based on the objective of exploring plausible farms futures, the research strategy of this step is primary situated withing an exploratory framework. However, it also seeks to discusses pathways that could lead to those futures, thus incorporating pathways from a transformative perspective (figure 1.7).

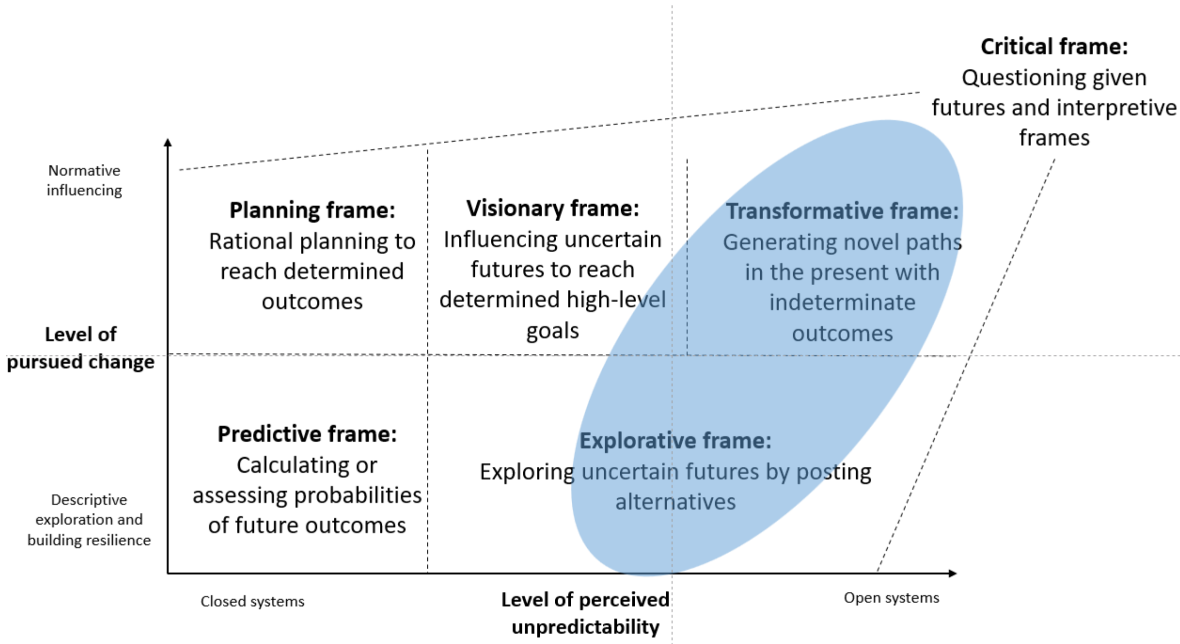

Figure 1.7 Positioning among foresight frameworks, adapted from (Minkkinen et al., 2019)

This positioning within the foresight frames, guided us in the selection of the methodological tool. I selected the futures triangle method (Inayatullah, 2008, 2023). This method is based on participatory foresight. It involves farmers in designing their future, through their visions of their ideal farms. The research was conducted in specific "patches" from step two. These patches were selected on specific characteristics, such as levels of deforestation, access to markets, the emergence of women's organizations, and the willingness of farmers' associations to participate. Four focus groups were conducted: two in Paragominas (Potirita and Caip) and two in Guaviare (Unilla and Guacamayas), with an exclusive group for women in each territory. The prospective exercise was carried out exclusively with smallholder farmers, since, in one of the case studies, they tend to be left out of the transitions towards sustainability (Piraux et al., 2020). The methodological process was based on the exploration of the "pull" of the futures (ideal farms), the "push" of the present (current trends), and the "weight" of the past (obstacles), and then analyzing the tensions between them and proposing levers for action.

The rationale for this step is inductive, as it starts from the specific experiences and visions of the farmers in the focus groups to generate a broader understanding of the challenges and opportunities for sustainable family farming in the Amazon. There is also an abductive component in exploring plausible futures based on interpretation of the past, present and ideal visions.

The participation to the focus group was made on a voluntary base, where farmers' associations played a key role. The number of farmers participating in each focus group varied. In Paragominas, the Potirita group was composed of 23 farmers (12 men and 11 women), while the women-only group in Caip had 17 participants. In Guaviare, the Unilla group included 17 farmers (9 men and 8 women), and the Guacamayas group involved 19 people (15 women and their children).

This thesis is organized in five chapters:

Chapter 1, this section includes the general introduction of the thesis, a presentation of Amazonian agriculture as well as the challenges for agricultural sustainability in the Amazonian pioneer fronts. This section presents also the research questions, and the research strategy implemented. The results are presented in the following three chapters, each answering to a specific research question.

Chapter 2 presents a systematic review of the literature on trajectories and farm pathways. It focuses on the analysis of the methodologies used and the identification of gaps in the literature, with the objective of proposing a renewed conceptual framework that integrates both retrospective and prospective dimensions. It focuses on the study of pioneering fronts in the Amazon.

Chapter 3 presents and empirical study of the farm trajectories in the two case studies of the thesis: Paragominas (Brazil) and Guaviare (Colombia). The analysis aims to identify sustainable trajectories for these Amazonian territories based on agroecological principles.

Chapter 4 presents the participatory foresight study conducted with smallholder farmers in the two case studies. Through focus groups, the plausible futures of the farms are analyzed, including two focus group sessions exclusively with women.

Chapter 5 comprehensively discusses the main results of the thesis, highlighting the contributions and importance of articulating past, present and future of farms in pioneer fronts, specifically in Amazon. It also shows the strengths and limitations found between the theoretical and empirical approaches. Finally, the essential contributions to the central research question are presented

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

Source: Author, Field photos, Dual-purpose cattle farm in the department of Guaviare, Colombia

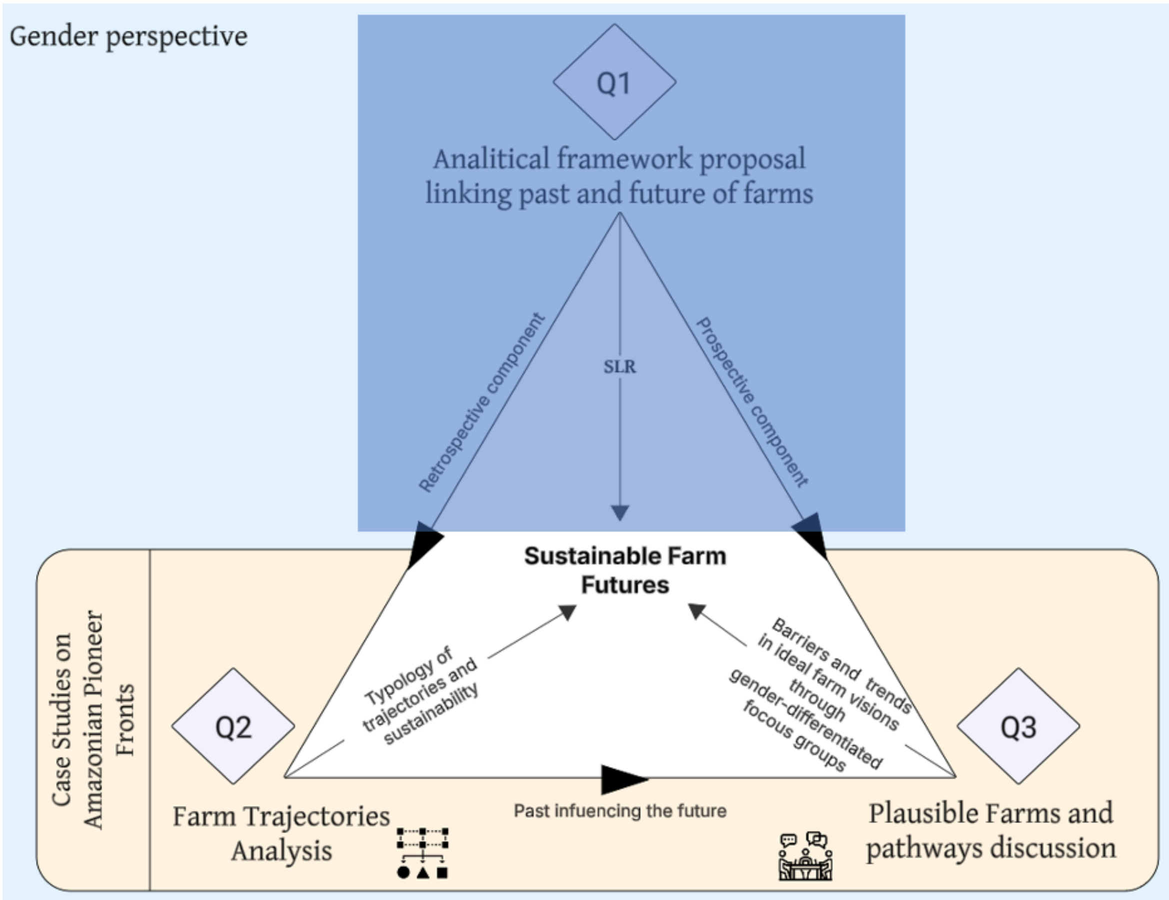

Diagram 1: Methodological framework Step 1 Chapter 2, adapted from Kong (2019)

This chapter constitutes the first methodological step (diagram 1) to answer the specific research question: "¿ Q1: How can we analyze the evolution of farms in the pioneer fronts and characterize their sustainability, considering their past, present and future?". The chapter establishes the theoretical and methodological foundation for the rest of the thesis. The systematic review analyzes the existing tools and approaches for studying the changes at the farm level, and based on the identified deficiencies, proposes an original analytical framework that will guide the empirical research presented in the subsequent chapters (Chapter 3 and Chapter 4).

The review highlights that the existing literature tends to overlook crucial aspects such as agroecological principles, the effects of territorial factors, and the contributions of women and the organization of family labor in shaping these trajectories. As a result of this review, Chapter 2 proposes a renewed analytical framework aimed at addressing these limitations, combining retrospective and prospective analyses to better understand the dynamics of agricultural change in the pioneer fronts and to support the identification of desirable strategies for the future that limit deforestation.

This work was published in Agricultural Systems in October 2024, volume 220.

Vega-Martinez A, Cialdella N, Andrieu N (2024) Understanding farms trajectories methods to build sustainable futures on pioneer fronts: Lessons from a systematic literature review and a framework proposal. Agricultural Systems 220:104093. https://doi.org/10.1016/j.agsy.2024.104093

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.

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 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.

Keywords: Farm trajectory; women's role; Agroecological transition; Family work organization; Amazon

2.1 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 & 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; Thalês et al., 2021)

On pioneer fronts, farmers manage extreme tensions between eco- nomic development and environmental protection, leading to variable rates of forest deforestation (Córdoba et al., 2018; Curtis et al., 2018; Knoke et al., 2022; Pacheco & Poccard-Chapuis, 2012; Solen et al., 2018). 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 (Chantre & Cardona, 2014; Cialdella et al., 2009), 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 recon- figurations of agroecosystems to produce following agroecological principles and improve the sustainability of farm and food systems (Duru et al., 2015; Ollivier et al., 2018; E. Polge & Pagès, 2022; Prost et al., 2023; Tittonell, 2020). 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 trans- formation (Barrios et al., 2020; Leippert 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 (Falconnier et al., 2015; García-Martínez et al., 2009; Obare et al., 2003), 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 (Madelrieux et al., 2015; C.-H. Moulin et al., 2008; Terrier et al., 2012)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 (Lamine, 2011; Ryschawy et al., 2017; Sutherland et al., 2012; Wilson, 2008) 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 (Ballon et al., 2016; Murphy, 2001). In addition, the framework should consider agroecological principles in order to high- light 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 & 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 frame- work based on the shortcomings found in the literature to specifically describe trajectories on pioneer fronts.

2.2 Method

2.2.1 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»

2.2.2 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 – Intelligent Systematic Review - 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 (Annex A, supplementary material table 1) were considered as eligible for the review. Fig. 2.1 summarizes the article selection process.

Fig.2.2 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 take place) and the size of the samples of farms.

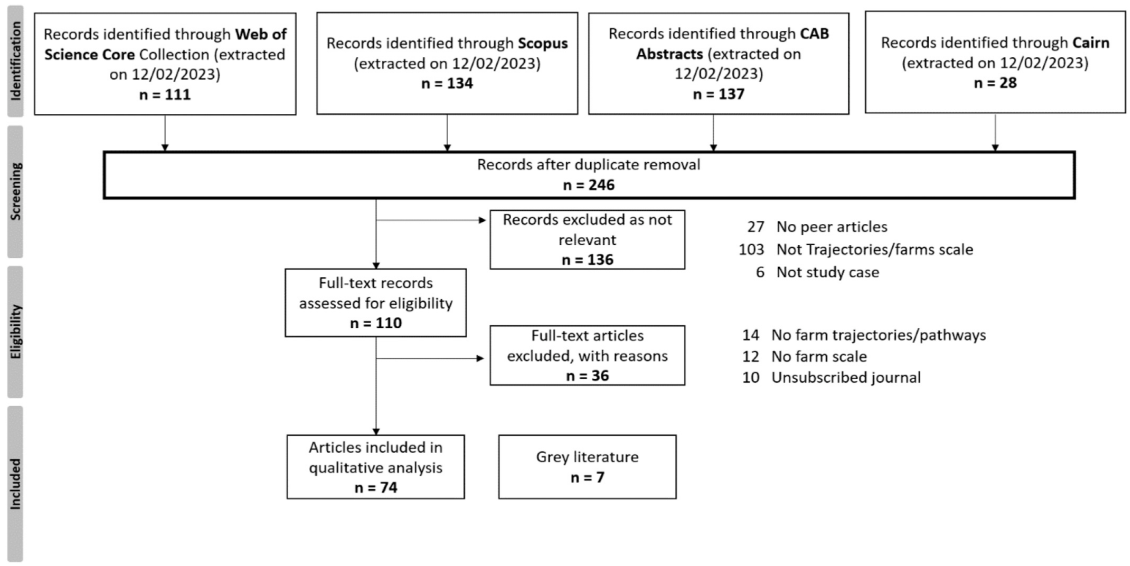

Figure 2.1 PRISMA flow diagram showing the complete article selection process (adapted from Page et al., 2021).

Figure 2.2 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.

2.3 What are farm trajectories and pathways and how are they analyzed?

2.3.1 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 & 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 & Frija, 2022) while 4 defined pathways as an alternative way to existing trajectories (Bruce, 2019; Navegantes-Alves et al., 2012; Song et al., 2022; Vall et al., 2017).

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 2.1). 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 (Alary & Frija, 2022; Alavoine-Mornas et al., 2014; Chantre & Cardona, 2014; Merot et al., 2019; Revoyron et al., 2018; Rouget et al., 2021; Zollet, 2018) 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 2.1 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 (1995)	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 field 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 et 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.

2.3.2 Main trajectory and pathway characteristics and methods.

The published articles used different tools for analyzing trajectories and pathways (Fig. 2.3) 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 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.

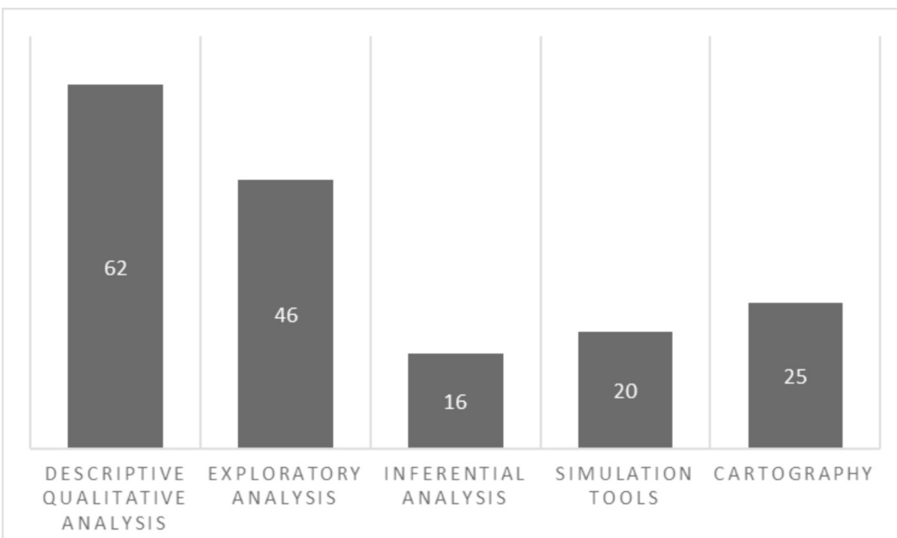

Figure 2.3 Methodological tools used in farm trajectories and pathways per number of occurrences (% of $N = 81$).

Fig. 2.4 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 be- tween 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 et 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.

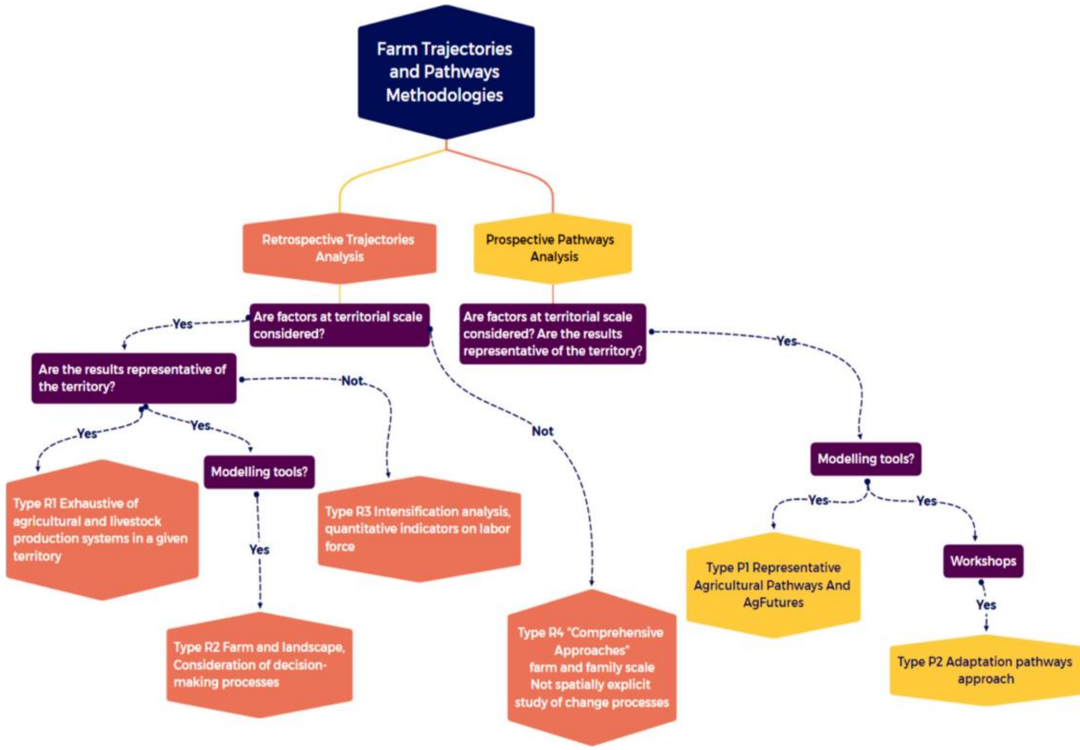

Figure 2.4 Main farm trajectory and pathway methodologies, left side shows retrospective trajectory analysis, right side shows prospective pathway analysis

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).

2.3.3 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 (Alavoine-Mornas et al., 2014; Carvalho et al., 2015; Kongmanee & Ahmed, 2019; Madelrieux et al., 2014; Terrier et al., 2012). 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(David et al., 2014; Ryschawy et al., 2013; 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 (Fischer et al., 2022; Greenville et al., 2019; Kong et al., 2019; Le Trouher et al., 2023; Mellisse et al., 2018). 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 & Stassart, 2017).

2.3.4 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 (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.

2.3.5 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 land- scape (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.

2.4 Discussion

2.4.1 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 (Carvalho et al., 2015; Chantre et al., 2015; Dedieu, 2009; E. Polge & Pagès, 2022), (ii) comparatively (Hirczak et al., 2013; Paquette, 2007; Perrot et al., 1995), 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 be- tween 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.

2.4.2 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. 2.5). 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 (Chantre et al., 2015; Moulin et al., 2008) 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 (Jahel et al., 2023; Miller et al., 2018; Minkkinen et al., 2019; Pereira et al., 2018) where the plausible future farm pathways 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. How- ever, these studies and the related database will help us in the construction of sustainable (prospective) pathways.

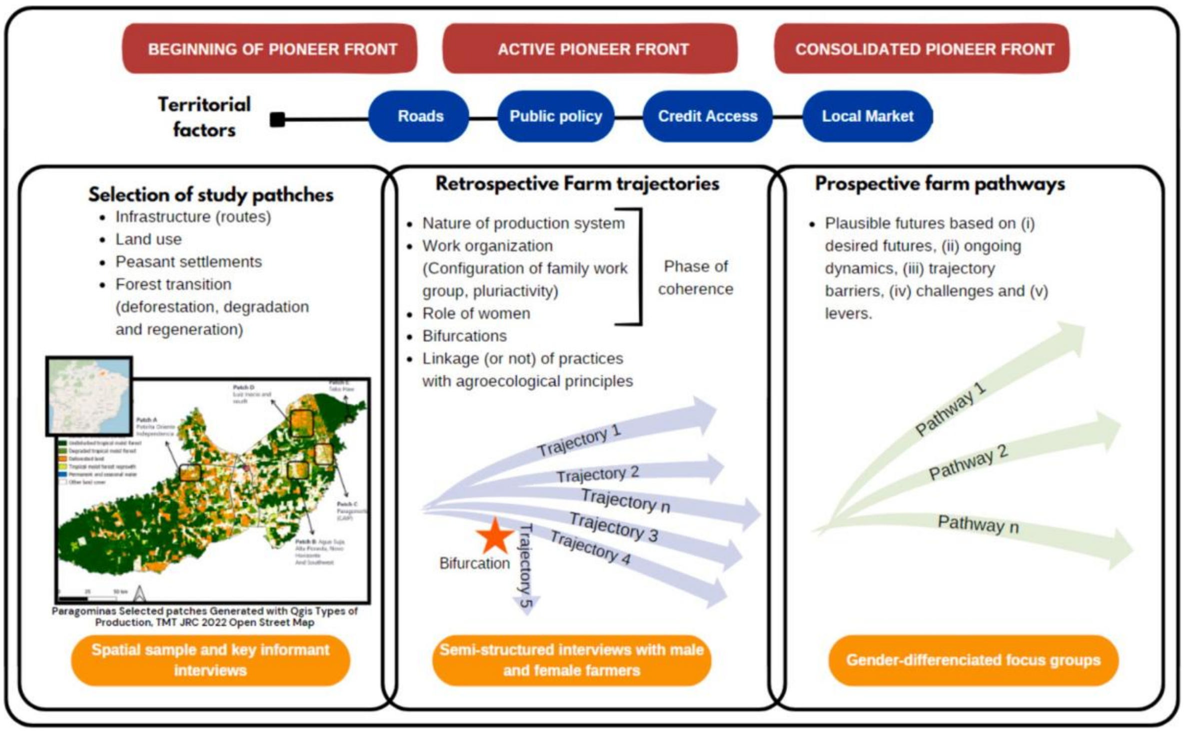

Figure 2.5 Analytical framework in a pioneer front context Farm trajectories depend on the stage of the pioneer front: Beginning, Active and Consolidated. The main territorial effects were identified: Public Policies, Infrastructure, Local Market, and Credit Access. The retrospective trajectories on 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.

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.

2.5 Conclusion

The systematic review allowed us to identify the types of method- ologies 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 short- falls: i) the articulation between retrospective and prospective analyses has not been explored at the farm scale, ii) the trade-off between con- ducting 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 frame-work 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.

Chapter three: Farm sustainability in the Colombian and Brazilian Amazon pioneer fronts: combining farm trajectories and agroecological principles

Source: Author, Field photos, Landscape in the municipality of Paragominas.

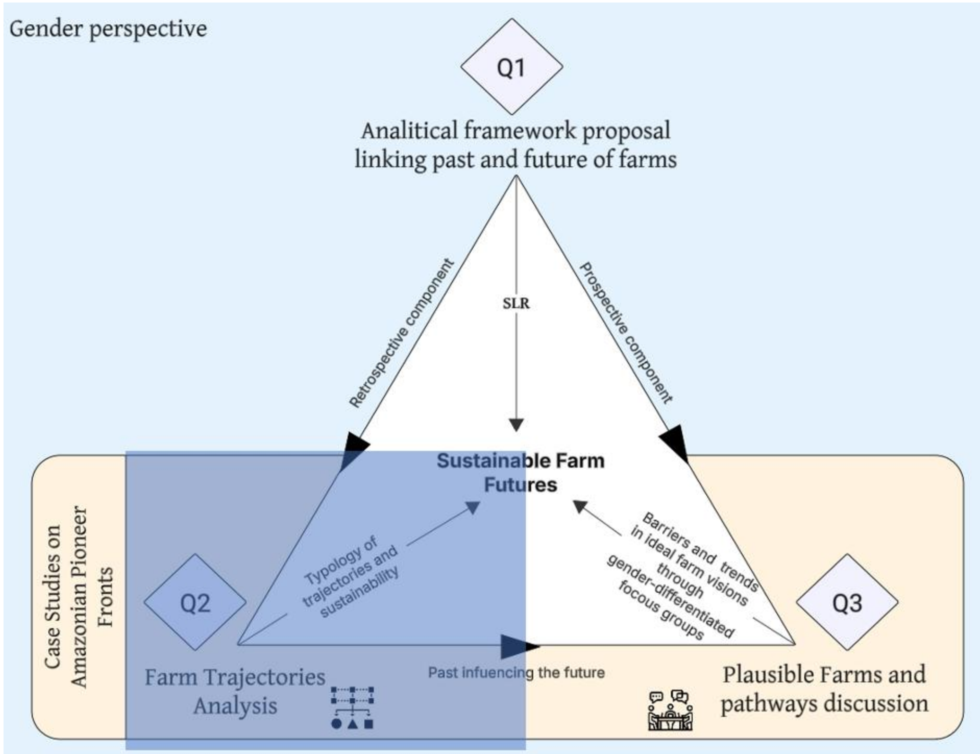

Diagram 2: Methodological framework Step 2 Chapter 3, adapted from Kong (2019)

This chapter constitutes the second methodological step (diagram 2) to answer the specific research question: Q2 Which farm trajectories are currently sustainable in Amazonian territories?

Chapter 3 presents the empirical application of the "retrospective component" of the analytical framework proposed in Chapter 2. It analyzes farm trajectories ("their past") and evaluates their current trajectories align with sustainability ("their present") through the lens of agroecological principles. This methodology is applied in two specific case studies in the Amazon: the municipality of Paragominas (Brazil) and the department of Guaviare (Colombia), an active pioneer front.

This chapter is the subject of an article that will be submitted to the journal *Agricultural Systems*.

Abstract

This study investigates farm trajectories in two pioneer fronts of the Amazon, Paragominas (Brazil) and Guaviare (Colombia), with the objective of identifying which ones are sustainable based on their alignment with agroecological principles. The methodology involved constructing a typology of trajectories based on retrospective semi-structured interviews with farmers, identifying sequences of phases in their production systems. Subsequently, the current phase of each trajectory type was evaluated using indicators based on agroecological principles adapted to the Amazonian context.

The analysis identified six main types of trajectories, with four of them present in both territories, suggesting common patterns. Most trajectories involve cattle farming, although with different management systems. Only one trajectory focused on agroforestry systems. The initial phase of the trajectories often involved slash-and-burn practices in Paragominas, and slash and burn and coca cultivation in Guaviare. The evaluation of agroecological principles indicated that no current trajectory fully aligns with all principles. However, the trajectories of progressive intensification of rotational grazing for cattle (Type 1), agroforestry (Type 3), and rapid shift to rotational grazing for cattle (Type 4) showed better overall alignment. The fundamental role of women in leading these more sustainable trajectories was highlighted. Cross-cutting challenges included connectivity and fair markets, as well as dependency on pesticides and synthetic fertilizers. The study concludes that there is no single solution for sustainability, and the coexistence of agroforestry systems and rotational grazing for cattle can support the development of sustainable agriculture in the Amazon. This requires differentiated public policies based on trajectory type and agroecological principles.

Keywords: Farm trajectories; agroecological principles; sustainable agriculture; Amazon farming, deforestation.

3.1Introduction

Agroecology is increasingly being presented as a solution to the challenges of agricultural sustainability and forest conservation (Altieri et al., 2024; Gliessman, 1992; Van Dexter & Visseren-Hamakers, 2018; Vikas & Ranjan, 2024). Agroecology is based on several principles, including biomass and nutrient recycling, soil and plant health, knowledge co-creation, and sustainable governance to create an enabling environment for the transformation of farming and food systems (Barrios et al., 2020; FAO, 2018; Leippert et al., 2020). Agroecological systems rely on enhanced biodiversity to reduce dependence on industrial inputs and their associated adverse ecological and social impacts (Duru et al., 2015; Malézieux et al., 2009), and place a strong emphasis on values such as equity, inclusion and justice.

In their review of agroecology in the Brazilian Amazon, Souza et al. (2021) highlight that existing studies emphasize ecological, techno-productive, socioeconomic, and policy aspects that promote alternative forms of production, such as agroforestry, integrated crop-livestock systems, silvopastoral systems, and improved management of vegetation in slash-and-mulch systems, in contexts characterized by high biodiversity and ecological vulnerability. Agroforestry systems have been presented as emblematic agroecological alternatives that, despite economic and technical limitations (Caicedo-Vargas et al., 2022), seek to balance agricultural productivity with biodiversity conservation (Porro et al., 2012; Souza et al., 2021). Silvopastoral systems also have been promoted to limit deforestation in the Amazon (Pizarro et al., 2025; Silva-Olaya et al., 2021). Such systems are seen as agroecological alternatives to cattle ranching, whose negative role in deforestation has been shown in various studies (Donoso et al., 2024; Margulis, 2003; Skidmore et al., 2021). Nevertheless, certain studies have highlighted risks linked to the intensification of sylvopastoral systems, including the expansion of these systems into newly deforested areas and the transfer of cattle from sylvopastoral systems to newly deforested areas, thereby exacerbating pressure on the forest (Castro-Nunez et al., 2021, 2024; Kaimowitz & Angelsen, 2008). However, other studies have shown that implementing resource-efficient agroecological practices and soil restoration could increase productivity while reducing demand on forests areas (Kpienbaareh et al., 2022).

Agriculture in the Amazon's pioneer fronts is characterized by family farming, which relies predominantly on family labor and aims primarily to supply households with food while generating profits when feasible. In parallel, there is agro-business farming, which focuses on large-scale production of raw materials such as soybeans and beef for global markets (Costa et al., 2024), often at the expense of environmental sustainability.

Farms evolve dynamically within their territories (Schiere et al., 2012). In the Amazonian territories of Brazil and Colombia, public policies have played a key role in farm sustainability and deforestation. For example, public policies aimed at exploiting natural resources such as timber were the initial impetus behind the state colonization of these territories (Taborda, 2002; Urzedo & Chatterjee, 2021). These policies led to an increase in demand for farmland to produce food, which also contributed to population growth (Léna, 1986). These land use changes resulted in forest degradation and deforestation, a loss of biodiversity and the depletion of ecosystems (Carvalho et al., 2019; Hänggli et al., 2023; Tanure et al., 2024). In the 2000s, the Brazilian government implemented restrictive policies such as the arc of fire plan, the creation of conservation units, and the recognition of indigenous lands to prevent the expansion of the agricultural frontier (Reydon, 2011; Rodrigues et al., 2017). This reinforced the application of the Brazilian Forest Code in the Amazon, which requires each farm to respect a permanent protection area (APP) for water resources and a legal forest reserve. In 2012, the Rural Environmental Cadastre (known by its Portuguese acronym, CAR) was created to monitor these areas (Borges et al., 2011; Laudares et al., 2014). In Colombia, conservation units and indigenous reserves for forest protection were created at the regional scale (Katz-Asprilla et al., 2024), while river protection areas monitored by the corporation for sustainable development for northern and eastern Amazon (CDA) were created at the farm scale (SINCHI, 2016).

In the Amazon, armed conflicts pose additional challenges to farm sustainability (Murillo-Sandoval et al., 2021) with the presence of guerrillas and other illegal groups, particularly in Colombia (Jonas et al., 2020; Vaz et al., 2020). Infrastructure such as road networks also have implications for land use and farm development (De Jesus Costa et al., 2023; Vaz et al., 2020).

Analyzing farm trajectories can provide insight into the progression of changes (Rueff et al., 2010; Chantre & Cardona, 2014; Mawois et al., 2019; Polge & Pagès, 2022) and their effects on deforestation in Amazonian pioneer front territories. Understanding the diversity of farm trajectories allows us to identify which ones could be sustainable, particularly trajectories limiting deforestation. Analyzing farm trajectories through the lens of agroecological principles allows us to understand where sustainable options that limit deforestation (Kpienbaareh et al., 2022) come from in order to design plausible futures for farms and recommendations for public policies.

Few studies have been carried out on farm trajectories in Amazonia, and all were conducted in Brazil (Ballon et al., 2016;Carvalho et al., 2019; Cialdella & Navegantes, 2014; Navegantes-Alves et al., 2012; Plassin, 2018). Navegantes et al. (2012) and Cialdella and Navegantes (2014) described the sequences of phases that build a farm trajectory. They highlighted that the common family farm trajectory in this context starts with slash-and-burn to plant "*a roça*" made of diverse plants (with cassava, beans, and maize the principal ones). This is then followed by the establishment of grassland pasture with the objective of raising cattle. The intensification of cattle farming enables an increase in animal production within the same area, which thus helps to preserve forests (Navegantes-Alves et al., 2012). In Paragominas, in Brazil, trajectory studies have focused on land use intensification practices and pasture systems in relation to the evolution of landscape patterns. Plassin (2018) showed that the first phase of the trajectory is mainly extensive cattle ranching with substantial changes in land use, followed by a phase of modernization of the cattle and pasture systems, and a cessation of deforestation. A third phase corresponds to the intensification of the cattle system. Ballon et al (2016) highlighted three types of farmers related to forest regeneration processes: (i) pioneer farmers practicing subsistence agriculture based on slash-and-burn practices, (ii) emerging farmers implementing agroforestry (açaí, copuaçu, pineapples, black pepper), and (iii) precarious or retired farmers without heirs. None of these studies describe the diversity of trajectories that may coexist, nor do they assess their sustainability and relationship with deforestation.

This paper aims to address the following question: Which farm trajectories are sustainable in Amazonian territories? We studied two Amazonian pioneer fronts, the Guaviare department (Colombia) and the municipality of Paragominas (Pará State in Brazil). We built a typology of farm trajectories based on the identification of phase sequences (Moulin et al., 2008). For each trajectory type identified, we then evaluated the extent to which the trajectory's current phase is aligned with agroecological principles (Wezel et al., 2020), building indicators adapted to the context of the Amazonian pioneer front.

After presenting the method used to describe farm trajectories and the variables used to characterize agroecological principles, we present the six types of farm trajectories identified and the alignment of their current phase with agroecological principles. We then discuss the relevance of our results with regard to identifying sustainable trajectories, and how the characteristics of the territories shaped the trajectories observed.

3.2 Material and methods

3.2.1 Study sites

- Paragominas pioneer front

The municipality of Paragominas is in the northeast of the state of Para, Brazil. It covers a total area of 19,341 km² and has a population of 105,550 inhabitants, 78% of whom live in the urban area (IBGE, 2022). Paragominas has a tropical monsoon climate, as classified by the Koppen system, with an average temperature of 26°C. It has two distinct seasons, a rainy season with rainfall above 60 mm from January to June, and a dry season from July to December, and an annual precipitation of 1,800 mm (Abrell et al., 2024).

The municipality of Paragominas was founded in 1965 during the construction of the BR-10 highway linking Bélem to Brasilia. The colonization process in Paragominas was initially promoted by the government, which provided access to land for people interested in investing in the development of the region. The government also gave loans at preferential rates through the Northern Constitutional Financing Fund (FNO in Portuguese), the Bank of Amazonia (BASA) and the Superintendence of Amazon Development (*Superintendência do Desenvolvimento da Amazônia*, SUDAM in Portuguese). Credit programs under the supervision of the Ministry of Agrarian Development, such as the National Program to Strengthen Family Farming (PRONAF in Portuguese), provided better access to credit for family farming (Abramovay & Piketty, 2005; Colonnelli, 2021; Mares Guia et al., 1997). The initial development of extensive cattle ranching required cutting down trees across large areas. Entrepreneurs coming from the southeast of Brazil benefited from the fiscal incentives offered by BASA and SUDAM, which led Paragominas to become the municipality of "*fat cattle*" at the time. The extraction of native timber started in 1970 (Stone, 1998; Vaz et al., 2012). In the late 1990s, farmers started to grow crops such as maize and rice, followed by soybeans in the 2000s, increasing demand for land and resulting in major deforestation (S. Plassin, 2018).

In 2008, Paragominas appeared in the list of Brazilian municipalities with the highest rate of deforestation in the Amazon. Credits were then cut, and the federal state imposed livestock embargos. The *Paragominas green municipality* project was created to address this problem, and led to a reduction of deforestation through supervision by public agents and satellite monitoring (Carneiro & de Assis, 2015). In the late 1990s and early 2000s, the family farming sector was boosted, led by former employees of closed sawmills and migrants from surrounding municipalities. The National Institute for Colonization and Agrarian Reform (INCRA in Portuguese) and the municipality officially settled these farmers (Pinto et al., 2009). Given the stabilization of deforestation rates and progress in land governance, Paragominas is now considered to be a consolidated pioneer front (Poccard-Chapuis et al., 2024; Thalês et al., 2021) .

Paragominas currently has 643,687 ha dedicated to agriculture, representing 33.28% of its total area. This includes 463,018 ha of grassland and 180,128 ha for crop production, primary soja crops (143,762 ha), as well as other annual crops such corn (*Zea mays*), cassava (*Manihot esculenta*) and beans (36,016 ha). Perennial crops such as açaí (*Euterpe oleracea*), cashew (*Anacardium occidental*) and black pepper (*Piper nigrum*) are also produced (IBGE, 2023; MapBiomas, 2023). Cattle farming is a major activity in Paragominas, with 375,902 bovines in 2023 (IBGE 2023).

- Guaviare pioneer front

The department of Guaviare is in southeastern Colombia. It covers a total area of 53,460 km² and has a population of 87,767 inhabitants (DANE, 2019), with 40.6% of this population located in rural areas. Classified as having an equatorial tropical rainforest climate according to the Koppen system, Guaviare is characterized by an annual precipitation of between 2,600 and 4,000 mm. The territory includes two primary physiographic units: (i) an extensive plain characterized by undulating areas reaching altitudes of between 50 and 100 meters, covered with tropical rainforest, and (ii) a river plain featuring alluvial plains, and recent alluvium (SINCHI, 2007). The soil in the area is clayey with low fertility, and poor drainage leads to high acidity during the rainy season (Gutiérrez García et al., 2020).

This pioneer front started with the extraction of natural resources such as animal skins and rubber. This early period, which extended from the late 19th century until 1950, was called *triguillero*. The colonization process in Guaviare was led by the Colombian State during the 1960s through the Colombian Institute of Agrarian Regulation (INCORA). In the 1970s, this colonization was stimulated by the introduction of coca (*Erythroxylum coca*) and marijuana crops. These illicit crops experienced a boom in the 1980s, attracting peasants coming mainly from the neighboring department of Meta, but also from Cundinamarca. The Colombian government implemented policies to combat the cultivation of coca, such as the Colombian plan that used aerial glyphosate fumigation to eradicate coca (Dion & Russler, 2008), and the National Integral Program for the Substitution of Illicit Crops policy (PNIS in Spanish) in which 7,251 families were enrolled in the department of Guaviare in 2019 (Mejía Hidalgo, 2021; UNODC, 2019). The government created a smallholder reserve zone (*Zona de reserva campesina* in Spanish) through decree 1777 of 1996, with the main objective of controlling the excessive expansion of the country's agricultural frontier (Marin, 2002; SINCHI, 1999, 2007).

Despite this, the process of colonization, armed conflict, and the establishment of agricultural and livestock farming have led to significant deforestation in Guaviare, resulting in a loss of 3,835 km² between 1990 to 2022, as reported by the Joint Research Center's Tropical Moist Forest report (Armenteras et al., 2018; Cabrera et al., 2019; Prem et al., 2020; Vancutsem et al., 2021), making the department an active pioneer front. This department exhibits a typical feature of pioneer fronts with a large expansion of deforestation on the periphery, and a consolidated central zone that includes the municipal seats of El Retorno and Calamar, as well as the department’s capital, San José del Guaviare, all connected by the department's main road. This department also has a fourth municipality called Miraflores.

In Guaviare, the settlement of farms and the cutting of forests were initially controlled by FARC-EP (*Fuerzas Armadas Revolucionarias de Colombia* in Spanish). Farmers who aimed to obtain credits had to obtain a property title, but they first had to be allowed to do so by FARC. Once permission was obtained from FARC, farmers had to clear at least 6 ha of forest to make way for pastures or crops. This was necessary to prove to the Colombian Institute of Rural Development (INCODER in Spanish) that they were effectively working the land. The armed conflict in Guaviare, coupled with the dynamics of coca cultivation, complexified the deforestation process and agriculture development (Bautista-Cespedes et al., 2021; Landholm et al., 2019; Negret et al., 2019). After the peace agreement was signed in 2016 between the Government of Colombia and FARC, initiatives were developed to contribute to long-term peace. The European Fund for Peace provided most of the financing for the *Caminemos territorios sostenibles* project in Guaviare, which seeks to help improve the living conditions of Guaviare’s rural population (Fondo Europeo para la Paz, 2019).

This department currently devotes 618,525 ha to agriculture, representing 11.15% of the department’s total area, mostly dedicated to family farming. The department has 17,706 ha of crops, with banana, peach palm, and cocoa accounting for more than 60% of the department's crops in 2022 (UPRA, 2023). Sugar cane and rice also are cultivated. Cattle farming is a major activity in Guaviare, with 549,246 bovines in the department in 2023 (UPRA 2023).

3.2.2 Methodological framework

The methodological framework was based on four sequential steps described below.

Step 1: Selection of patches

Data collection was conducted in specific patches of each study site.

The definition of the patches in Paragominas considered:

- The main roads, corresponding to federal or governmental roads used to market agricultural products. These roads also shape the agricultural landscape in the territory. We divided the territory into three road zones based in the distance to the roads (Annex B Supplementary Figure 1, A).
- The types of production (e.g., soybean, pasture, other annual or perennial crops) (Annex B Supplementary Figure 1, B). The territory is characterized by agro-industrial production concentrated near the city (mostly zone 1), which gradually dissipates as one moves away from the center of the territory.
- Smallholder settlements (e.g., *assentamentos*, *Zona de reserva campesina*) and agro-business sites (soybean, livestock) (Annex B Supplementary Figure 1, C).
- The type of forest transition processes corresponding to areas of (1) cumulative regeneration from 1990 to 2022, (2) degradation over the last 2.5 years, and (3) cumulative deforestation from 1990 to 2022, when all the forest area is cleared (TMF JRC data, 2022) (Annex B Supplementary Figure 1, D). Each of these processes were categorized from low to high, with low (deforestation/degradation/regeneration) representing the lowest area found for the whole territory and high the highest area (Table 3.1). A single patch could include specific combinations of these three forest transition processes depending on their location within the territory.

Table 3.1 Deforestation, degradation, and regeneration levels

Forest transition process	1 Low	2 Moderate	3 High
Deforestation	<15 km^2	15-30 km^2	>30 km^2
Degradation	<3 km^2	4-5 km ^{2}	8-10 km^2
Regeneration	<2 km^2	2-4 km^2	6-8 km^2

We then conducted 15 semi-structured interviews with key informants from the agricultural sector of the territory to discuss the challenges of sustainability in the patches. These interviews involved representatives of agricultural research institutions, the local university, private suppliers, the financial institution for agriculture, farmers' associations and local government institutions such as the Secretary of Agriculture and the Secretary of the Environment.

Patches were selected according to the key informants' perceptions of agricultural sustainability challenges and the diversity of farm activities (Table 3.2), using the pre-selected patches (Annex B Supplementary figure 2, A to I). Key informants had different definitions of sustainability, with some emphasizing environmental and economic dimensions, while others only focused on the economic dimension. We added patch E to capture the conservation of forest zones and indigenous farm trajectories (Figure 3.1).

Table 3.2 Selected patches in Paragominas

Patch	Patch ID	Zone roads	Sustainability challenges according to interviews of key informants	Forest RDD
Potirita	A	1	High land pressure, land title	High deforestation, Low degradation, Low regeneration
Agua Suja, Alta Floresta, Nuevo Horizonte	B	2	Land pressure, productivity	Low deforestation, High degradation, Low regeneration
CAIP Paragonorte	C	3	Social organizations, non-agricultural migration.	High deforestation, Low regeneration
Luís Ignacio: Nova Paragonorte, Cacimbão, Cajueiro	D	3	Land pressure, land title, productivity	High deforestation Moderate degradation Low regeneration
Teko Haw	E	3	Fires	Low deforestation

*Zone roads refer to the distance to the main roads developed in step 1 (Annex B Supplementary figure 1, B).

In Guaviare, the selection of patches was guided by a non-governmental organization (NGO) due to security constraints that restricted our movement.

The patches were selected for their embeddedness in the field, forest dynamics and the presence of farmers potentially interested in participating in the study (Figure 3.2). Two patches had the same levels of deforestation (F and G) since we wanted to compare the trajectories of the different municipalities of San Jose and El Retorno. Although the municipality of Miraflores had more regeneration, it was not considered given its difficult access (no main roads) and security issues with FARC insurgents. The patches corresponded to different distances to the capital of the department, which has the biggest market and is the main exit point to larger markets at a national scale such as Meta department or Bogota. Table 3.3 shows Guaviare's selected patches.

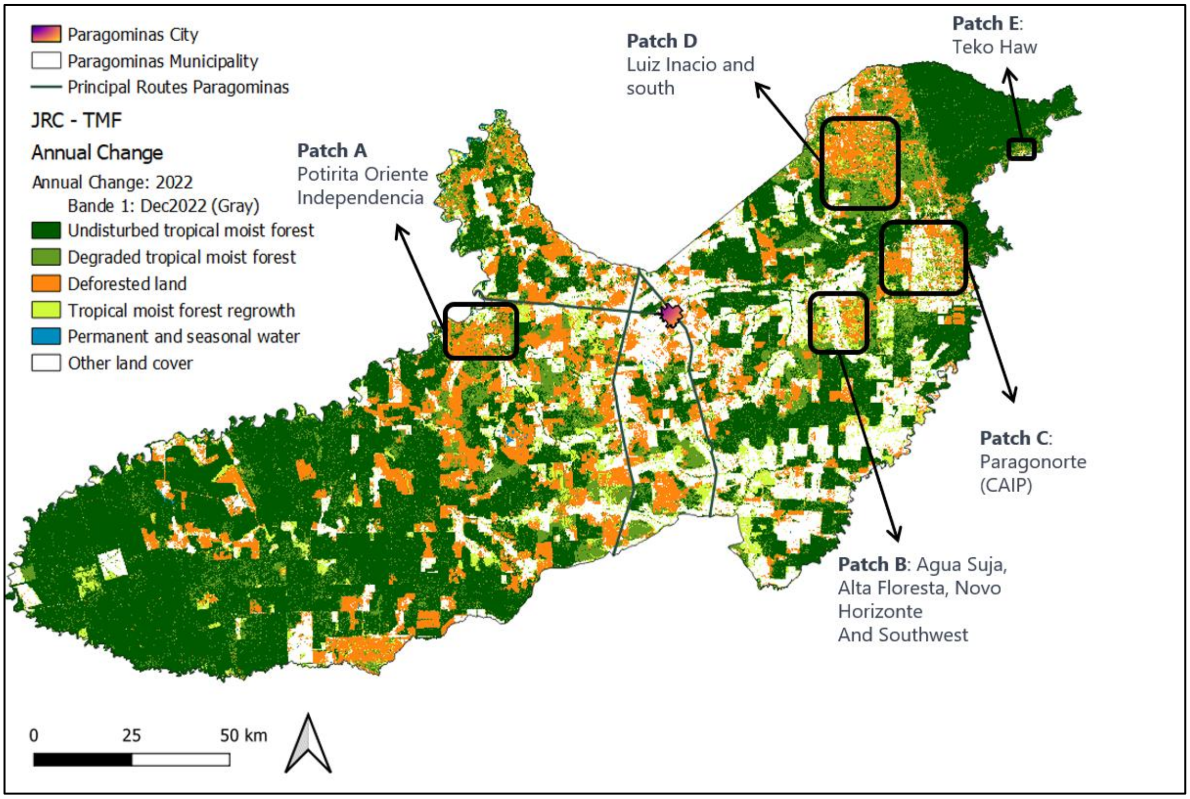

Figure 3.1 Patches selected in Paragominas through discussions with agricultural stakeholders, the patches capture different levels of deforestation, degradation, regeneration and conservation, farming settlements, and distances to main roads 'Source: EC JRC 2022'

Table 3.3 Selected patches in Guaviare

Patch	Patch ID	Distance to department capital	Forest RDD
Unilla	F	Moderate (50 km)	Low deforestation, Low degradation, Low regeneration
Guacamayas	G	Close to the capital (25 km)	Low deforestation, Low degradation, Low regeneration
Calamar	H	Far to the capital (80 km)	High deforestation, Low degradation, Low regeneration
Charras	I	Far to the capital (100 km) without paved roads	Low deforestation, Low degradation

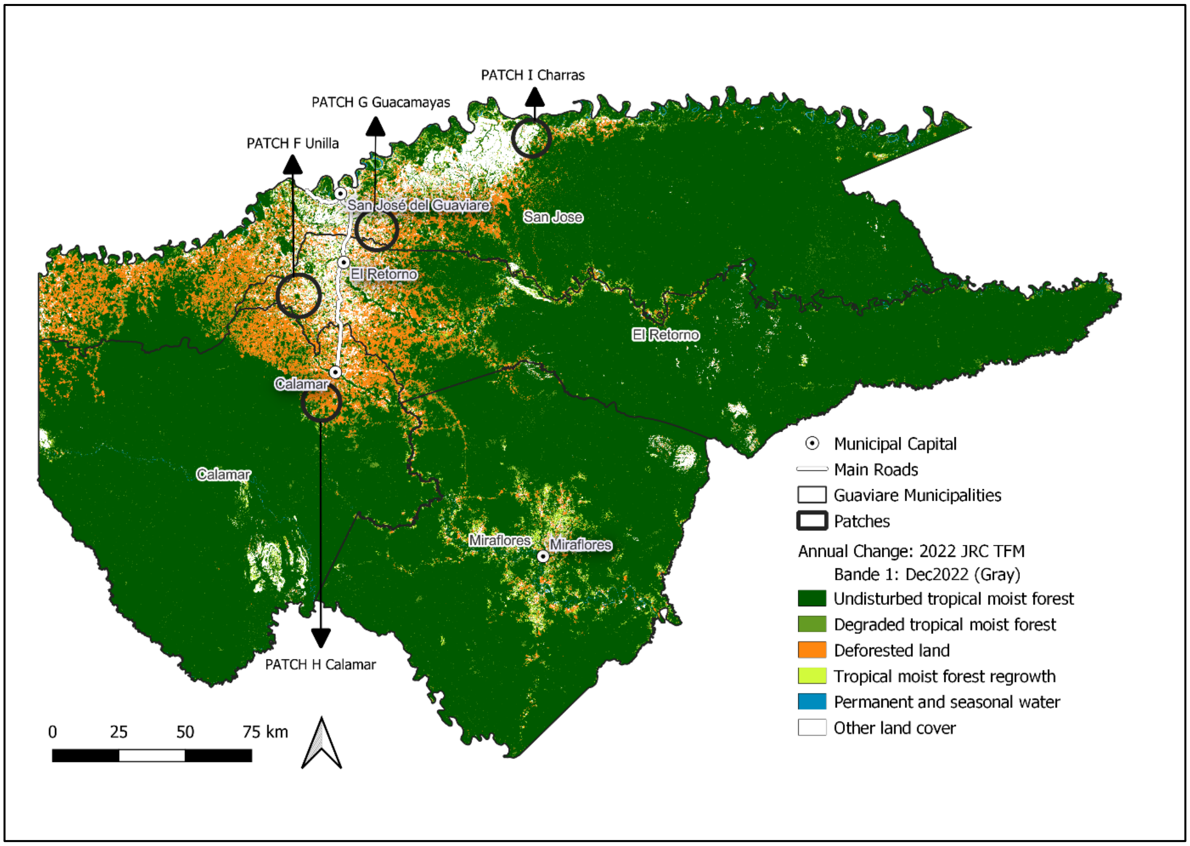

Figure 3.2 Patches selected in Guaviare, 'Source: EC JRC 2022'

Step 2: Farm sampling and interviews with female and male farmers

Using a snowball sampling method (Goodman, 1961), we interviewed farmers in each patch (women and men). At the end of each interview, we asked the surveyed farmer to identify another farmer who has had a different trajectory than the one described. When it was determined that the information of the trajectories had been saturated (no more new trajectories) (Saunders et al., 2018), the process was repeated in another patch. We interviewed 40 farmers in Paragominas and 15 in Guaviare, the semi-structured interview guide can be found in Annex B.

The trajectory was identified through a retrospective interview that allowed the farmers to describe their history and changes that occurred in their farms. During the interviews, farmers identified their farm trajectory phases. A phase is a period in which a coherent organization and management of activities is maintained (Moulin et al., 2008). In our analysis, a phase may correspond to a period in which the farm maintains a specific production system reflecting a coherent organization and management associated with its land use. Unlike Moulin (2008), who considered that a land purchase could occur within a phase, we considered that a land purchase was a signal of the start of a new phase. We did so due to the associated land use change (conversion of forest to grassland or new crop), and because we aimed to emphasis the relation between grassland, crops, and forest.

Farm spatial diagrams (Annex B, Supplementary Figure 3) were used during the interviews. Farmers were invited to use these diagrams to describe their current phase, then the initial one, thereby reconstructing intermediary phases of the trajectory. Data were also collected on farm management practices, use of synthetic inputs, diversification of the farm and economic activities, and participation in associations or cooperatives during the current phase of the farm to capture agroecological principles defined by (Wezel et al., 2020) (see step 4).

Step 3 Design and typology of trajectories

The data collected were entered in a database. We subdivided the initial phases built by farmers based on changes in the production system, forest status, land use practices and the relationship of the farming family with their land (Table 3.4). In the data entry classification of a production system, we considered agroforestry as defined by (Atangana et al., 2014): "associating trees with crops on the same piece of land simultaneously for increased, diversified and sustained benefits, and for environment preservation". We put rotational cattle grazing and silvopastoral systems into the same category, which we called rotational cattle grazing production systems. While silvopastoral and rotational cattle grazing systems are different practices, we found that they shared similar practices based on the rotation of animals in grazing fields including trees and forest protection. Each phase of a farm trajectory may include various crops and livestock that make up the production system. However, each phase was named according to the two main livestock and crop activities.

Table 3.4 Phase categorization

Criteria	Description	Example
Change in production system and work group configuration.	This occurs when there is a new production system that affects farmers' work.	A shift from a "slash-and-burn" system to a new production of cattle that will change the configuration of the work group (number of members working for other farms/hire day workers/pluriactivity of family members) that affects the distribution of tasks among family members. It could affect both on farm or off-farm activities and all family members.
Change in forest (%)	A forest area ratio of 15% is considered a significant change in the farm, considering forest and agricultural dynamics. This takes place when at least 15% of the total farm area experiences a transformation in the forest areas. These changes could involve conversion of forest areas into agricultural land but also includes the purchase of new land because it may change the forest ratio on farm.	Shifting from a "slash-and-burn" system to a mixed system combining "slash-and-burn" with cattle farming, where at least 15% of the forest is converted into pasture.
Change in practices of land use	Changes in agricultural management practices affecting land use.	Shifting from extensive cattle to rotational grazing, or from traditional "slash-and-burn" to a fire-free slash method. These changes require an adaptation or a technical improvement that directly impacts soil sustainability and productivity.
Farm abandonment	Household decision to temporarily or permanently abandon their farm to move to the city. This change reflects a break in the agricultural trajectory, where the farm may become inactive or be managed differently during the family's absence.	Family migration to the city for economic, educational, or social reasons, leaving the farm.

To build a typology of farm trajectories, we ran a Multiple Correspondence Analysis (MCA) followed by a Hierarchical Ascending Classification (HAC). Phases were the active variables used for the MCA.

Step 4: Agroecological principles and indicators

In this step, we examined the alignment of the current phase of the farm trajectory with agroecological principles for each trajectory type identified in the previous step (Wezel et al., 2020).

Ten of the thirteen agroecological principles suggested by Wezel et al. (2020) were considered. We excluded three principles (soil health, synergy, and animal health) because they are described mostly at the field and animal level while the focus of our study was the farm level. The principles of fairness, connectivity, land and natural governance and participation, applying mostly at the territorial scale, were included to link farm level characteristics with patch characteristics.

Some of the ten principles were merged because we assumed that they would not individually allow us to differentiate farmers in the Amazonian context. The fairness (such as fair trade, fair employment) and connectivity (proximity and confidence between producers and consumers) principles were merged because they are perceived as being linked to a farm's access to markets (Futemma et al., 2020). Land and natural resource governance and participation principles were merged because membership in an association was one of the modalities found to improve farmer governance of land and natural resources (Da Silva Medina et al. 2021). We also emphasized two additional criteria: (i) forest area and (ii) gender equity. The forest area could be included in the biodiversity principle; however, we wanted to emphasize the changes of forest cover within the trajectory. Similarly, although gender equity is included in the social values principle, we wanted to emphasize the specific role of women in Amazonian farms.

For each principle, we identified one or three variables based on both the definition provided by Wezel et al. (2020) and existing literature on the Amazon (see Table 3.5). For the recycling principle, we considered compost and manure utilization (Morello et al., 2018; Silva & Franzini, 2024). For the input reduction principle, we considered the two main inputs used in this context, fertilizers and pesticides, with the former including herbicides and insecticides (Abrell et al., 2024). The biodiversity principle referred to cultivated biodiversity, also known as planned diversity, corresponding to the crops and animals managed by the farmer (Duru et al., 2014). For the forest area, the variable considered was the farmer's estimated changes in forest area throughout the trajectory, as we lacked access to GIS shapefiles for the farmers in these remote zones. For the economic diversification principle, found compatible with forest conservation in the Amazon (Perz, 2004), the chosen variable was the number of economic activities that may include in this context the transformation of agricultural or forest products, the sale of labor, and pluriactivity. The co-creation of knowledge principle was based on social exchanges with neighbors, which are important in a context where the state has a limited capacity with regard to education (Laurens et al., 2023). For the social values and diets principle, the variable considered was the farmers' perception of their welfare and the quality of diets, seen as essential for farmers to establish themselves and remain in these territories (Vizuete-Montero et al., 2024). The gender equity principle was based on the existence of empowerment spaces for women, which would improve their capacities, autonomy and leadership in the territories. We also considered women's participation in decisions about a farm's strategic orientation (Aubry & Michel-Dounias, 2006) and women's financial autonomy. The principles of fairness and connectivity were assessed through how agricultural products were sold: directly to consumers (fair market) or through intermediaries (unfair market) (Futemma et al., 2020). The land and natural resource governance and participation principles were assessed through land owning combined or not with participation in a farmers' association. The relationship between land tenure and forest cover change is controversial (Pacheco & Meyer, 2022). The proper regulation of land titling, when paired with sustainable management policies (e.g., Forest Code in Amazonia), can create incentives for the conservation of the Amazon's forests (Lipscomb & Prabakaran, 2020; Pacheco & Meyer, 2022). Moreover, belonging to a group can also help farmers access productive resources and participate in decision-making on a local scale (Futemma et al. 2020).

Each agroecological variable was scored on a scale of 1 to 4. The scale was built in reference to the data collected (step 3), with 1 corresponding to the modality of the variable assumed to be less agroecological in the context, and 4 the modality of the variable assumed to be more agroecological. For example, we assumed that a farmer who does not hold a title to land and is not an active member of an association has a score of 1, while a farmer who is a title holder and is actively engaged in an association has a score of 4.

We then calculated for each agroecological principle the median score for each type of trajectory.

Table 3.5 Principles, scale of assessment, indicators, and scoring for agroecological characterization

Principle	Scale	Indicator	Scores
Recycling	FI, FA	Compost and manure utilization	(1) No manure or compost use (2) Uses manure for crops and fertilizers (3) Uses animal manure for crops (4) Produce and use organic compost for crops
Synthetic Input reduction	FA, FS	Fertilizers	(1) High use of synthetic fertilizer (≥ 150 kg/ha) (2) Low use of synthetic fertilizer (< 150 kg/ha) (3) Use of synthetic fertilizer and organic fertilizer (4) No synthetic fertilizer use
		Pesticides	(1) High use of Synthetic Pesticide (≥ 20 ml per 20 liters of water) (2) Low use of synthetic pesticide (< 20 ml per 20 liters of water) (3) Use of synthetic pesticide and organic pesticide (4) No synthetic pesticide use
Biodiversity	FI, FA	Number of crops and livestock	(1) < 3 crops and/or livestock (2) 3-4 crops and/or livestock (3) 5-6 crops and/or livestock (4) > 6 crops and/or livestock
Forest area	FS	Estimated deforested area during the trajectory	(1) > 70% of deforested area (2) 42%-69% of deforested area (3) 24% - 42% of deforested area (4) < 23% deforested area
Economic diversification	FA, FS	Number of economic activities	(1) One to two economic activities (2) Three to four economic activities (3) Five to six economic activities (4) > six economic activities
Co-creation of knowledge	FA, FS	Exchange of information and change of practices	(1) Does not exchange knowledge with neighbors (2) Exchanges information and experiences with neighbors but not used on his/her farm (3) Exchanges information with neighbors and implemented incremental changes at farm scale (4) Knowledge exchanges with neighbors and adopter of management practices used broadly at community level
Social values and diets	FA, FS	*Welfare *Diversity and quality foods	(1) Low welfare, low diversity, and low quality of food (2) Regular welfare, regular diversity and quality of food (3) Moderate welfare, moderate diversity and quality of food (4) High welfare, good diversity and quality of food

Gender Equity	FS, FS	* Women's empowerment and women's decision-making on the farm, and on use of income	(1) No space for women's empowerment and no decision-making by women, family income managed by the husband (2) No space for women's empowerment and little participation in decision-making by women, family income managed by both wife and husband (3) No space for women's empowerment and some participation in decision-making by women, own limited income (eggs, chickens) (4) Space for women's empowerment and high participation in decision-making by women, own income
Market Fairness/ Connectivity	FA, FS	Fair market and sale of agricultural products to intermediaries or direct consumers	(1) No fair markets and sell to intermediate dealers (2) No fair markets and sell to at least one direct consumer (3) Fair market and sell to some direct consumers (4) Fair market and sell to mostly direct consumers
Land and natural resource governance/ Participation	FA, FS	*Title of property; *Level of participation in associations or cooperatives	(1) Does not have any title, does not belong to any association (2) Holds a certificate of possession of the land not recognized by the local government and is member of associations, does not take part in the activities proposed (3) Holds a title regularized by the local government. Belongs to associations and participates occasionally in proposed activities (4) Holds a legal title of property, belongs to associations and participates actively

3.3 Results

3.3.1 Typology of farm trajectories

The MCA showed a cumulative variability of 68% in the first five factors. Figure 3.3 presents factors F1 and F2. The F1 axis allowed us to discriminate between the trajectories of farms that started with grains (4.546) from those that started with slash-and-burn and cattle (-2.746). The F2 axis discriminated farms that started with slash-and-burn and cattle (2.160) from those that started with cattle only (-2.560). It also allowed us to discriminate slash-and-burn (-2.424) from slash-and-burn and cattle (2.160). In sum, F1 and F2 allowed us to discriminate the sequences of the trajectories. By applying the cluster analysis on the coordinates of the MCA for the five factors, we were able to identify six types of trajectories (Figure 3.4 dendrogram). Table 3.6 shows the statistical significance of the variables in association with the factorial axes.

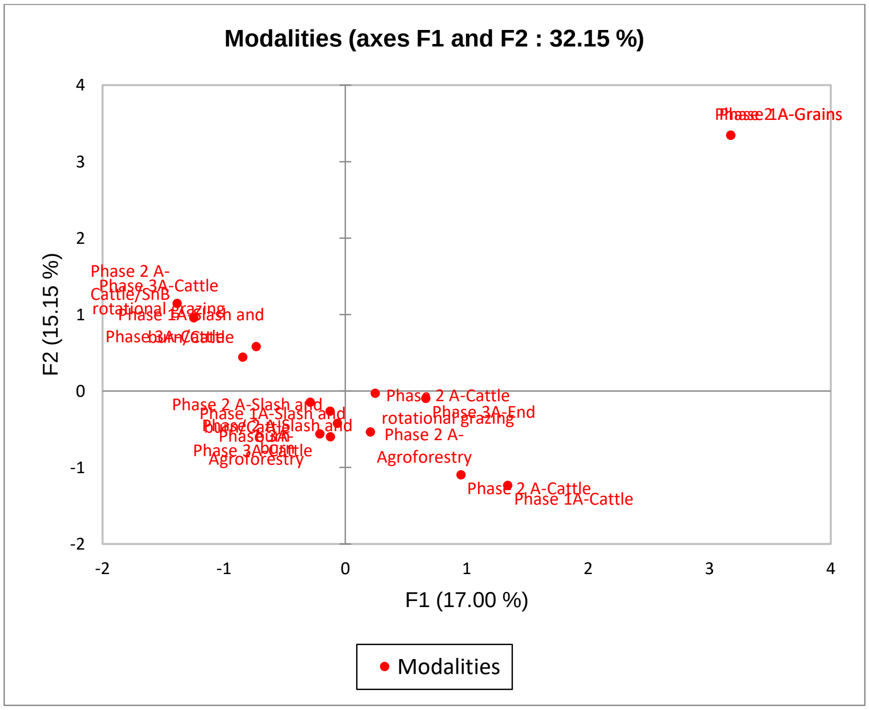

Figure 3.3 The MCA chart shows the distribution of the phases as points in a two-dimensional space, where distances reflect disassociations. For example, the phases 'P1Grains ' and 'P2Agroforestry' are far apart, indicating a negative correlation between these variables.

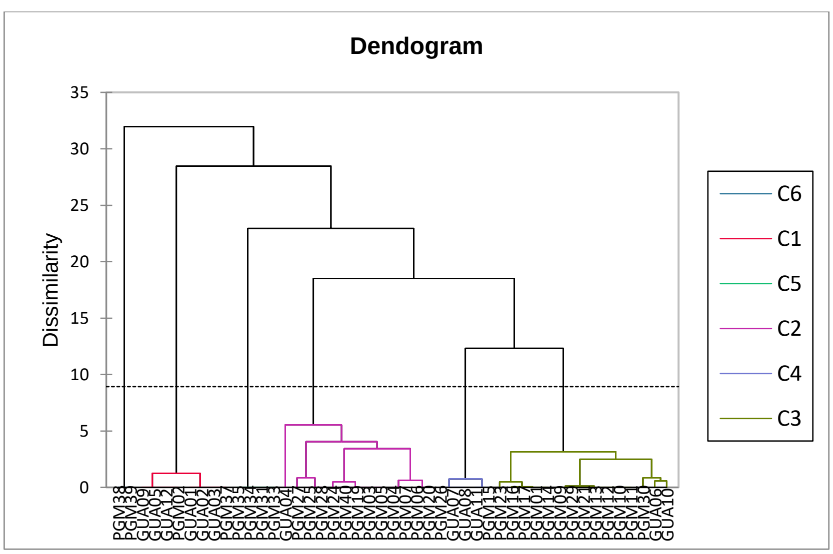

Figure 3.4 Dendrogram showing the formation of six types of trajectories that are grouped hierarchically, with each merger representing the similarity between farmers phases.

Table 3.6 *Test values (Variables)*

	F1	F2	F3	F4	F5
Phase 1A-Cattle	**2.772**	**-2.560**	**-4.332**	**-1.962**	0.479
Phase 1A-Grains	**4.546**	**4.778**	0.885	0.396	1.101
Phase 1A-Slash-and-burn	-1.100	**-2.424**	**3.606**	-0.487	1.912
Phase 1A-Slash-and-burn/Cattle	**-2.746**	**2.160**	-1.660	1.657	**-3.011**
Phase 2 A-Agroforestry	0.370	-0.957	**2.081**	-1.209	-0.732
Phase 2 A-Cattle	**2.708**	**-3.120**	**-4.137**	-1.299	1.688
Phase 2 A-Cattle rotational grazing	0.581	-0.076	-0.251	0.131	**-5.131**
Phase 2 A-Cattle/ Slash-and-burn	**-4.252**	**3.502**	**-2.204**	**-2.513**	1.142
Phase 2 A-Grains	**4.546**	**4.778**	0.885	0.396	1.101
Phase 2 A-Slash-and-burn	-0.232	-1.590	**4.229**	-1.944	0.343
Phase 2 A-Slash-and-burn/Cattle	-1.075	-0.565	-0.234	**5.682**	0.859
Phase 3A-Agroforestry	-0.487	-1.321	**4.184**	**-1.976**	-0.003
Phase 3A-Cattle	-0.842	0.439	-0.660	**3.265**	-1.764
Phase 3A-Cattle	-0.372	-1.854	0.129	**3.974**	**3.669**
Phase 3A-Cattle rotational grazing	**-4.397**	**3.358**	-1.862	**-2.414**	1.468
Phase 3A-End	**4.424**	-0.667	-0.963	-0.736	**-3.449**

Note: Values in bold indicate statistically significant differences ($p < 0.05$).

Type 1 Progressive intensification cattle rotational grazing

This type includes eight farms located in patches F, G, and H in Guaviare, and in patches B and C in Paragominas. At the beginning of the trajectory, the size of the farms ranged from 4 to 300 ha. Farmers were between 29 and 60 years old. The trajectories lasted between 15 to 34 years. The oldest trajectory started in 1989. These trajectories had three phases (Figure 3.5).

The first phase was characterized by slash-and-burn; cashew was also cultivated in Paragominas, and coca in Guaviare. Coca was planted far from the house, divided into small plots with a maximum size of 1 ha located in the forest, or next to a slash-and-burn plot to be less visible. The duration of this first phase ranged from 4 to 10 years. Starting dates for this phase were between 1989 and 2013, and finishing dates were between 2000 and 2017. This first phase of the trajectory corresponded to the establishment of the farms in the territory. In Paragominas, the farmers' initial project was to establish pastures to develop cattle farming, whereas in Guaviare, the aim was to combine slash-and-burn and coca for as long as possible. To conduct slash-and-burn, an initial plot was cut in regenerated forest or in undisturbed forest, but in the latter case the cost for cutting was higher. The cutting was done collectively with neighbors in Paragominas and Guaviare, and could involve 4 to 12 people, mostly men. When access to roads for the transportation of agricultural products did not yet exist, the cut plots were located next to the river. Other plots were later cut to leave the riverside as a reserve, either because of regulations (e.g., the river protection areas in Colombia and areas of permanent protection in Brazil) or due to farmers' awareness of water conservation. "*We did the first slash-and-burn (Roça) in a regenerated (capoeira) on the riverbank. At that time, it was not normal to make a roça that was not on the slope of the river because we had no roads, everything was transported by the river. So, then we started working there, on the plateau, and we left the river slopes behind. We stopped doing that [slash-and-burn on the riverbank] because we realized that we were polluting the water and that working on the slope of the river was more difficult*". The area of the plot cut for slash-and-burn ranged between 0.25 to 4 ha. After the plot was harvested, it was left fallow for forest regeneration, except in some cases when grass was planted, depending on the financial resources of the family. The family work group was composed of 2 to 4 people. The family's labor was sold to other farms, which could be either large farms or family farms. In Guaviare, days of labor were mostly sold for coca harvesting. Three women conducted off-farm activities, working as a gasoline trader, seamstress, and elementary school teacher. Women's off-farm activities were fundamental for the stabilization of the first phase of the trajectory.

The second phase lasted from 4 to 14 years. This second phase started between 1999 and 2016 and ended between 2013 and 2022. The second phase was characterized by cattle ranching as the main activity, with slash-and-burn as a secondary activity. In this phase, the livestock system was stabilized. Pasture areas ranged from 3.5 to 75 ha for farms ranging in size from 4 to 100 ha. The beginning of this second phase started with the fencing of paddocks, which ranged in size from 6 ha to a maximum of 37 ha. The average cattle density was 0.57 animals per hectare. This phase was the one that led to the highest forest cutting of the trajectory. Farmers in Guaviare also grew coca, cocoa, peach palm, and sugar cane, while in Paragominas they grew cocoa, açaí, and passion fruit. In Guaviare, there was a partial or total abandonment of coca production during this second phase that was driven by multiple factors. Farmers mentioned glyphosate fumigations between 2000-2002 and the PNIS in 2017. According to the farmers, coca did not help them economically. While two farmers reported that it helped them to invest in cattle, six farmers mentioned that coca cultivation helped them to eat and save a little money, but not much more. Farmer09: *"The coca investment was loaned to you, the seed was given to you, everything was on credit, but in the end, it was not profitable"*. Farmer 04: *"Coca...doesn't give you money, it is useful if you save and it is just a little, and for food"*. Farmer 01: *"Coca did not work because we had to pay for everything, workers' expenses, inputs and nothing, a lot of work and nothing. So, the substitution was calves"*. Farmer 05: *"After all that situation of fumigations, guerrillas, military, my project after leaving coca was to become a cattle rancher, that is to say I wanted to have cattle"*. In this second phase, the family work group consisted of 2 to 3 people. Nobody worked for other farms, except in Guaviare where in case of financial difficulties they could occasionally work on coca harvesting. In this phase, they started hiring 1 to 3 workers on a daily basis depending on the farm and the calendar, generally to fix paddocks, harvest or fumigate. Women were engaged in off-farm activities, working as health agents and selling gasoline.

The third phase corresponded to the abandonment of slash-and-burn and a focus on cattle rotational grazing. This phase lasted from 1 to 7 years, starting between 2016 and 2023, and was not yet completed at the time of the surveys. In Guaviare, this phase was also characterized by the total abandonment of coca cultivation. In Paragominas, farms adopted açaí, cacao, and pisciculture, while in Guaviare they adopted peach palm and beekeeping. In Paragominas and Guaviare, cassava, beans, rice, and maize were cultivated without the use of fire but only for self-consumption. Farmer PGM02: *"I stopped working the fields with fire, because the tractor of the municipality helps me, the tractor plows and we sow again here. We gave oil and food to the tractor driver. But not everyone has the help of the tractor, we must talk with the president of the community, we go and make the demand to 25 settlers"*. In this phase, the total area of the farm remained constant; however, the number of cattle increased. The average size of the paddocks was 1 ha, and average cattle density was 2.06 animals per hectare. The family work group consisted of 1.5 to 3 people with nobody working for other farms. In this phase, they continued to hire 1 to 8 workers depending on the farm and the season of the year, generally to fix paddocks, harvest peach palm, and prune. During this phase, working off-farm was rare, but some men and women mentioned occasional work, in day jobs or on short contracts in the city as electricians or technicians working with NGOs. According to farmers in Guaviare, the switch to phase three involved the substitution of coca crops, which was promoted by PNIS in 2017, the "*caminemos territorios sostenibles*" project in 2019, and recent projects in 2023 which supported the transition to cattle rotational grazing. In Paragominas, multiple factors drove the switch to rotational livestock, with farmers mentioning technical projects and training organized by local and international research and extensions institutions, which led to exchanges between farmers and an appropriation of this practice.

In this trajectory type, farmers reported an average net deforestation of 54% of their area.

Type 2 Steady cattle trajectory

This type included 13 farms, nearly all from Paragominas in patches B and C, with one case observed in Guaviare in patch F. The size of the farms ranged from 25 to 65 hectares at the beginning of the trajectory. Farmers ranged in age between 44 and 70 years old. The oldest trajectory started in 1996. The duration of the trajectories varied from 10 to 34 years. Most of these trajectories consisted of three phases; however, four farm trajectories had two phases (Figure 3.5).

As observed in type 1, the first phase of the trajectory was characterized by slash-and-burn. Other activities could be observed, such as growing cashews in Paragominas and peach palm in Guaviare. This first phase lasted from 4 to 19 years. This phase started between 1996 and 2013 and ended between 1998 and 2021. The initial project was to plant pasture in order to later develop cattle farming. As described in type 1, an initial plot was opened in the secondary forest or in the primary forest. In both Guaviare and Paragominas, the practice of slash-and-burn was carried out with a long period of fallow for forest regeneration. The size of the slash-and-burn area varied between 0.3 ha and 6 ha. Farmers hired laborers for cutting and planting. Farmer PGM06: *"When I had to cut it, I cut it, I cut the forest, then when it was already cut, after a month...Then I would let it dry. Then, when it was dry, we would make a firebreak around it and set fire to it, and I would get three or four people to plant the rice and I would plant the cassava myself, with a hoe"*. The family work group was composed of 2 to 4 people. Family labor was sold to other farms in 8 of the 13 trajectories. In five farms, men and women were involved in off-farm activities. In Paragominas, men worked for sawmills in the city while women worked on the farm. Women also worked in elementary schools or washing clothes in the large farms.

The second phase lasted from 3 to 19 years. This phase started between 2004 and 2020 and ended between 2011 and 2018, except for five farms that were still in this phase at the time of the surveys. This second phase was characterized by cattle ranching with slash-and-burn crops as a complement. From 5 to 32 hectares of forest were cut during this phase, but the total farm areas did not change when compared to phase one. This phase started with the fencing of paddocks, which ranged in size from 7 ha to a maximum of 20 ha. The cattle density was 1 animal per hectare. This phase led to the highest amount of forest cutting in this trajectory. Farmers in Guaviare also grew peach palms, while those in Paragominas grew açaí and cashew. In Paragominas, farmers mentioned that they obtained cattle through: (i) credits from the national government (e.g., FNO and PRONAF), (ii) renting out pasture land in exchange for keeping half of the calves born, (iii) pluriactivity that allowed them to buy the first set of cattle, and (iv) payments for their work on larger farms. Farmer PGM05: "*I wanted to have cattle, I saw that the cassava was not working so after cutting, I put grass, because I wanted to have cattle, then I took the FNO credit to buy my first cattle"*. The family work group consisted of 2 to 6 people. During this second phase, 1 to 2 family members worked for other farms. This means that although the production system had improved and the trajectory was at a stable stage, the marginal value of the sale of labor was still higher than the opportunity cost of working on another farm. In this phase, they started to hire 1 or 2 workers on a daily basis depending on the farm and the season of the year. The same five family farms maintained off-farm activities.

The third phase was characterized by a focus on cattle production with a constant number of animals and the abandonment of slash-and-burn in most cases. This phase lasted between 5 and 14 years, starting between 2011 and 2018, and was still ongoing at the time of the surveys. Farmer PGM04 said: "*My husband decided not to work with the slash-and-burn (roça) anymore, it was too much work for his age, besides he was sick, I couldn't do the roça alone, besides it doesn't even sell like in the beginning*". During the third phase, farmers also engaged in açaí and fish farming in Paragominas, and peach palm farming in Guaviare. The abandonment of slash-and-burn was explained by the fact that farmers could not find a market to sell their products, and that working was now painful given health and age-related problems. In this phase, farms had the same total area as in phase 2 except for one case where the area decreased from 50 to 37 ha after the farm head retired and decreased the farmland. The size of the paddocks in this phase was the same as in phase 2. The average cattle density remained constant at 1.04 animals per hectare. During this phase, the constant number of animals combined with the decrease in cropping areas allowed for an average forest regeneration of 11%. The family work group consisted of 1 to 2 people, the sons who helped in the previous phase had now left. In this third phase, no one worked for other farms, because most of the farmers were older (only two farmers under 50 years old). In this phase, they hired 1 to 2 workers on a daily basis, depending on the farm and the season of the year, to fix paddocks, harvest peach palm or pruning. The off-farm activities at this phase disappeared.

In this trajectory type, the average net deforestation reported by farmers for the entire trajectory was 37% of their area.

Type 3 Agroforestry

This type included 15 farms. They were located in patches G and H in Guaviare, and in every patch in Paragominas with the exception of patch D. The farm size ranged from 25 to 65 ha at the beginning of the trajectory. Farmers ranged in age from 34 to 71 years old. The oldest farm trajectory started in 1995. The duration of the trajectories varied from 9 to 28 years. For seven farmers, these trajectories consisted of three phases, the rest were still in the second phase at the time of the survey (Figure 3.5).

The first phase was characterized by slash-and-burn. Other crops could be observed, such as açaí in Paragominas and coca cultivation in Guaviare, as described for phase 1 of type 1. This phase lasted from 4 to 20 years, with starting dates between 1995 and 2014, and finishing dates between 2000 and 2018. This initial phase corresponded to farms' installation in the territory, cattle were not part of the farming project. Farmer 029 said: "*I have never liked it [cattle], I like to work with the land with the crops of slash-and-burn. But it has been difficult, I know that there are credits or cattle projects, but I don't like it. Also because the people who get into these projects have to have support from their husbands and technical support and that is something I don't have*". In Guaviare, slash-and-burn and coca were maintained as long as possible. The size of the slash-and-burn areas ranged from 0.3 ha to 17 ha. The family work group was composed of 2 to 4 people. The family's labor was sold on a daily basis to other farms, as observed for phase one of previous trajectories. Four farms described off-farms activities, three men worked as drivers, carpenters and operators of heavy machinery and one woman as a cook for coca harvesting workers.

The second phase ranged from 4 to 20 years. Starting dates for this phase ranged between 2000 and 2020, finishing dates between 2013 until 2022, except for seven farmers who were still in this phase at the time of the interviews. The second phase of the trajectory was dedicated to slash-and-burn and agroforestry (cocoa, açaí, cashew, black pepper, banana). The farm area varied from 25 to 75 ha. The slash-and-burn area ranged from 0.3 to 5 ha while the agroforestry area ranged from 0.5 to 7 ha. Farmers in Guaviare also grew coca, while in Paragominas they grew passion fruit. In Paragominas, farmers explained that they were not interested in raising cattle: Farmer PGM09: "*We didn't want to deal with cattle, we always had other sources that were better than cattle [...] We've always had fruit; we've always worked with fruit. Açaí, lemon, passion fruit*". The family work group consisted of 2 to 8 people. During this second phase, at least one member of the family worked for other farms. At the same time, however, they began to hire 1 to 4 workers per month/year, generally for harvesting or pruning. Off-farm activities increased, and eight families had at least one pluriactive member, women who were health agents and selling handicrafts or working in general services of schools.

The third phase was characterized by the end of slash-and-burn practices and a focus on agroforestry. The duration of this phase ranged from 3 to 10 years. It started between 2012 and 2020 and was not yet completed at the time of the surveys. In Paragominas, farms also produced fish, while in Guaviare, they grew copuaçu. In Paragominas and Guaviare, cassava, beans, rice, and corn were produced without the use of fire and only for self-consumption. For some farmers in Guaviare, this production without fire was a problem: Farmer GUA06: “*I stopped burning because I supposedly got a very heavy sanction from the CDA. But also, because I am involved in conservation projects. I'm regretting it because even though they give you good things like barrels, hoses, shovels and hoes, but now you can't burn. I can't clear for one hectare... I can't plant half a hectare of rice, which is what one consumes the most, or at least plant bananas, now everything has to be bought, everything has to be bought”.* In Paragominas, farmers explained that they did not use fire because of the risk that fires could spread. Farmer PGM29 *“I prefer agriculture without fire because it does not have the risk, having the capital it is better to do without fire, I get sad when I see the fire enter my land or the land of others".* In this phase, farmers increased their agroforestry area. Agroforestry in this third phase was produced on an area from 4 to 14 ha. The family work group was made up of 2 to 4 people. During this phase at least one member of the family worked for other farms. They continued to hire between 1 and 3 day workers for 3 weeks a year. Off-farm activity was less frequent, but some women were still working as health agents, in general services of schools or producing handicrafts. Farmers said their income also depended on subsidies such as the *bolsa familia* (a subsidy for the poorest families provided by the federal government of Brazil) and retirement, and that these helped them to maintain agroforestry.

In this trajectory type, the net deforestation reported by farmers was on average 33% of their area.

Type 4 Rapid shift to rotational grazing

This type included five farms located in patches G and H in Guaviare and in patches A and C in Paragominas. The farm area ranged from 14.5 to 46 ha at the beginning of the trajectory. The farmers were from 37 to 53 years old.

The trajectories lasted from 6 to 15 years, with the oldest starting in 2008. These trajectories consisted of two phases (Figure 3.5).

The first phase was characterized by slash-and-burn and cattle ranching. This first phase lasted between 3 and 5 years. Starting dates for this phase were between 2008 and 2017, and finishing dates between 2012 and 2018. This initial phase corresponded to the establishment of farms in the territory by slash-and-burn. If the land had no grassland, forest was cut, and grass was planted after the harvest of the slash-and-burn crop products. The farmers' initial project was to raise cattle, which they had learned from their families. Farmer GUA11: *"Because my father has been a cattle rancher all his life, and my mother too. Although they also planted coca, later they had a lot of cattle. I grew up driving those cattle and I knew I wanted to have my own someday"*. In Guaviare's patch G, the government, through the INCODER institution, provided 25 ha of land and five cows to the farmers who settled in 2017 on the condition that they would not plant coca. Pasture areas ranged between 5 and 21 ha. Slash-and-burn crops at this phase were commercialized but were not an important source of income, the areas opened for slash-and-burn varied between 1 to 2 ha. The family work group was composed of 2 to 5 people. For three of the five farms, at least one family member worked for other farms. Four families conducted off-farm activities, in this case women worked as cooks, nurses, and mending clothes. These off-farm activities of women in the first phase were a fundamental pillar for the stabilization of the trajectory, as in phase one of trajectory one.

The second phase then lasted from 2 to 11 years. This second phase started between 2012 and 2021 and has not yet ended at the time of the surveys. The second phase was characterized by cattle rotational grazing. In this phase, the cattle system was intensified. The pasture area was from 10 to 41 ha for farms from 18.5 to 46 ha. Paddocks had an area from 0.33 to 4 ha. The cattle density was 1.62 animals per hectare. Farmers in Guaviare also grew coca. In both territories, they grew annual crops without slash-and-burn and without the intention of selling them commercially. In this second phase, the family work group consisted of 2 to 3 people. At least 1 family member still sold their labor to other farms. In this phase, the family started hiring 1 to 4 day workers (for 1 week per year), generally to set up or divide paddocks. Three of the five farms were managed by women, and the other two by a couple where the woman participated in strategic decisions such as investments in cattle and the establishment of rotational cattle grazing infrastructure. Women continue to be involved in off-farm activities as cooks, nurses, and mending clothes. In Guaviare, farmers mentioned that the switch to phase 2 involved the "*caminemos territorios sostenibles*" project in 2019, which supported the transition to cattle rotational grazing. In Paragominas, farmers mentioned the support of CIRAD through the Terramaz and SENAR (National Rural Learning Service) projects to understand and implement the rotational grazing practice.

In this trajectory type, the net deforestation reported by farmers was 39% of their area on average.

Type 5 Extensive cattle ranching

This type was composed of four farms located in patches B, C and D in Paragominas. The farm area ranged from 75 to 6,851 ha at the beginning of the trajectory. The farmers were between 39 and 69 years old. The duration of the trajectories ranged from 3 to 34 years, with the oldest starting in 1990. These trajectories consisted of two phases. This type included middle and large landowners (*fazenderos*) who arrived in the territory more than three decades ago, new *fazenderos* who had the same trajectory pattern in search of improving their income by investing in cattle production, and children of the *fazenderos* who settled in the territory three decades ago after an initial period in big cities to earn money and to learn the business of their parents.

The first phase was characterized by forest clearing, the planting of pastures, and the installation of cattle in large paddocks covering at least 25 ha. Farmers who began setting up after 2015 sought out land that had already been cut to make the start of their cattle operations easier. In this phase, they exclusively raised cattle for meat. This first phase ranged from 1 to 20 years. Starting dates for this phase were between 1990 and 2018, and finishing dates between 2013 and 2022. In this phase, the pasture area ranged from 189 to 2,000 ha. The cattle density was 0.82 animals per hectare. The family work group was made up of 2 to 3 people. During this phase, nobody worked for other farms, they hired 1 to 8 day workers during 4 weeks per year on average, and had 1 to 5 permanent workers. There was usually a livestock manager who managed the cattle and reported to the head of the farm.

The second phase was characterized by an expansion of the cattle production system, in terms of both heads and land area. This phase lasted from 3 to 11 years. It started between 2013 and 2021 and was not yet completed at the time of the surveys. In this phase, farms increased their area, the size of the farms ranged from 300 ha up to 8,151 ha. Cattle density was 0.91 animals per hectare. Since 2013, one farmer has started to diversify with soja crops but explained that it was only a complement. Farmer PGM34: "*The farm is focused on raising cattle, so we always had in our minds that the land was bad and would not yield anything, today it is still raising cattle but there is this part of soybeans as a complement*". The family work group consisted of 1 to 3 people with nobody working for other farms and nobody involved in off-farm activities. In this phase, they continued to hire 1 to 8 day workers, but the number of permanent workers increased from to 2 to 9. These permanent workers generally lived with their families within the fazenda. While some wives of permanent workers may have been cowgirls, the labor force consisted primarily of men.

In this trajectory type, the net deforestation reported by farmers was 62% of their area on average.

Type 6 Soja and cattle ranching

This type was composed of two farms located in patches A and C in Paragominas. The size of the farms ranged from 400 to 1,100 hectares at the beginning of the trajectory. The farmers were 49 years old. The trajectories lasted from 9 years to 16 years, with the oldest trajectory starting in 2007. These trajectories had two phases (Figure 3.5).

The first phase was characterized by the cultivation of crops such as soja, maize, and rice, and lasted from 4 to 11 years. Starting dates for this phase were between 2007 and 2015, and finishing dates between 2018 and 2019. The family work group in this first phase was composed of 2 to 3 people. The family's labor was not sold and focused exclusively on the farm (no off-farm activities). They had between 5 to 12 permanent workers. These farmers had migrated to the north from southern states of Brazil (*Rio grande do sul-Mato grosso do sul*), looking for cheaper land and good conditions to work on grain crops. The farmers mentioned that they bought degraded lands. Farmer PGM38*: "I came to work in these degraded areas that had opportunities. I worked with rice and corn at first (fist year), I was already working with soybeans in Rio Grande, but I didn't start with that because I had to learn about the conditions in Paragominas. The cropping issue, for example, was that we didn't have the proper knowledge to work with soya in the region, the fertility levels, you know, correction, phosphorus, potassium. The areas that are degraded pastures are areas that are not suitable for planting soybeans. Because you have to harvest, soybeans have to be harvested lower"*. The farmers said that Embrapa's help in developing techniques for soybeans was essential for their establishment in the region. Farmer PGM38: "*Embrapa invested in knowledge that was transmitted to us to be able to make the soja crops here in Paragominas, so first we plant soybeans and then we plant other grains in the same plot after harvesting soja, such as sorghum or corn."*

The second phase lasted between 4 and 5 years. This phase started between 2018 and 2020 and was still ongoing at the time of the survey. The second phase was characterized by the insertion of cattle production in a second cycle. After harvesting soja, farmers planted pasture in some plots for the cattle (25% of the area harvested in soja), but soja remained the main activity. Famers explained this diversification by the market instability and the rise in the price of fertilizer inputs. Farmer PGM38*: "We started with cattle as an option but it's not our thing, we did it to lower the risk and adapt to the market, the war in Ukraine made the inputs increase a lot. So far it is working well and we are still looking at how we can improve."* Farmers in this second phase cultivated sesame, maize, or sorghum. The family work group consisted of 4 people with nobody working for other farms. Women played essential financial roles by monitoring budgets. In this phase, farmers hired between 4 to 8 day workers, but the particularity was a rising number of permanent workers, ranging from 9 to 29 permanent workers. During this phase, farmers were more pluriactive, they created a company to buy inputs for soja producers that possess around 14,000 ha.

In this trajectory type, the net deforestation reported by farmers was 57% of their area on average.

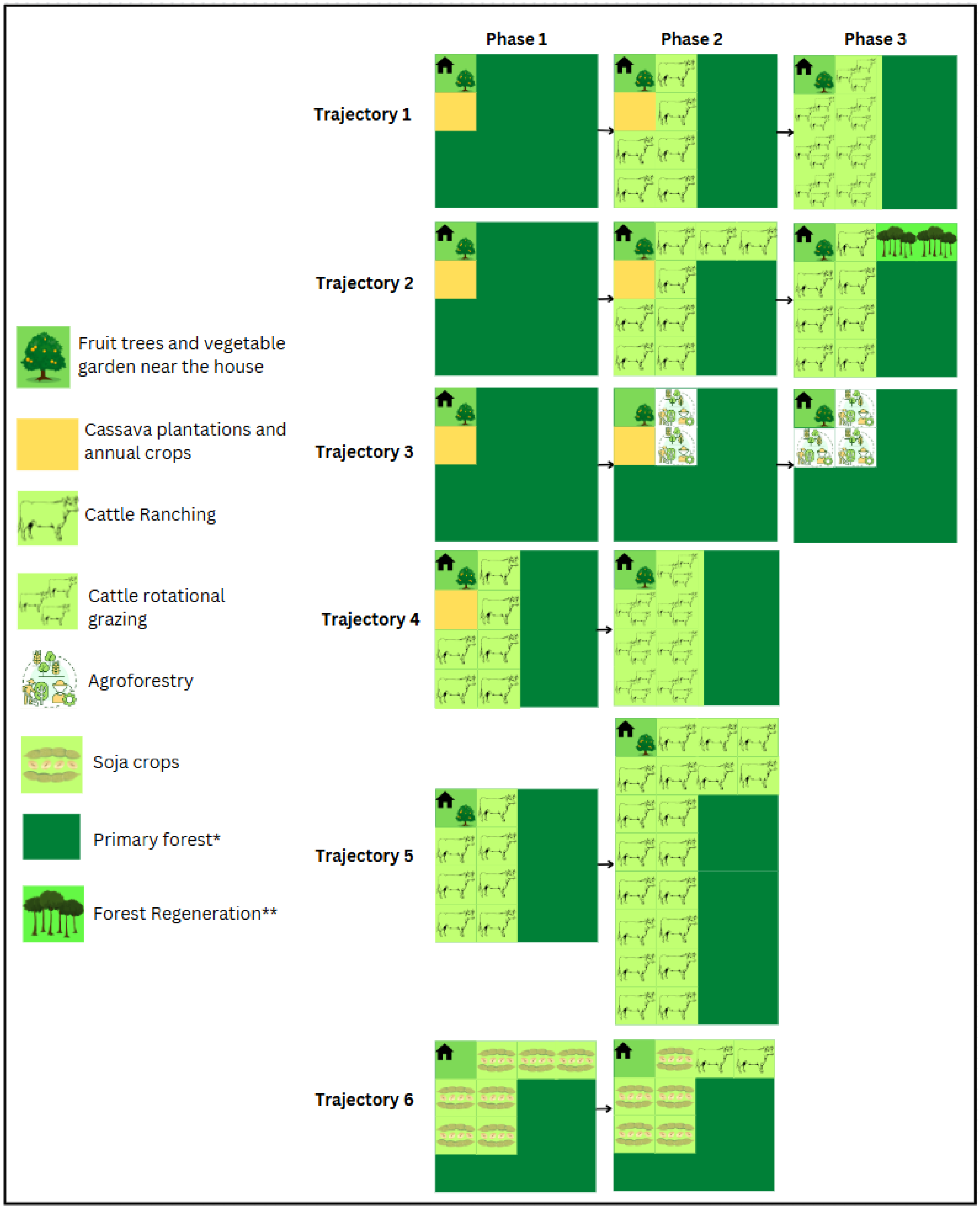

Figure 3.5 Main farm trajectories T1 Progressive intensification cattle rotational grazing - T2 Steady cattle trajectory - T3 Agroforestry - T4 Rapid shift to rotational grazing - T5 Extensive cattle ranching - T6 Soja and cattle ranching *could be primary or secondary forest **forest regeneration of at least 15 years

Table 3.7 Patches, level of forest regeneration, deforestation, degradation, and trajectory types

Patch	Patch ID	Forest RDD	Trajectory Types
Potirita	A	High deforestation, low degradation, low regeneration	3, 4, 6
Agua Suja, Alta Floresta, Nuevo Horizonte	B	Low deforestation, high degradation, low regeneration	1, 2, 3, 5, 6
CAIP Paragonorte	C	High deforestation, low regeneration	1, 2, 3, 4, 5
Luís Ignacio: Nova Paragonorte, Cacimbão, Cajueiro	D	High deforestation, moderate degradation, low regeneration	3, 5
Teko Haw	E	Low deforestation, high forest conservation	3
Unilla	F	Low deforestation, low degradation, low regeneration	1, 2
Guacamayas	G	Low deforestation, low regeneration, low regeneration	1, 3, 4
Calamar	H	High deforestation, low degradation, low regeneration	1, 3, 4
Charras	I	Low deforestation, low degradation	

Table 3.7 shows the distribution of trajectory types across different patches. It shows that some types were found in all patches (e.g., type 3), while others were only observed in specific ones (e.g., type 6 was only observed in patches A and B). Conversely some patches (e.g., patches B and C) include diverse trajectories while others have only one or two trajectories (patches D, E, and F).

3.3.2 Agroecological principles on current phase of trajectory types

Figure 3.6 highlights that none of the current phases of the six trajectories align with all of the agroecological principles. Each type had its own specific strengths and limitations regarding these principles.

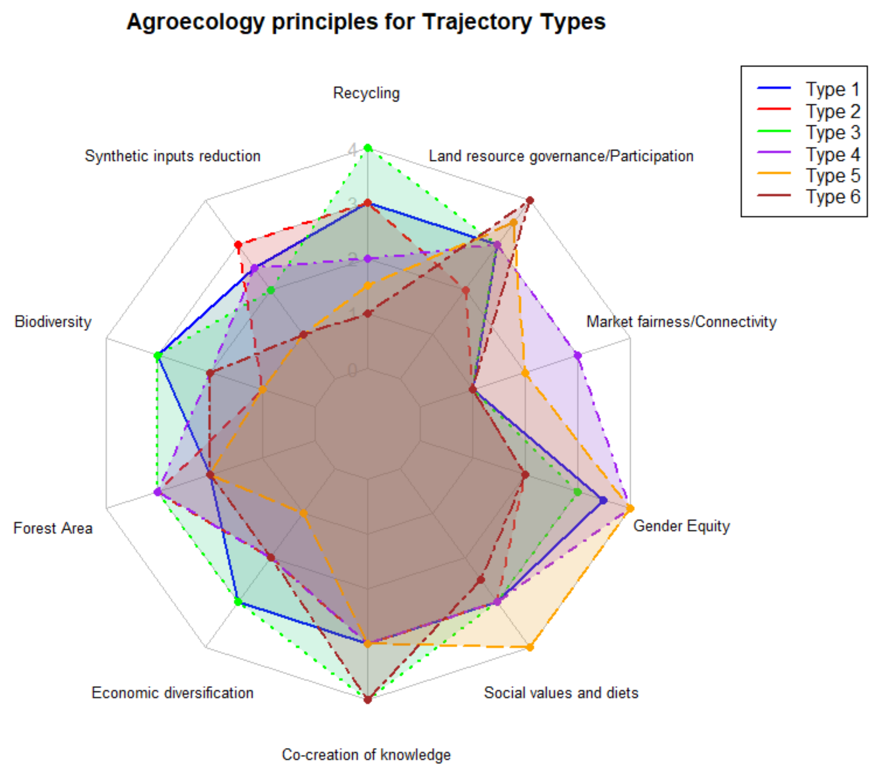

Figure 3.6 Scores on agroecological principles of the six trajectory types

Type 1 had a relatively good score for the recycling principle (3), farmers currently use manure produced by their cattle production system. This type also presented a relatively good score for the biodiversity principle (3), which can be linked to the good score they had in the social values and diets principles permitted by the various productions of their farm. However, they had a lower score for the input reduction principle due to their use of synthetic fertilizers and pesticides (2.5). This type cut the forest to develop its production system during its trajectory, which led to a low score for the forest area principle (2). This type presented a relatively good score for the gender equity principle (3.5) given the role played by women in the farm's strategic decisions of investing in cattle and paddocks for rotational grazing.

Type 2 was relatively well aligned with the forest area, social values and diet, recycling (3), and reduction of synthetic inputs (3) principles. Farmers used the manure produced by cattle, but it should be noted that the low use of synthetic inputs by farmers was mostly due to a lack of financial resources to buy them. This type had low scores for the biodiversity (1), economic diversification (2), and land resource governance and participation (2) principles. In the current phase of their trajectory, diversification or investment in new cropping or livestock systems was no longer their priority, and they were unsure about the benefits of having a property title or participating in farmer associations. Although women participated in some farm decisions, they did not participate in the strategic choice of investing in productive systems, which led to a poor score in the gender equity principle (2).

Type 3 had good scores (3) for various principles such biodiversity, forest area, economic diversification, social values and diets, gender equity and land resource governance/participation, and poor scores for the reduction of synthetic inputs (2) and market fairness/connectivity principles (1). Their good economic diversification was due to their off-farm activities in the current phase of their trajectory, while in other trajectories, off-farm activities were mostly observed in the initial phases.

Type 4 had good scores for the gender equity (4) and forest area principles (3). This trajectory was driven by women farmers focused on cattle rotational grazing. Their low impact on forest areas can be explained by an initial settlement in places where the forest had already been cut and converted to pasture. This type had the best scores for the market fairness/connectivity principle (3) due to the farmers’ positive perception, mentioning selling their products to fair markets. Type 4 had poor scores for the synthetic input reduction, recycling, economic diversification, and biodiversity principles.

Type 5 had poor scores for the recycling (1.5), reduction of synthetic inputs (1), biodiversity (1), forest area (2), and fair markets/connectivity (2) principles. It had good scores in the knowledge co-creation (3), social values and diets (4) and gender equity (4) principles. Women played a role in the strategic decision to buy land. They reported that they had a diversified diet and their welfare was good, but they did not produce most of the food in their diets on their own farms.

Type 6 had poor scores for most of the agroecological principles, including the recycling (1), reduction in the use of synthetic inputs (1), biodiversity (2), forest area (2), economic diversification (2), gender equity (2) and social values and diets (2.5) principles. However, it had goods scores for the knowledge co-creation (4) and land governance and participation (4) principles. These farmers mentioned spaces for the exchange of knowledge, they were involved in groups for the improvement of their production, and had property titles to their land.

Transversal patterns were found across types such as good scores for the knowledge co-creation principle. Co-creating knowledge with neighboring farmers was critical for achieving a desired production system in this Amazonian context. Conversely, only one out of the six types had good fair market and connectivity scores, indicating that in this context, it can be challenging to reach direct consumers due to inadequate road infrastructure.

3.4 Discussion

3.4.1 A limited set of possible trajectories in the Brazilian and Colombian Amazon

Conducted in two different Amazonian territories, Paragominas and Guaviare, our study highlighted six main trajectories. These trajectories have been described in the literature in Brazil (Cialdella & Navegantes, 2014; Navegantes-Alves et al., 2012; Plassin, 2018). Four of the six trajectory types were found in both territories (the extensive cattle and the soybean-based trajectories were not found in Guaviare) highlighting common patterns in both territories. This suggests that pursuing a trajectory other than one of these six might require farmers to make an extra effort to learn about new production systems (Bredart & Stassart, 2017).

Five of the six trajectories involve cattle, showing that this production system is still a strong factor for farm resilience (Powell et al., 2019). Some farmers mentioned the role of cattle farming in coping with adverse conditions (crops destroyed by pesticide fumigation in Guaviare, bad road conditions, long distances, the absence of cold chains) and the existence of a stable demand for cattle in capital cities. However, the management of cattle differed between types (rotational grazing, extensive grazing, etc.) depending on the human and financial resources of the family. Although it may not be possible to sell animals on fair markets, as some farmers indicated, several authors have shown the resilience and lower transaction cost of this production system during financial emergencies (Bilotto et al., 2024; Duru & Therond, 2015; Faraz et al., 2023; Siegmund-Schultze et al., 2010). Cattle also are a source of savings for farmers on the pioneer fronts (Moll, 2005; Moreira-Dantas et al., 2023; Torres et al., 2023). In the view of farmers, by investing in cattle, they maintain and even increase the value of their money.

Agroforestry systems were at the heart of only one trajectory (type 3). In this trajectory, farmers were not interested in cattle production. Although not the main focus, agroforestry systems were starting to be implemented in types 1 and 2 as a means of diversifying. This was primarily accomplished through the cultivation of açaí crops in Paragominas and peach palm in Guaviare.

3.4.2 Trajectory types leading to various patterns of agroecology and sustainability

The current stage of a farm trajectory is the result of a succession of phases. Analyzing the alignment of the current stage of farm trajectories with agroecological principles has helped to identify trajectories that lead to sustainable situations.

Based on the scores obtained for different agroecological principles, each trajectory type had a specific agroecological pattern. The current phases of types 1, 3, and 4 were globally well aligned with agroecological principles. Type 3 is the trajectory most aligned with agroecological principles and stands out as the most sustainable. Various studies highlighted that agroforestry is an emblematic system for agroecological transitions (Ollinaho & Kröger, 2021; Plieninger et al., 2020; Quintero et al., 2024).

Types 5 and 6 can be regarded as the least desirable trajectories from the agroecological principles standpoint due to their excessive reliance on productive resources such as forests, as well as their limited economic diversity and lack of access to fair markets. However, their scores on social principles were good, which highlights their improved social and human capital.

Farm trajectories explain current agroecological patterns. In these trajectories, development projects, or the emergence of new markets, play a crucial role in the changes that occur. For example, in types 1 and 4, especially in Guaviare, development projects served as the primary catalyst for the observed intensification of cattle farming practices. For type 4, which was implemented on land where the forest had already been cut, the trajectory was relatively short, allowing for a more efficient production process by skipping the slash-and-burn phase. For the type 4 trajectories in Paragominas, market demand for black pepper supported their initial diversification. Farms then diversified with passion fruit and cocoa, the latter promoted by local government projects. In Guaviare, peach palm played a fundamental role in diversification, combined with the income that farmers received from PNIS. In the type 2 trajectories, sustainability also was affected by the lack of transmission of farms, with a decrease in activity when farmers got older.

Few studies have linked trajectory analyses with agroecology (Polge & Pagès, 2022; Vega-Martinez et al., 2024). The link made in this study could facilitate the design of policies that promote more sustainable trajectories. For example, the challenge for types 5 and 6 is to support the intensification of systems based on biophysical principles. Recycling the biomass produced can be a way to decrease the number of inputs used in these systems. Conversely, the challenge for type 3 is to support their access to fair markets with, for example, the development of quality labels.

Our study highlighted strengths and opportunities for these trajectories. Our findings emphasize that connectivity and fair markets, two key agroecological principles, are a recurring challenge affecting farm trajectories in Amazonian territories. Pesticides and synthetic fertilizers were used in various trajectories, from agroforestry to soybeans and cattle, highlighting an opportunity to use agroecological practices such as push pull practices, improved composting practices, and biofertilizers. With the exception of type 5, women were driving sustainable trajectories, such as trajectory types 1, 3, and 4, demonstrating their fundamental role as highlighted in other studies (Castro-Nunez et al., 2024; Mello & Schmink, 2017), indicating that they can be a lever for sustainable trajectories.

3.4.3 Individual trajectories not considered in the typology

Eight individual trajectories were removed from the MCA analysis. Four were recent, having been in existence for only 4 years, and consisted of only one phase at the time of the surveys. Three of these four trajectories started with slash-and-burn and cattle (two from patch I and one from patch C), which could probably correspond to the first phase of a type 2 trajectory. One of these four trajectories consisted of a 3-year-old açaí monocrop. The farmer used to work in banking and wanted to invest in açaí when she retired.

Two additional trajectories from patch C started in 2000 with a first phase of slash-and-burn, a second phase of slash-and-burn and cattle, and then a departure to the city. This departure was due in one case to the death of the husband, and in the other case to work opportunities and education access for the children. During this period, the management of the farms was left to relatives who quasi abandoned them, or only managed a small area for cattle grazing, and the forest regenerated. Finally, both farmers returned to their farms in 2020, and have been practicing slash-and-burn cassava crops without fire since 2022.

Two additional trajectories showed similar patterns with the difference that the farm was sold. In one case in patch D, the farm started with slash-and-burn and after a separation of the couple, the woman initially stayed on the farm with her children, then sold it two years later to move closer to the settlements and seek middle school education for the children. In the other case in patch B, the farm started in 2000 with slash-and-burn, then slash-and-burn and cattle from 2008 to 2017. After 2017, the farmer fell ill and finally sold the farm in 2022.

In our sample, the trajectories ending with a migration to the city or the sale of the farm were affected by endogenous farm factors, especially family factors such as separation, illness, or the pursuit of education for the children. This highlights the importance in the Amazon of access to health services and education to support farm trajectories.

3.4.4 Influence of the characteristics of patches on the types of trajectories

We found some patterns linking farms to patches.

- Most of the type 2 trajectories were found in patch B, which had low deforestation rates that are in accordance with the observed low deforestation rate of this patch. Type 2 trajectory farmers exert less pressure on the forest, their trajectory characterized by older farmers who do not intensify their production system, indirectly limiting deforestation. In patches with high deforestation rates such as A and D, trajectory types showing high rates of deforestation were also observed (type 5, 6).
- Conversely, in patches with low deforestation rates (E, F, G), trajectories with low rates of deforestation were also observed (type 3, 4).
- In patch H, where there was a high rate of deforestation, we found trajectory types 1, 3, and 4 that do not show high levels of deforestation, suggesting that there are trajectories that were not captured in this patch.
- Patch I included trajectories that were not classified into the main types (short trajectories of a maximum of 5 years based on slash-and-burn production system and cattle ranching). However, at the time of the interview, these were the only ones reporting having coca on fields located 5-10 km away and only accessible by horseback or walking.

The trajectories observed in Paragominas can help understand current and future dynamics in Guaviare. At the same time, in Guaviare, thanks to agriculture development projects promoting rotational cattle grazing, some typical trajectories observed in Paragominas (extensive cattle ranching (type 5) or family faming steady cattle trajectories (type 2) can be intensified leading to the emergence of new trajectories such as type 4.

Armed conflict and coca cultivation were two specific features of Guaviare affecting farm trajectories. The settlement of farms, forest clearing, and land tenure regularization were previously agreed upon by the FARC. Farmers also did not systematically plant pasture after the initial phase of slash-and-burn as observed in Paragominas. They would rather maintain forest cover to hide small coca plots. The first phase of slash-and-burn and coca in Guaviare could last 18 years, while in Paragominas, the initial phase of slash-and-burn lasted a maximum of 12 years. For the trajectories that started before the 2000s, the slash-and-burn and coca phase was longer (12 to 18 years) than the one that started after the 2000s (only 3 to 6 years). This is mostly linked to the PNIS program and glyphosate spraying.

In Paragominas, trajectory type 4, corresponding to a rapid process of intensification of farming systems based on rotational cattle ranching, was found in patches A and C, which are close to villages. In Guaviare, we also found type 4 in more isolated areas such as patch H, with difficult access and the worst infrastructure. This type is promoted by development projects as having low repercussions on forest cover change. In Guaviare, the agroforestry trajectory type 3 was only found in patch G, which is close to the city, while it was found in all of the Paragominas patches where the most distant patches have a market for fruits, especially açaí (Silveira et al., 2023).

3.4.5 Strengths and limitations of the method

This study is based on a typology of farm trajectories combined with a description of the alignment of the current phase of each trajectory with agroecological principles. We sampled farms on two different pioneer fronts. We found that some characteristics of patches (road access, market, village, soil) can be associated with some of the characteristics of the trajectories. However, since we used snowball sampling, some patches may contain a higher diversity of trajectories than what we have described here. This is the case of patches in Guaviare that, due to the limits of our sample in terms of security protocols for conducting interviews, did not allow us to capture extensive cattle trajectories.

Our study is one of the unique research studies linking trajectories to agroecological principles. Various analyses on agroecological transitions fail to describe the initial state of the farming systems and the sequences of changes involved in the transitions. Ideally, it would be relevant to assess the alignment of each phase of the trajectory with agroecological principles. However, in some cases these trajectories are long and have no available registries. Collecting such a large amount of data would not be feasible. Consequently, we chose to collect data for the current phase of the trajectory that can also be a declining phase (e.g., type 2) hiding more sustainable phases of the farm trajectory.

For these kinds of analyses, which describe the history of farms and households, we relied on farmers' memories. Farmers may simplify or forget some events. In the absence of databases and farm registries, farm interviews are often one of the few viable options. To limit this bias, we conducted the interviews visually using diagrams of phases in which farmers built their own production system trajectory. Farmers tend to remember the significant changes which are the most memorable (Bakker et al., 2021; Candau, 2005) and the long-term elements relevant to reconstructing the trajectory (Chantre et al., 2015; Cialdella et al., 2009). Although visual methodologies reduce bias, it is difficult to ensure that trajectory narratives are accurate. Future studies therefore should consider focusing on spatial data to corroborate previously collected data, such as changes in forest area. However, this would require investments to make shape files of farms, and it is difficult to access the required information in the Amazon.

3.5 Conclusion

Conducted in two different pioneer fronts, Guaviare in Colombia and Paragominas in Brazil, this study provided us an overview of the diversity of farm trajectories. Six main trajectories emerged. With the exception of the agroforestry trajectory, most of these trajectories included cattle, highlighting the preponderant role of cattle in the production systems. The characteristics of the pioneer front territories exerted a determining influence on the configuration of production systems, since factors such as colonization, geography, and social conflicts shaped their characteristics and development. This unique study, one combining farm trajectory analysis and agroecological principles, showed that among the current stages of trajectories, the ones most aligned with agroecology were those of cattle intensification at different speeds (types 1 and 4) and agroforestry. These trajectories differed with regard to technical principles, such as recycling and diversity of crops and livestock, but converged on social values principles, such as welfare and diversity of diets. These trajectories were aligned with the principle of gender equity, showing that women are increasingly taking the lead in both agroforestry and cattle farming. Furthermore, the principles of fair market, connectivity regarding sales to end consumers, and dependence on synthetic inputs were important challenges, regardless of the pioneering front.

Our study represents a significant step forward in the field of agroecology in the Amazon. It demonstrates that there is no single solution for achieving sustainable outcomes or reducing deforestation. The co-existence of production systems based on agroforestry and cattle rotational grazing can support the development of sustainable agriculture in the Amazon. Encouraging women's participation, through women-only associations for agroforestry or cattle rotational grazing systems, could be a valid approach. Despite public policy efforts, the use of forest areas in Amazonian contexts remains a challenge due to the absence of land titling.

Targeting objectives by trajectory type and agroecological principle could be a strategy to boost sustainable trajectories with targeted public incentives, combined with the support of advisors and NGOs. In this Amazonian context, future research is needed to support farmers in exploring additional trajectories that incorporate more agroecological principles.

Chapter four: Exploring farm visions in the Brazilian and Colombian Amazon: a participatory study of futures with a gender perspective

Source: Author, Field photos, Agroforestry farm in the municipality of Paragominas, Brazil.

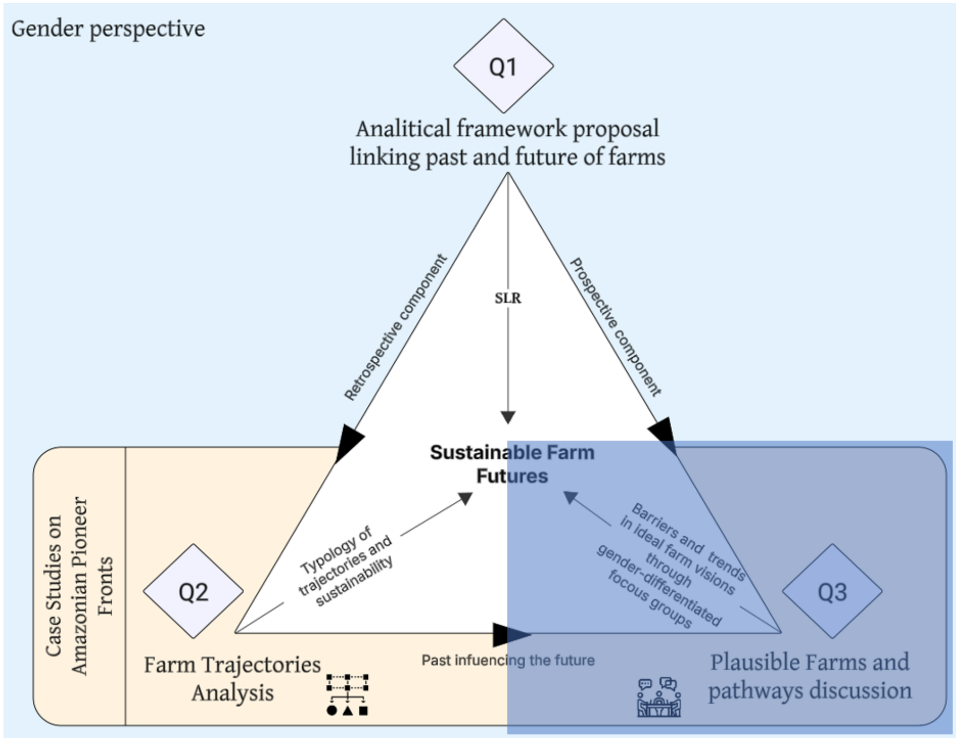

Diagram 3: Methodological framework Step 3 Chapter 4, adapted from Kong (2019)

This chapter constitutes the third methodological step (diagram 3) to answer the specific research question: Q3 How do women farmers and men farmers in the Amazon envision their ideal farms on the medium term (2034)?

Chapter 4 presents the application of the "prospective component" of the analytical framework proposed in Chapter 2. This chapter explores the visions of ideal farms for the year 2034 as perceived by smallholders' farmers in Paragominas (Brazil) and Guaviare (Colombia), with particular attention to gender differences in these visions.

This chapter is the subject of an article that will be submitted to the journal *Futures*.

Abstract

This study explored the visions of small farmers in the Brazilian (Paragominas) and Colombian (Guaviare) Amazon for the middle term (2034), with the objective of understanding how men and women imagine their ideal farms in this context. The research was based on a participatory foresight methodology using the Future Triangle method to analyze the forces of the past (weights), the present (pushes) and the future (pull) that shape these visions. Four focus groups were conducted, two in each territory, including women-only groups to capture their specific perspectives. The results revealed that ideal farms are mainly oriented towards a combination of silvopastoral/rotational grazing for cattle and agroforestry systems, with different percentages of conserved forest area ranging from 5 to 50. Common tensions were identified in both territories, such as lack of land titling, limited access to credit, market barriers, gender inequalities, workforce shortages and institutional distrust. Tensions specific to each territory also emerged, such as the armed conflict and coca cultivation in Guaviare, and coexistence with agroindustry in Paragominas. The study highlights the crucial role of farmers' associations as levers for action to overcome these tensions, including negotiating with government and credit institutions, developing training programs and seeking financing. Gender differenced visions were observed, with women showing a greater inclination towards diversification and agroforestry. In conclusion, building pathways to sustainability in the Amazon requires a gender-sensitive approach, with institutional coordination and capacity building of smallholder farmers.

Keywords: Farm pathways; foresight; smallholders' visions; ideal farms, Amazonian agriculture.

4.1 Introduction

Despite the progress that has been made in controlling deforestation large land ranchers and soybean producers are the main contributors of deforestation in the Amazon (Barbosa De Andrade Aragão et al., 2024; Garrett et al., 2021a; Lima et al., 2011; Salisbury & Schmink, 2007; Song et al., 2021), however smallholder farmers also play a role in forest cutting, as the development of their farm trajectories involves the use of land (Billard et al. 2014; Ballon et al. 2016, Chapter 3). In these smallholder farming systems, when expansion into primary or mature secondary forest is neither possible nor desired, the reduction of the fallow period, together slash and burn, can lead to a decrease in soil fertility (Abrell et al., 2024). Smallholders can also cut down the forest to establish pastures for cattle grazing, often preceded by the slash and burn practice (Ferreira 2001; Navegantes-Alves et al. 2012; Plassin 2018, Chapter 3). This strategy, contributes to soil degradation and forest loss intensifying environmental challenges in the region (Pacheco 2009; Castro-Nunez et al. 2024, Chapter3).

Smallholder farmers are dealing with various challenges including geographical, constraints, low productivity, climate change, gender inequalities, as well as the migration of young farmers to the cities (Costa et al., 2024; P. P. Braga et al., 2023). However, their role is fundamental for food security and rurality in the Amazon (Diniz et al., 2015; Garrett et al., 2021).

Past trajectories of smallholder farmers in the Amazon have been analyzed (Plassin 2018, Chapter 3). Such studies are key to understanding the dynamic of changes that contribute to farm sustainability. However, to ensure the inclusion of smallholders into sustainable farming pathways in the Amazon, it is essential to understand how smallholders envision the future of their farms. Special attention should be paid to women, as they play a crucial role in the connection between family and farm management (Terrier et al., 2012) and often adopt more sustainable agricultural practices (Centrone et al., 2018). But their contribution to agriculture is still understudied (Barrow et al., 2024; Hodel, 2023). To achieve this, we assume that a prospective study is necessary to interpret the past, guide the present, and explore the future (Abdullah, 2023).

Pathways are multiple potential routes to reach desired goals (Pearson & Dare, 2021), in this study, the desired goals are represented as ideal farm visions. Using the future as an object of analysis is essential to rethink the present (Inayatullah, 2006), allowing a proactive reflection on the way to be followed towards future farms. Through a participative foresight exercise, conceptualized by Jahel et al. (2023) as a systematic, participatory approach to exploring futures and the drivers of change, we seek to identify tensions between historical barriers and present trends, as well as farmers' levers of action to overcome barriers and move toward their ideal farms. This exercise is framed within the logic of contributing to the empowerment process of farmers, particularly women farmers, enabling them to take an active role in building the future of their farms. Furthermore, such participatory approaches aim to contribute to the development of pathways that lead to the sustainability of farms, recognizing that the farmers' visions are a key element in this process.

The main objective of this paper is to explore plausible futures farms based on the farmer's visions of ideal farms for the 2034 horizon (Representing a ten-year vision from the time of this exercise, taking into account that some participants are elderly, which allows them to envision the future of their farm), considering present trends and past barriers. We seek to answer the question: How do women and men farmers envision their ideal farms in 2034 in Amazon context?

The study has been conducted in the municipality of Paragominas, in Brazil and in Department of Guaviare, Colombia. Paragominas is an emblematic municipality that achieved the status of a "green municipality", thanks to a municipal pact, after decades of high deforestation rates (Piketty et al., 2015; Viana et al., 2016). However, this transition focused on large landowners, leaving smallholders marginalized (Piraux et al., 2020). Conversely, in the department of Guaviare, despite environmental commitments in a post-conflict context, (Katz-Asprilla et al., 2024), deforestation rates are still high (Rodríguez-de-Francisco et al., 2021).

Conducting the participative foresight exercise in these two different territories, helps us to highlight common trends and challenges in the Amazon, facilitating a comparative understanding of the past structural barriers and present forces that shape agriculture in the region. However, it also helps to highlight specific differences between territories to provide key information for addressing local challenges.

After describing the methodology for participatory foresight exercise (Inayatullah, 2006, 2008, 2023), we present the results of the focus groups discussions. Finally, we discuss how the past farm trajectories affect the visions, future pathways and the strengths and limitations of the methodology are also discussed.

4.2 Material and Methods

4.2.1 Study Sites: based on patches characteristics and farm trajectories

- Paragominas and Guaviare

The municipality of Paragominas is located in the northern region of Brazilian state of Pará (Figure 1). According to IBGE data (2022), population reaches 105,550 inhabitants and covers an area of 19,342.565 km². Its climate has an average annual temperature of ~26 °C and an annual rainfall of approximately ~2000 mm. This municipality is characterized by a predominance of large-scale farming, mainly for grain and livestock, that coexist with smallholders. Smallholders' farms occupy approximately 17% of the agricultural land of the municipality (Resque et al., 2021), which in turn reach near 37% of total municipality area (MapBiomas, 2023). Smallholder agriculture in Paragominas is manly characterized by crops such as cassava (*Manihot esculenta*), corn (*Zea mays*) and beans (*Vigna unguiculata (L.) Walp*) (often cultivated in areas locally named as *roça*). Additionally, farmers cultivate pepper (*Capsicum spp*) and cocoa (*theobroma cacao)*, while açaí (*Euterpe oleracea*) is either grown or collected from the wild. Smallholder farmers also raise cattle for meat and milk production (Plassin 2018, Chapter 2). They are mainly established in areas where large-scale mechanized agriculture is not viable (Osis et al., 2019).

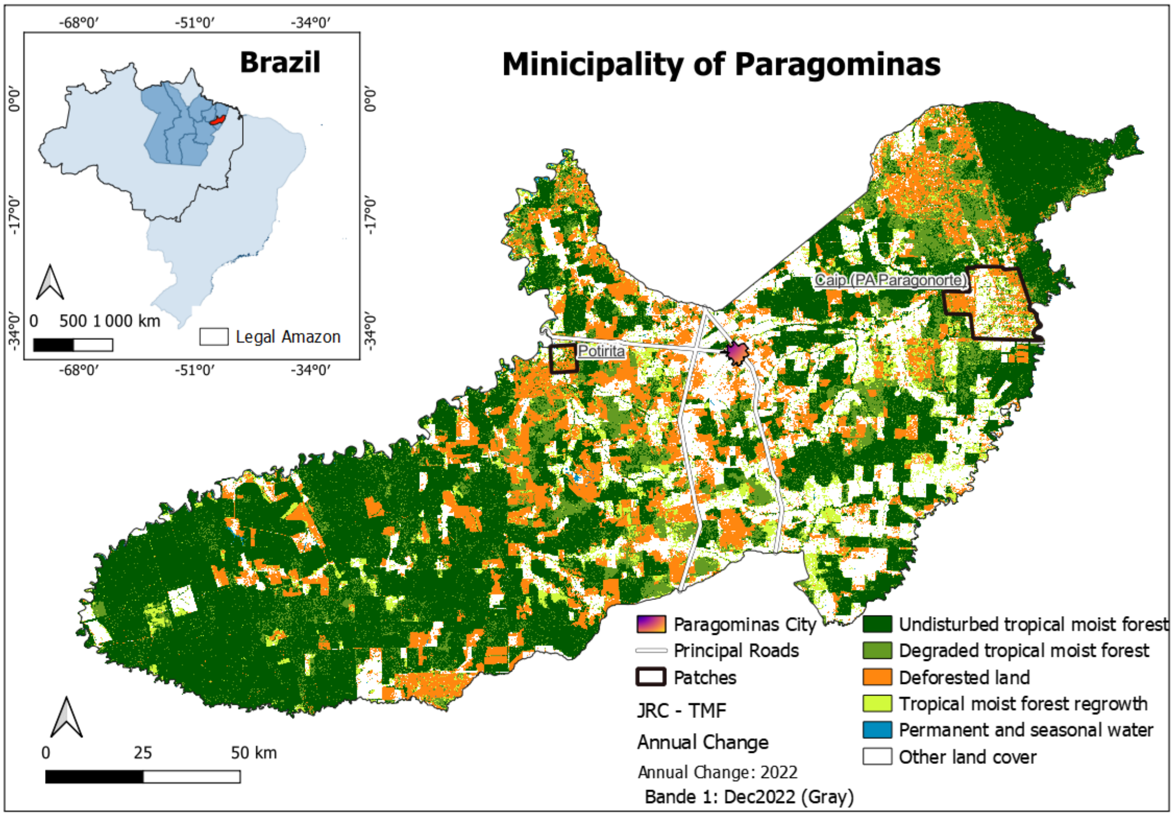

Figure 4.1 Map of the forest cover of the municipality of Paragominas, Brazil, displaying the patches selected for the focus group study (elaborated by the authors, based on data from the EC JRC 2022).

Guaviare is a department located in the Amazon region of Colombia, with a population of 87,767 inhabitants and an area of 53,460 km² (DANE, 2019) (figure 4.2). Its average annual temperature is ~26.5 °C, and it records annual precipitations of ~2,800 mm (Herrera-Builes et al., 2025). The economy is mainly based on the agricultural sector, where livestock plays a predominant role. Other crops such as corn (*Zea mays*), plantains (Musa paradisiaca), dry rice (*Oryza sativa*), cassava (*Manihot esculenta*) (often cultivated in the same areas locally as *Pancoger)*. They are also, cacao (*Theobroma cacao*) and peach palm (*Bactris gasipaes Kunth*) (Orozco, 2022)". In the past decade, the agricultural sector has undergone a transition from an illicit economy based on coca cultivation, which reached 28,435 hectares in 1999 to a licit economy mainly focused on plantains, cocoa, and livestock, reducing the coca area down to 4935 hectares in 2022 (Bravo Parra et al., 2018; UNODC, 2023). This was promoted by the National Integral Program for the Substitution of Illicit Crops (PNIS). 11.15% of the department's area is used for agricultural activities, with a strong presence of family agriculture (UPRA, 2023).

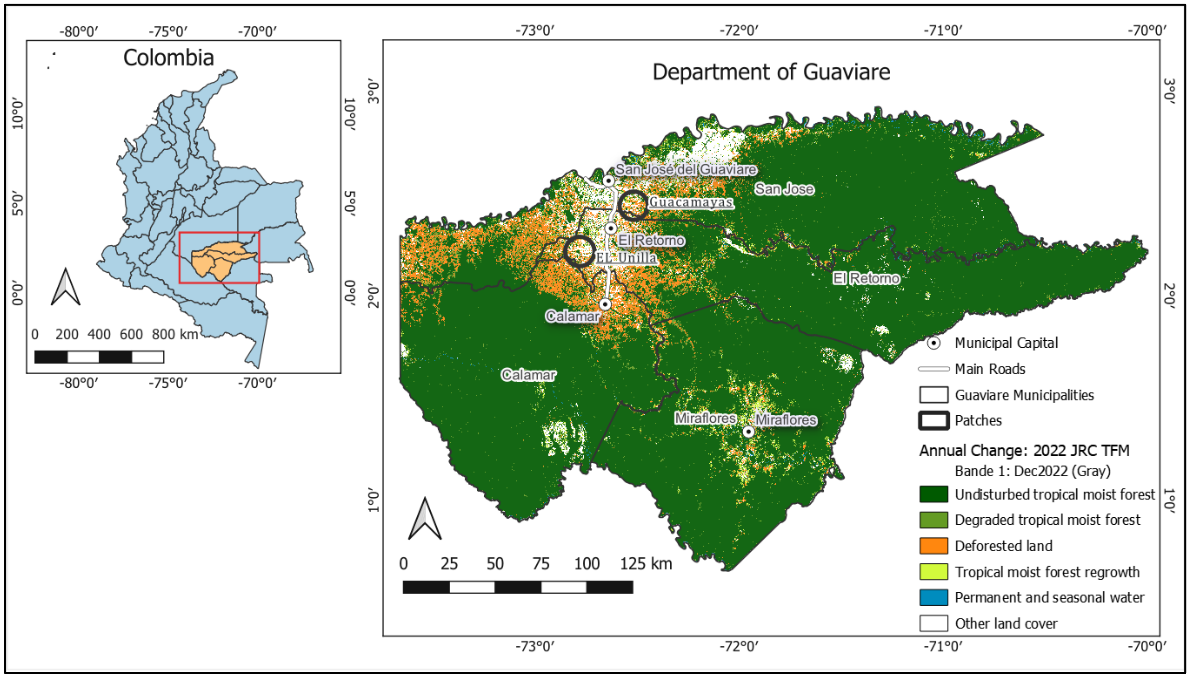

Figure 4.2 Map of the forest cover of the Guaviare department in Colombia, displaying the patches selected for the focus group study (elaborated by the authors, based on data from the EC JRC 2022).

- Case sites selection for foresight focus-group

The study cases that we will refer later as "patches" were chosen based on a previous study on farm trajectories (Chapter 3), with the ambition of linking these past farm trajectories to farmers' visions in the future. Two patches in Paragominas (Potiria and Caip PA-Paragonorte) (figure 4.1) and two in Guaviare (Unilla and Guacamayas) were selected for their specific characteristics (figure 4.2). Potirita was firstly selected for being close to the city of Paragominas, and thus supposed to have a better access to market (40 km) with most of its roads paved. Secondly, Potirita is interesting due its high levels of deforestation since 1990, 31km² of accumulated deforestation within the settlement (total area 45 km²), according to the Joint research center (JRC) data (Chapter 3). In contrast, Caip was selected for its isolated situation, with unpaved roads, its location far from the city of Paragominas (70 Km depending on the exact location within the patch), and its high level of deforestation since 1990, 97 km² of accumulated deforestation withing the settlement (total area 320 km²), according to JRC data (Vancutsem et al., 2021). It was also selected for the emergence of women organizations, there, a focus group was exclusively conducted for women.

In Guaviare, the patch of El Unilla located in the municipality of El Retorno was selected for being moderate far (around 50 KM) to the market in the capital, San Jose del Guaviare, its low deforestation since 1990 according to the JRC data (11km²) (Chapter 3). Guacamayas was selected for being closer (about 25 km) to the markets in the capital. Like El Unilla, its deforestation has been low since 1990, according to the JRC data (9km²) (Chapter 3). This patch was selected specifically because of the emergence of women's movements, allowing us to conduct a focus group composed exclusively of women.

In all cases, patches selection was also determined by the willingness and motivation of smallholder farmers' associations to participate to the study, and feasibility of organizing focus groups (logistic and security concerns).

4.2.2 Futures triangle

We used the Futures Triangle method (Inayatullah, 2008, 2023) as a straightforward foresight tool to map different visions on the future. This exploration of futures is done considering different past and present forces that affect the future. The fundamental principle of the method emphasizes that the future is not fixed but the result of the interplay of three main forces:

- (i) The “pull” of the future that represents visions of the future that pull on the present. These can be driven by images of evolution towards progress but can also be negative images.
- (ii) The “push” of the present, that corresponds to ongoing trends driving futures. This force influences the directions in which the futures unfold.

- (iii) The “weight” of the past are structures, barriers or obstacles that constrain change, e.g., institutional inertia. This force binds to old patterns that hinder the design of a different future.

This foresight tool has been used to conceptualize transitions towards desired futures. For example Blundo-Canto et al. (2024), used the futures triangle to analyze the potential crop diversification of abandoned banana plots. They identified weights from the past, such as markets that do not value diversified products other than banana exports crops; pushes from the present, such as young farmers who aim to develop diversified production systems; and pulls from the future such as increased land pressure and climate change affecting arable land. This method has also been used in a participatory approach to analyze groundwater governance in Aousja Ghar El Melh in Tunisia, where the tool was adapted to identify tensions and contradictions between the past, the present and the future, facilitating the identification of possible actions to achieve the desired future (Hassenforder et al., 2024). The authors also integrated into the method the identification of tensions, specifically identifying conflicts between weights of the past and pulls of the present, to identify levers of action.

In this study we specifically used the triangle to explore the plausible futures of farms, we define plausible futures according to its internal coherence and logical connection with reality (Jahel et al., 2023). We explored ideal farms in 2034 as “pull” of the future. The "push" of the present represents ongoing dynamics that facilitate farmers’ progress toward this ideal vision. The "weight" of the past represents barriers or resistance that hinder this progress, including deeply embedded cultural practices and influential social organizations committed to maintaining the status quo. Like Hassenforder et al. (2024), our study examines tensions and identifies levers of action. We classified the tensions into three categories: nearly resolved tensions, partially resolved tensions, and unresolved tensions, where there are no current pushes to counterbalance the weights of the past, according to the farmers.

During each session, a triangle that represented the pull, push, and weight was placed on the wall or on a paper board to support the discussion, figure 4.3 summarizes the five steps of the method.

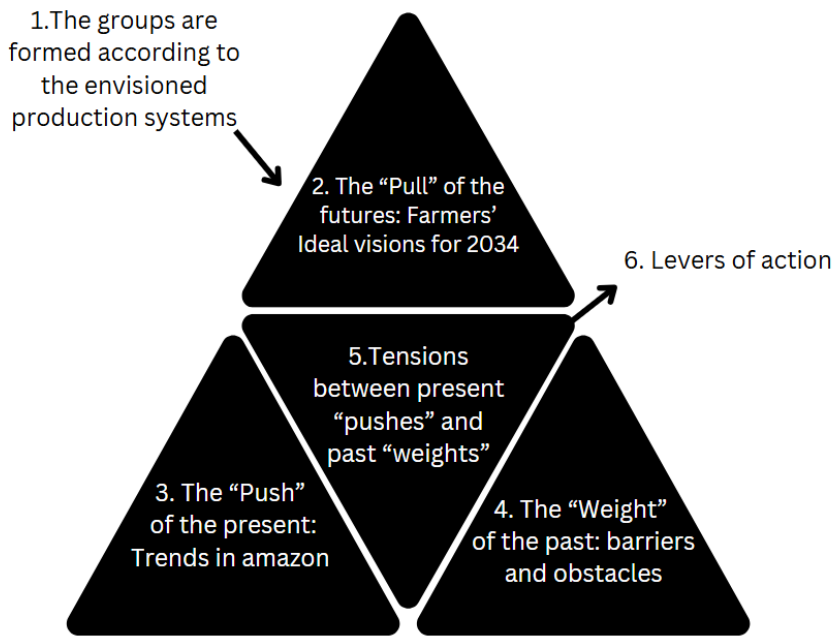

Figure 4.3 Futures triangle steps adapted from (Inayatulla, 2008)

During the first step, participants were asked about the production systems they envisioned for their farm by 2034. Afterward, groups were formed based on the similarities in their responses. If a focus group revealed that all participants wanted the same production system (e.g., all farmers want to implement agroforestry), the group was divided into smaller subgroups of 4-5 people to foster more interactive discussions and ensure everyone had the opportunity to contribute.

The second step focused on the "pull of the future." The participants in sub-groups were asked, "What would be the ideal future of your farm in the context of this patch in 2034?" They then draw a map of their ideal farm, including the percentage of the total area dedicated to production systems and forest. This was done to enable farmers to visualize their productive space areas in percentage, integrating different production systems (crops, pastures, livestock, etc.) and forest conservation, allowing the capture of information between agricultural production and forest conservation. Since the ideal farm was co-constructed between farmers within each group, they referred to area percentages, as farm sizes varied among them. Additionally, the farmers were asked who would work on the ideal farm (including family and external workers) to understand the family work configuration. Questions about gender were also raised, what will the woman work on in this ideal farm, and what about the man? What past barriers or present trends are related to women, and which ones to men? Then, each group named their ideal farm and placed it at the top of the triangle, explaining the details to the rest of the group in plenary.

The third step focused on the push of the present. The farmers were asked in the same sub-groups, "What trends are currently shaping the future of farms in the community (patch) and/or region? What present factors are helping you achieve your ideal farm?" Each group discussed these questions internally, listed the most relevant pushes on posters, and then explained them to the plenary. Then, these "pushes of the present" were placed in the bottom left corner of the triangle in plenary and regrouped based on their similarities (e.g., training in pasture rotation, training in forage cultivation for cattle feeding).

The fourth step focused on the weight of the past. The plenary was asked: "What are the barriers preventing you from reaching your ideal farm? What has held you back from advancing toward that ideal farm until today? What are the deep structures that resist change?" As with the push of the present, each ideal farm group discussed these questions internally, listed the most relevant "weights of the past" on posters, and then explained them to the plenary. The "weights of the past" were placed in the bottom right corner of the triangle and regrouped based on their similarities (e.g., lack of tractors, lack of machinery for land cultivation).

After listing the main pushes of the present and weights of the past, the fifth step focused on the tensions. This step involved confronting the weights of the past to the pushes of the present. The focus group facilitator took a weight of the past and asked the farmers if any of the listed pushes of the present were counteracting that weight. In some cases, farmers mentioned other pushes of the present that had not initially been listed. The same exercise was repeated for each weight of the past.

Once listed the tensions, they were classified into three categories:

1. Nearly resolved tensions: These tensions corresponded to pushes of the present that have a greater effect than the weights of the past. Farmers expressed that they were on the right track to resolving these tensions. Nearly resolved tensions capture ongoing positive dynamics towards achieving their ideal farms.
2. Partially resolved tensions: These are tensions where the weight of the past had a greater effect than the push of the present, according to the farmers.
3. Unresolved tensions: In this case, there was no present push to counteract weights of the past.

Finally, for unresolved tensions, farmers were asked to propose a lever that could counteract the weight. The question raised was: "What action can you take regarding unresolved tension X to progress towards your ideal farm?". The identification of levers gives us the opportunity to discuss the farmers' perceptions on their room for maneuver. It also shed light on the feasibility of the proposed solutions and gave insights into the strategies farmers perceive as most viable for addressing their own and collective challenges.

4.2.3 Focus group organization

We conducted four focus groups, two in Paragominas and two in Guaviare, including one exclusively for women in each territory. The women's focus groups were held to make them feel at ease, allowing them to express themselves freely, away from men's influence or judgment, on topics such as weights from the past that may incur discussion of gender inequities or women's specific challenges. These women's focus groups also aimed to capture perspectives on women-specific visions of the ideal farm that might be diluted in mixed focus groups (Valerio et al., 2024).

The focus groups not only make it possible to interweave individual and collective knowledge, experiences and desires (Gundumogula, 2020), but also make visible the contributions of women in agriculture and inequities they undergone. In addition, women specific focus groups facilitate the questioning of dominant assumptions and generate spaces for debate and reflection on gender issues in the context of farming in the Amazon (Pini, 2002).

In Guaviare, NGO National Forestry Office Andina (ONF according to French acronym) played an important role in linking with these smallholder associations, while in Paragominas, the forum of the Paragominas rural communities (local coordination of Paragominas' settlements), supported the organization and logistics.

Each association leader was asked to invite farmers representing the diversity of agricultural production systems within a given patch. Table 4.1 presents the composition of the focus groups.

Table 4.1 Focus group characteristics

Study Site	Study case sites	Total	men	women	Main production systems	Main area (ha)	Average age
Paragominas	Potirita	23	12	11	Livestock and casava (18 farms), acaí with cocoa and fish farming (6 farms)	15 Median (22-120)	51
	Caip	17	-	17	Cassava crops and livestock (14 farms) and açai and vegetable garden (3 farms)	25 for all participants	43
Guaviare	Unilla (figure 4.4)	17	9	8	Dual purpose livestock (15 farms) and peach palm and cocoa (2 farms)	54 Median (4-130)	50
	Guacamayas	19	-	15 + 4 children*	Dual purpose livestock (for all 15) and peach palm (for 5 of them)	38 Median (12-60)	42

*Children of the 15 women between 13 to 15 years of age

Figure 4.4 Pull of the present using the triangle of the future in Unilla Guaviare

The focus groups were facilitated in Guaviare by the main author and the NGO ONF Andina, with three facilitators per focus group. In Paragominas, the focus groups were facilitated by two people, the main author and a local expert in rural law. The facilitation team oversaw the collection of information, note taking, while one facilitator was responsible for one of the steps of the methodology.

4.2.4 Data analysis

For each focus group, we merged the ideal farms proposed by each subgroup into a single category based on the similarities in their production systems (e.g. ideal farms rotational grazing of cattle + agroforestry systems but with different percentages of land use was classified in the same category). Next, using the merged visions from each focus group, we classified these visions into types according to their envisioned production systems. Then, we analyzed the invariants and variants across focus groups for the pushes, weights, tensions and levers. We classified the pushes, weights and tensions (partially resolved and unresolved) that were common across the two study sites or specific to each territory or patch.

4.3 Results

4.3.1 Ideal farms visions in the Amazon

During the focus groups, fourteen ideal farm visions emerged from the subgroups, details regarding their productions systems, land use and work group configuration can be found in Annex C, Supplementary table 1 and 2. The merging of ideal farms from the subgroups resulted in eight ideal farms (Paragominas: 2 visions for Potirita, 1 vision for Caip; Guaviare: 2 visions for Unilla, 3 visions for Guacamayas). Merged Ideal farms were then classified into five types based on the specific productions systems envisioned by farmers (table 4.2).

In Paragominas, two types of ideal farms were found. In one type, participants tended to envision a combination of cattle production based on rotational grazing systems and agroforestry systems (combining fruits such as açaí (*Euterpe oleracea*), banana (*Musa spp*.), (*Musa spp*.), cocoa (*Theobroma cacao*), copuaçu (*Theobroma grandiflorum*), orange (*Citrus sinensis*), peach-palm (*Bactris gasipaes*), lemon (*Citrus limon*), Soursop (*Annona muricata*), and wood species such as, andiroba (*Carapa guianensis*), magno (*Magnolia spp*.), ipê (*Tabebuia spp*.) (6 subgroups). The other type derived from a single subgroup (in the Potirita patch); participants envisioned an ideal farm with agroforestry only. This highlights farmers' aim to diversify their production systems.

In Guaviare, three types of ideal farms were found. One type is based on silvopastoral systems for meat only or dual-purpose (meat and milk production) as known locally (3 subgroups). Another type combines cattle production based on silvopastoral systems with agroforestry systems of palm-peach (3 subgroups), and the last type combines silvopastoral systems with agroforestry and agrotourism (1 subgroup). This highlights an emphasis on silvopastoral systems in Guaviare. Indeed, cattle production was central in all ideal farms except in one case observed in Potirita.

In the ideal farms proposed across focus groups, the forest is preserved. However, its proportion varied, accounting for only 5% of the envisioned farm area in some cases, while reaching up to 50% in others. Ideal farms based on agroforestry tended to preserve a bigger percentage of forest (except in Unilla).

The vision of the work group configuration was based on the couple and their children. However, farmers expressed uncertainty about whether their children would remain on the farm. They also mentioned the possibility of hiring day workers. In the women's focus groups, participants emphasized that they would take over the farm management, would specialize in finances and share the farm work with their husband.

Table 4.2 Ideal farm visions for 2034 in the four patches

Types of Ideal farm per production system	Paragominas merged visions of ideal farms	Guaviare merged visions of ideal farms
• Rotational Grazing of cattle + Agroforestry System	• Pot_RG_AFS (merged from 2 subgroups, A and C) • Caip_RG_AFS (merged from 4 subgroups, D, E, F and G)	
• Agroforestry System	• Pot_AFS (only 1 subgroup B)	
• Silvopastoral System		• Uni_SPS (merged from 2 subgroups, H and I) • Guaca_SPS (only 1 subgroup L)
• Silvopastoral System+ Agroforestry System		• Uni_SPS_AFS (only 1 subgroup J) • Guaca_SPS_AFS (merged from 2 subgroups, M and N)
• Silvopastoral System+ Agroforestry System + Agrotourism		• Guaca_SPS_TOUR (only 1 subgroup K)

Pot: Potirita, Uni: Unilla, Guaca: Guacamayas, RG: Rotational grazing of cattle, AFS: Agroforestry system, SPS: Silvopastoral system, TOUR: Agroecotourism. Details about the sub groups visions of ideal farms, including their ID (A, B, C, etc.), can be found in Annex C, Supplementary Table 1 and Table 2.

4.3.2 Between pushes and weights in Amazon, a transversal and specific lecture

Table 4.3 summarizes the results on pushes and weights across the four focus groups. Farmers mentioned the support of different actors such as NGO’s and public extension services through training in agroforestry systems, rotational grazing or Silvopastoral systems as pushes of the present. In Paragominas this support was mainly from the National Rural Learning Service (SENAR) and the Amazon Institute of People and the Environment (IMAZON) and in Guaviare the support was mainly from the Research Institute of the Colombian Amazon (Sinchi) and ONF-Andina. According to farmers, their association plays a crucial role in resource mobilization, both from government projects and those related to international cooperation, which are typically executed by NGO's.

Table 4.3 Key pushes and weights in the Amazon and specific patches

	Transversal	Potirita	Caip	Unilla	Guacamayas
Pushes	• Farm structure and new practices in Silvopastoral systems and rotational grazing of cattle • Knowledge and experience in rotational gracing of cattle and management of crops • NGO's and research centers support and in training for Silvopastoral and agroforestry systems • Experience gained in their farm trajectories • Government support with roads and electricity • Farmer Associations	• no-fire *roça* pact • Technical assistance and in cocoa by municipal government • Strong organization for land regularization	• Women managing the farm • PNAE (Federal policy) help to develop market of vegetable garden • Women in Associations	• Environmental Conservation • Commercial alliances in milk • Peace agreement Post conflict • Rotational fonds (Caminemos and *Terramaz*)	• Environmental Conservation • commercial alliances with companies that collect and purchase the milk • Peace agreement and Post conflict • Funds for rotational grazing (Caminemos and *Terramaz*) • Training for Sinchi and GEF Amazonia in peach palm fertilization • Women on cattle markets • National federation of peach-palm (FENACHO) open markets • Association in Agroecotourism
Weights	• Lack of knowledge and technical assistance • Roads in bad conditions • Lack of land title • Poor health and electricity services • Credit access • Climate change	• neighborhood Externalities (e.g. pesticide contamination, land acquisition pressure) • Political representation • Lack of technical assistance for seedling maintenance (cocoa, açai) • Lack of transportation to the market • Pressure to sell the land • Pest in cocoa crops	• neighborhood Externalities • Political representation • Women Credit and health access • Lack of support for women-only initiatives • Workforce is scarce • Associations for men and are not organized • Schools are being closed • Lack of market for crops	• Lack of farm vision • Market access • Armed conflict • Soil Quality degraded by coca glyphosate fumigation • Lack of farm workforce • Lack of machinery • Unclear about what type of cattle genetics they are looking for • Investment loss risk	• Lack of farm vision • Market access • Armed conflict • Soil Quality degraded by coca glyphosate fumigation • Lack of farm force workforce • Lack of machinery, tractors and peach palm transformation • overlapping indigenous land • Heavier workload for women • Women lack of confidence

In Paragominas and Guaviare, participants mentioned pushes of the present such as infrastructure and experience they have acquired along their farm trajectories, e.g., improvements in paddock divisions, rotational grazing practices, installation of elevated tanks filled by rainwater to improve water allocation and availability for cattle, and the establishment fodder banks for cattle. They also mentioned the experience gained through their farm trajectories in cattle and diary production.

Regarding Paragominas, in Potirita, participants mainly mentioned pushes of the present like associations and government assistance, particularly rural extension for cocoa crops. These include technical assistance on cocoa provided by the municipal government, and the strength of the associations to collectively enhance access to land titles.

In Guaviare Institutions such as the Corporation for the sustainable development of the northern and eastern Amazon (CDA) and the Sinchi were mentioned as a push of the present for the important role they play in the conservation of forests. Participants identified the peace agreement between the Colombian government and the Revolutionary Armed Forces of Colombia-People's Army (FARC-EP) as a push from the present. Additionally, participants mentioned, rotational fonds from Caminemos and Terramaz projects, that are focused on the promotion of sustainable agricultural practices and the conservation of the natural environment, especially forests. These funds consist of self-managed and associative microcredit systems that allow local communities to access financing to improve their productive practices and quality of life.

In Unilla, pushes of the present included rotational financial funds from development projects (that correspond to a collective share of the credit more accessible than credit from bank) and financial education provided by the National Training Service (SENA), while in Guacamayas they mentioned the opening of markets for peach palm and training in its cultivation stand out.

Regarding weights of the past, farmers across sites mentioned the low capacity of the government in delivering services such as road maintenance or health services. Land titling was also identified by farmers, and this issue emerged in relation to the lack of access to credit. Climate change was also mentioned in both study sites, heavy droughts and rains have already affected the farms specifically açai crops and affected the pasture for the cattle. They mention that water stress has been increasing since the last decade.

In Potirita, the past weights mentioned by farmers highlighted challenges at both the plot and territorial levels. Farmers mentioned issues such as pests, lack of technical support, and limited market access. Despite the proximity of these farms to the Paragominas city market, participants expressed that they have limited access for transporting their products to the market city. External pressures from agribusinesses for small landowners to sell their land was also a major weight in the past.

In Guaviare, farmers mentioned past weights related to the armed conflict and the coca production, which prevented them from having a vision of an ideal farm in the future. In Unilla specifically, weights were related to their risk aversion to credits. They also mentioned a lack of knowledge on the genetics performances of the livestock that they wanted to adopt. In Guacamayas, farmers more specifically mentioned past weights related to gender, such as a heavier workload, but also technical topics associated with transformation and peach palm cultivation. The details of the pushes and weights for each focus group are provided in Annex C, Supplementary Tables 3, 4, 5, and 6.

4.3.3 Main tensions in the Amazon, levers and patch specific trends

The tensions shared by smallholder farmers across the four patches, along with their respective identified levers, are presented in Table 4.4. This table focuses on the weights of the tension, as the pushes vary across the patches. Detailed tensions for each focus group can be found in Annex C (Supplementary Tables 7, 8, 9, and 10). Across the sites, road conditions, access to credit, and land ownership were recurrent weights of the tension over time.

Roads, often maintained by farmers' association with the support of the government, continue to constraint market access, especially during winter, rainy, months. Additionally, public policies have been implemented to address past weights, such as access to credits in Paragominas with the National Program for the Reinforcement of Family Farming (PRONAF) and in Guaviare with Fund for the financing of the agricultural and livestock sector (FINAGRO). Participants mentioned that they are in a vicious circle when the lack of access to land property, in most cases, blocks access to credit. Land titling was a common tension identified across focus groups, with bureaucratic processes and high costs, along with a complex situation in which some farmers are located in indigenous protected areas.

Moreover, tensions such as lack of credibility in governmental institutions were commonly identified, although in Paragominas the farmers have a more proactive position in terms of political representation in local institutions, in Guaviare there is a persistent dissatisfaction with policies such as the PNIS that did not comply with the agreed payments for the substitution of illicit crops.

The lack of workforce was commonly identified, affecting manly participants who want to adopt agroforestry systems. Farmers reported that an increasing number of young people are leaving for the cities due to a lack of interest in rural work, depending on to two main factors: the strenuousness of the work and the low wages (in case of dairy workers or employees) or low incomes. According to women farmers from CAIP and Unilla, this issue is also compounded by the lack of opportunities in education for children in rural areas, forcing them to move to cities (or send them there). The armed conflict adds another layer of complexity the rural employment in Guaviare. Farmers explained that they face a dual dilemma: sending their children to the cities to prevent them from being recruited by armed groups, or training them on agricultural practices, given the lack of interest of young people for agriculture. In both cases, the future of the farm is not guaranteed.

Gender inequality was a tension identified across the focus groups but particularly discussed by women of Paragominas: disparities associations governance, in access to health, and in access to support from government. Women felt that the credit institutions perceive them as less trustworthy since by habit they see women as less qualified to lead agricultural projects. They also mentioned that women do not usually have their own bank account or financial autonomy, except single women head of their farm. However, they have noticed some improvements with the nomination of women at the head of some rural associations, the forum of the rural settlements of Paragominas, CONTAG (National Confederation of Agricultural Workers) and FETAEG (Federation of Agricultural Workers). In Guaviare, gender tensions emerge on the farm scale, such as higher workloads or lack of confidence for the farm management. In general, women farmers affirmed that they were still underrepresented in these leadership positions.

In addition, farmers in all patches highlighted specific barriers to the implementation of agroforestry systems, such as the lack of irrigation infrastructure, limited access to technical knowledge and the absence of adequate machinery to add value to crops such as peach-palm.

Table 4.4 Transversal tensions for smallholders in the four patches

Shared tensions (weight of the tension)	Paragominas (Potirita and Caip)	Guaviare (Unilla and Guacamayas)	Levers
Markets barriers	Poor roads infrastructure, mainly in CAIP. Transportation to reach markets in Potirita.	Poor roads infrastructure. saturation and volatility of prices on Peach palm.	Associations
Land titles	Lack of land title constrains investment in sustainable agricultural practices, especially in Potirita.	Lack of land title does not allow farmers project themselves, special attention to overlapping claims with Indigenous reserves in Guacamayas (*Naranjales*)	
Credit access	Farmer's report having no access to credit, and even women report having less information about credits.	Farmers claim they do not have access to credit particularly in Unilla, and rotating credits founds do not reach all farmers. Women have worse access to credit.	
Institutional distrust	Limited political representation of family farming in territorial planning, accompanied by weak support from the municipal government in family farming.	Farmers distrust government institutions due to non-compliance with policies such as the PNIS.	
Workforce availability	Manly in Caip, lack of initiatives to attract young people to stay.	Lack of initiatives to encourage young people to stay, resulting in a persistent farm workforce scarcity, exacerbated by competition from coca harvesting related work.	
Rural Gender inequalities	Lack of space in associations for women, access to health care is more complicated, lack of support for women's initiatives.	Heavier workload for women farmers (family, farm, house), lack of confidence in leading farming projects. Women have faced greater hardship due to the assassination of their husbands and the recruitment of their children into armed groups.	
Technical Agroforestry challenges	Pest control of cocoa, lack of irrigation infrastructure, limited knowledge on agroforestry practices.	Uncertainty about profitability of agroforestry investments and lack of training, Lack of machinery for peach palm transformation.	
Climate change	Unstable climatic conditions affect agroforestry productivity, droughts and rainfalls	Heavy rains cause pasture degradation and flooding	Preserve forest areas within farms

For most of these tensions, the levers of action proposed by farmers rely on their associations. Among these levers, a key mentioned strategy was the creation of negotiation tables with government institutions, particularly in Guaviare, to strengthen trust in the government. In addition, farmers highlighted the need to negotiate with credit institutions and strengthen associations to collectively advocate for land titling. Another initiative highlighted was the development of attractive agricultural training programs for young people through associations, encouraging them to remain in rural areas. Associations were also mentioned as playing a crucial role in securing financing for acquiring machinery, such as tractors and peach palm processing equipment. In Unilla, farmers proposed to create a "green label" through the association that would certify the sustainability of livestock production to improve their access to markets.

Regarding gender inequalities, the proposed levers included creating associations exclusively for women or strengthening leadership positions within existing associations. A key difference between the two territories was the rural organization that is emerging in Paragominas, which is being driven by Rural settlements Forum (*Fórum das comunidades rurais de Paragominas*). This forum was frequently mentioned as the central platform for implementing levers for action, providing a space for negotiation, advocacy and collective decision-making among farmers. In contrast, rural organizing in Guaviare still depends on local associations, which play a crucial role in addressing tensions, but lack a broader social coordination at the departmental level.

Specific tensions were also identified (table 4.5). Among these tensions, the armed conflict in Guaviare emerged as one of the most challenging for farmers. Indeed, the conflict has affected them in multiple ways. They were caught in the middle of a war between the Colombian government and the FARC guerrillas, which has led to highly unstable and uncertain living environment. Farmers reported that coca was the only possible production before the peace agreement. The conflict violence caused the forced displacement of many families, both within and outside the department. Forced displacement and the incursion of illicit crops have generated a lack of vision for smallholder's future farm. In addition to kind of "taxes" they had to pay to the guerrillas, women have been the most affected, as many of them have been widowed, worsening their capacity to reach their ideal farm. Due to the sensitive subject, participants did not want to share details. But they agreed that the situation has improved after the signing in 2016 of the peace agreement between the government and the FARC-EP. However, participants expressed that uncertainty still prevails and that they continue to feel pressure regarding this issue

In Paragominas, a specific tension comes from the coexistence with agribusiness. In particular, the Potirita focus group reported strong pressure from agribusiness farmers on smallholders to sell their land. In both Potirita and Caip, farmers also reported being affected by agribusiness farmers using pesticides at large scale, with Potirita being the most affected. To face this issue, women farmers in CAIP proposed to collect in their land damage evidence done by neighbor pesticides application and then raise awareness among the community to take adaptive actions (example of tree barriers). Potirita farmers proposed to negotiate with the environmental authorities to control and fine those who dump pesticides into their farms.

Table 4.5 Specific Tension for smallholders in the four patches

Specific tensions	**Potirita**	**Caip**	**Unilla**	**Guacamayas**
Armed and coca market	N/A	N/A	Lack of farm vision,soil degradation from glyphosate spraying used to eradicate coca crops	Lack of farm vision,soil degradation from glyphosate spraying used to eradicate coca crops
Co-exitance with agribusiness	Pressure to sell the land and pesticide issues from agribusiness	Pesticide issues from agribusiness	N/A	N/A

Improvement has been documented in both Potirita and Caip regarding specific tensions stand out, such as access to knowledge and experience in rotational grazing practices promoted by CIRAD within the TerrAmaz project, as well as the management of agroforestry systems (AFS) facilitated through courses by IMAZON and SENAR. Farmers in both areas emphasized that the exchange of knowledge among themselves has been crucial for scaling these practices at settlement level. A similar trend was observed in Guaviare, but with a focus on the implementation of silvopastoral systems. In both Unilla and Guacamayas, farmers reported that they had actively implemented silvopastoral systems, starting with farm infrastructure (paddock divisions, fodder banks, and trees planting) and that they had been trained in rotational grazing practices. Their changes have been supported mainly by ONF Andina. The consolidation in agroforestry systems was supported by SINCHI, more specifically.

These results provide evidence on the fact that ideal farms oriented toward cattle breeding with rotational grazing and silvopastoral systems face fewer tensions compared with those more diversified ideal farms that incur on agroforestry or agroecotourism. Farmers pursuing cattle-based systems report fewer barriers related to workforce scarcity, technical knowledge and market uncertainty. These results also show that women farmers face even more tensions to tend to agroforestry in their ideal farms, as agroforestry require higher workforce demand, while women already report heavier workloads and gender inequalities.

4.4 Discussion

4.4.1 Which ideal farms in the two amazon pioneer fronts

Most of the visions in Paragominas are based on a combination of cattle breeding with rotational grazing and agroforestry systems where rotation grazing systems for cattle breeding remains dominant. In Guaviare, silvopastoral systems (SPS) is the dominant transversal production system.

Both in Paragominas and Guaviare, farmers' ideal farm visions are largely grounded in local past trajectories founded in patches (Chapter3). Indeed, in Potirita, smallholder farm trajectories include agroforestry and rapid shift to rotational grazing. These past trajectories may explain why in the future, farmers mostly envision combining agroforestry and rotational grazing, while few envision exclusive agroforestry. In Caip, smallholder past trajectories showed more diversity, including agroforestry, rapid shift to rotational grazing for cattle, stagnant cattle production and progressive intensification of rotational grazing for cattle. These past trajectories are reflected in the visions of ideal farms of this patch, where a combination of rotational cattle grazing and agroforestry systems are preferred.

In Guaviare, the ideal farm visions of developing silvopastoral systems for milk and meat production were due to the existence of past trajectories based on cattle production (progressive intensification with rotational grazing, steady cattle trajectory and rapid shift to rotational grazing). Some visions also included agroforestry that was in the case of Guacamayas due to existing trajectories but quite new for farmers in the case of Unilla. In this last case it has been proposed by women.

The most innovative vision observed was the GuacaSPS_AFS_TOUR farm (see table Annex C Supplementary table 2 ideal farm K- *Tierra bella*), which integrates silvopastoral systems, agroforestry, and agroecotourism. This vision may be influenced by the proximity of Guacamayas to the department capital and the increase of ecotourism since the signing of the peace agreement (García Muñoz, 2019).

Past trajectories described in the different patches influence these ideal visions farms and are influenced by external factors like development initiatives and governmental public policies that play an important role. For instance, in Guaviare, the "*Caminemos Territorios Sostenibles*" project has promoted silvopastoral systems and consequently ideal farms visions. Similarly, the Peach-palm production policy in Guaviare has raised interest in agroforestry systems (Orozco, 2022), even in patches without an established agroforestry trajectory, such as the case of Uni_SPS_AFS. In Paragominas, intensification projects for rotational grazing of cattle led by The French Agricultural Research Centre for International Development (CIRAD) within the Terramaz project have promoted farmers' visions toward combining cattle grazing with agroforestry. However, it is important to highlight that the rotational grazing for cattle was initially promoted by Brazilian Agricultural Research Corporation (Embrapa) in Paragominas during the 2010s, although it was focused in large properties as part of the "*pecuária verde*" project, which aimed to integrate economic profitability with improved animal and worker welfare and environmental sustainability (Silva, 2014).

This suggests a cycle in the construction of the ideal farm, which is based on local past trajectories, i.e., largely on what farmers observe in their own patches, but also at the departmental or municipal level. In turn, these trajectories are influenced by the effects of development projects and public policies, which feedback and stabilize these trajectories in the patches, thus influencing the vision of a larger number of farmers.

4.4.2 Visions by Women or by Men smallholders

Women may exhibit a stronger inclination toward diversification strategies that go beyond usual farm practices. The emergence of agro-ecotourism in the Guacamayas patch, exclusively within a women's focus group, underscores this tendency. Such a vision integrates silvopastoral systems, agroforestry, and tourism, reflecting a holistic approach to land use and income generation that resonates with women farmers' aspirations. This result could be attributed to the specific challenges women face in agriculture, such as lower access to resources, greater workload burdens, and the necessity to develop alternative livelihoods (Adefare et al., 2024; Mello & Schmink, 2017; Quisumbing & Pandolfelli, 2010). Women's focus on diversification may also stem from their distinct role in household management, where they prioritize sustainable and resilient farming systems to ensure food security and family well-being (Centrone et al., 2018).

Another notable differentiated trend is that more women express a preference for integrating agroforestry into their farms. This was particularly evident in the focus group exclusively made-up of women in CAIP, where all participants expressed a desire to incorporate an agroforestry system in their ideal farms. Similarly, in the women focus group of Guacamayas, 13 out of 17 participants confirmed their interest in including agroforestry on their farms. Additionally, in Unilla the group that proposed agroforestry was made-up of two women. However, the gender gap in the adoption of agroforestry systems, particularly concerning access to education, credit, and land, may hinder its implementation (Gonçalves et al., 2021; Kiptot & Franzel, 2012)

While men in Potirita also emphasized their interest in agroforestry, this inclination may be more closely tied to the specific characteristics of this Patch, including better road infrastructure, closer markets, and strong local government support for cacao production. This suggests that the desire for agroforestry among farmers in Potirita could be influenced by the existing conditions that make its implementation more feasible. Public policies play a key role in this feasibility; for example, the literature shows that the National School Feeding Program (PNAE) has facilitated the adaptation of agroforestry systems in Paragominas (Resque et al., 2019), combined with farmers' willingness to adopt such systems.

4.4.3 What are the levers farms pathways?

In the Amazonian study sites, collective action and co-creation of knowledge in farm pathways seems crucial. This is reflected in the proposed levers, most of them based on collective actions of associations. These include negotiation with public institutions, for land titling, adaptation of public policies or negotiation with credit institutions. However, these issues do not only depend on farmers but also in the capacity and willingness of public institutions (Campbell, 2015; Garrett et al., 2017; Moreira-Dantas et al., 2023).

Associations also play a catalyst role for funding (e.g. tractor machinery, cattle genetic experts and biologist studies to control pests) in part by leveraging project resources. These levers have their own challenges, such as the collective management within association, which requires investment in capacity building for effective governance. Additionally, rural extension is needed to promote sustainable practices, along with the support and monitoring of government entities to minimize risks such as the unintentional deforestation in the scaling up of silvopastoral systems (Castro-Nunez et al., 2021; Fonseca Morello, 2022).

Levers for action also rely on association partnership with institutions that provide agricultural training (e.g SENAR, SENA), essentially on topics such as pest control, cocoa management, and attractive programs for young people. Co-creation of knowledge based on multi-stakeholder collaborations is thus required in order to enhance sustainable practices and their essential dissemination among farmers (Futemma et al., 2020). Gender-focused levers that address inequalities in the two study sites, aiming to improve access to credit, work overload and confidence. Empowering women through women-exclusive microenterprises or cooperatives can improve their decision-Making Power and sustainability in land use (Mello & Schmink, 2017).

In summary, levers addressed three dimensions, i) the conditional levers (e.g., land title negotiation) that depend on external institutional support or external funding, limiting their immediate actionability by farmers, ii) the organizational levers, both Guaviare and Paragominas where the challenge is in organizing associations and creating collective strategies, hindering the implementation of the levers (e.g. financing a biologist to control pests in CAIP), iii) the levers addressing gender inequalities, these levers face patriarchal structures that limit access to resources for women, hindering their emancipation.

4.4.4 Which pathways in the studied Amazon pioneer fronts?

A farm pathway, is the route to reach desired goals(Pearson & Dare, 2021), in this study referring to ideal farms. It depends on coordination of diverse actors, including NGOs, farmers associations and governmental institutions. Making this coordination effective and these pathways feasible rely on three dimensions:

- Capacity building, co-creation of knowledge and dissemination:

Strengthening access to technical training and support on silvopastoral systems, rotational grazing of cattle, as well as on agroforestry is the first step valuing the knowledge already acquired by farmers in their farm trajectories and involving them in the co-creation of knowledge on these systems (Cartagena et al., 2025). This co-creation of knowledge should be more specifically tackle the integration of these various systems, identifying how to favor synergies and to articulate silvopastoral systems/ rotational grazing, and agroforestry, emphasizing their economic, social and ecologic benefits (Costa et al., 2024; Domiciano et al., 2020; Nahed-Toral et al., 2013). Mechanisms for exchange of this knowledge among farmers need to rely on existing associations.

- Market and strategies for added value

Access to market allowing to differentiate social and environmental products values has been shown to be key for sustainable pathways (Stringer et al., 2020). In Paragominas, cocoa and açaí production emerged as important value chains to be strengthened, so as peach palm in Guaviare. Strategies such as certification through participatory guaranteed systems to differentiate agroforestry and livestock products, developing sustainable market niches, could improve economic returns while maintaining farm sustainability (Clavijo Ponce, 2024; Grovermann et al., 2024). Additionally, cooperative schemes can play a vital role in overcoming transport and storage tensions. Existing initiatives in Paragominas, such as Cooperuraim (Alves dos Reis & Farias, 2022), could be strengthened to reach a municipal scale, as is the case of the Mixed Agricultural Cooperative of Tomé-Açu, that is an emblematic example of organization and value added in the Amazon (Abramovay et al., 2021).

- Institutional coordination and gender inclusive pathways

Various studies already highlighted the deficiencies in the infrastructure of the Amazon region coupled with limited access to technical, financial services and land titling, requiring equitable development policies among the different types of farmers (Porro et al., 2012). We showed the importance of the inclusion of gender in the development of these pathways, which has been scarcely studied (Hodel, 2023; Vega-Martinez et al., 2024). The pathways require coordination and institutional commitment between governmental institutions, farmers associations and NGOs to develop gender sensitive policies on access to credit, land titling and market integration. Policies such as PRONAF for Women in Brazil should be reinforced (Moreira-Dantas et al., 2023) or as in China, land tenure policies focused on women (Han et al., 2019) can empower women to both benefit from and contribute to these pathways. This is essential in the Amazonian regions, but particularly in the Guaviare where the history of the conflict has left deep scars, with women farmers being among the most affected (Sinclair et al., 2022).

4.4.5 Strengths and limits of the triangle of the future foresight method

Although anticipation studies have been conducted in Paragominas, most have focused on future land-use scenarios (Osis et al., 2019; Pinillos, 2021). Piraux et al. (2020) also carried out a participatory foresight analysis with smallholder farmers, highlighting the importance of empowering them through foresight tools. Anticipation studies have also been conducted in Guaviare, focusing on land-use scenarios (Camacho Peña, 2022) and territorial foresight for public policy formulation (Camarena et al., 2022). However, to our knowledge, no foresight studies in Guaviare have been carried out at the farm scale. Our study is the only one that focused on the farm-scale vision into the foresight process, providing a more detailed and context-specific understanding of productive dynamics over two Amazonian territories and their potential futures.

Using triangle of the futures method encouraged a systemic discussion of futures among the participants. Unlike other anticipation methods such as layered causal analysis that is used to understand complex systems by dividing causes into multiples layers, this method stands out for its simplicity (Inayatullah, 2023). Farmers in the different study sites easily understood the instructions. The step-by-step flow between what is desired (pull), weights from the past and pushes from the present structured the discussion not only on a unique vision of an ideal farm but also considering other alternative visions in the same patch. One of its main contributions is to collectively explore futures of farms, encouraging a proactive stance by farmers to take charge of their pathways towards their ideal farms (Piraux et al., 2020), using the future to rethink the present.

Conducted in four case studies or patches, this method gave us an overview of various farmers' visions in the Amazon. Its flexibility allowed us to explore plausible futures, in this case ideal farms in terms of the forces that shape it from the past and the present (Inayatullah, 2008). We focused on the tensions that emerge between the confrontation of the weights of the past and the pushes of the present. Identifying these tensions helped capturing ongoing dynamics, dynamics in progress, and inertia from the past. The identification of tensions can guide decision-making and actions in the future (Abdullah, 2023).

The use of the triangle approach helps identifying the plausible different futures in the Patch, however this methodology does not aim to define a structured pathway to reach an ideal farm (Minkkinen et al., 2019). Other authors combined this method with back-casting to define such a pathway (Blundo-Canto et al., 2024). Another limitation is that the focus groups were only carried out with farmers. The integration of key stakeholders in the territory, such as environmental authorities, governments and NGOs, represents an interesting perspective in a foresight exercise. However, this process must ensure spaces for smallholders. Future studies can build on our results, which are based on discussions with smallholder farmers and have facilitated the recognition of their knowledge about on pulls, pushes and tensions affecting Amazonian agriculture.

The future vision of the ideal farm by a group, is beneficial to value collective thinking and explore innovative aspects that farmers would not have explored individually. This avoids fixation effects however a challenge is then to adapt this ideal farm to the specific situation of each farm. In the same way as other future studies methods, the use of the future triangle supports a cognitive process where the coherence between the weights of the past and the thrusts of the future shape plausibility, leaving aside extraordinary futures (Abdullah, 2023).

4.5 Conclusion

This participatory exercise, conducted in two Amazonian territories, Paragominas in Brazil and Guaviare in Colombia, explored with smallholder farmers their ideal farms visions by 2034. Women and men farmers involved in focus groups co-designed their future acknowledging the past, present, and future forces shaping their ideal farms. Our findings indicate that the combination of silvopastoral systems/rotational grazing of cattle and agroforestry are the preferred ideal farm with different ranges of forest reserve (from 5 to 50%). This result highlights the heterogeneity in the importance attributed to the forest. However, for the percentage of forest to grow in the ideal vision and thus in the future of the farms, it is necessary to address this issue through collective actions, adequate support policies and strengthening farmers' capacities. This includes continued technical assistance in agroforestry and silvopastoral systems as alternatives to slash and burn, as well as the development of markets that value sustainable products.

In those future visions, women's see themself as the ones managing their farms. However, the analysis revealed various common tensions across the two territories: land titling, limited credit access, market barriers, gender inequalities, workforce availability, heavy rains and droughts and institutional distrust. Specific territorial tensions such as the armed conflict in Guaviare and the co-existence of agribusiness in Paragominas further complicate the pathways to these ideal farms.

Women specific focus group, highlighted additional barriers faced by women in these territories, such as heavier workloads, worse credit access and have been the most affected by the armed conflict in Guaviare. Women and mend Farmers were able to identify various levers for pathways. These pathways intertwine capacity building, knowledge co-creation, value addition for market access and effective institutional commitments and coordination among stakeholders. These findings point up the urgent need for gender-sensitive pathways for achieving sustainability.

Further prospective research should include stakeholders such as NGOs, government institutions and large landowners, to include contrasting visions and take advantage of synergies at territorial scale. Overall, the transitions towards the combination of silvopastoral systems and agroforestry systems in the Amazon rise a promising pathway balancing environmental and economic benefits, provided that relevant policy frameworks are designed.

Chapter five: General discussion and conclusion

The central objective of the thesis was to answer the following question: To what extent do past farm trajectories enable farmers to envision plausible sustainable farms?

The study was oriented by three hypotheses, i) The integration of retrospective and prospective analyses of farm changes can enable the design of an innovative analytical framework for building sustainable futures ii) in the Amazonian pioneer fronts, farm trajectories affect their current alignment of the farm with agroecological principles iii) In the Amazonian context, ideal visions of farms differ according to gender and shape their plausibility.

To answer this overall question and explore the hypotheses, three main methodological steps were carried out:

- The first step addressed a methodological challenge by proposing an analytical framework based on a systematic review that allows us to analyze the dynamics of change of farms by articulating retrospective and prospective studies (Chapter 2).
- The second step was the empirical application of the retrospective component of the analytical framework, to a diversity of farms in two Amazonian pioneer fronts at different stages, the municipality of Paragominas, Para State in Brazil, representing a consolidated pioneer front and the department of Guaviare in Colombia representing an active pioneer front (Chapter 3).
- The third step focused on the application of the prospective component of the analytical framework; four study patches were selected based on the results of the second step. This was based on gender-differentiated focus groups with smallholder farmers, envisioning the ideal farms in the medium term (2034), considering present forces and past barriers to explore the plausible futures of these farms (Chapter 4).

This last chapter discusses the main contributions, the empirical lessons, and research perspectives of the thesis.

5.1 Going back to the hypotheses and empirical lessons

The thesis articulates farms trajectories analysis with the analysis of agroecological principles, offering an original methodology. It provided a comprehensive assessment of farm sustainability. In addition, the combination of retrospective and prospective methods contributed to understand how past trajectories influence the future of these farms, giving important bases for sustainable pathways in Paragominas and Guaviare but also in other Amazonian pioneering front areas. The integration of farmers' aspirations and the main farm trajectories allows us to identify issues to be addressed in the construction of farm pathways towards sustainability. Among these trajectories, the predominance of cattle in the farms trajectories and, consequently, in the farms visions stands out, suggesting that, in these regions, pathways to sustainability should be based on the transition towards more intensive practices like silvopastoral or rotational grazing for cattle, for cattle production systems. However, the pathways must consider the heterogeneity of the farms trajectories and plausible farms futures to be relevant to farmers, seeking a sustainable future in pioneer front areas, in the Amazon.

The results validated the first hypothesis regarding the design of an innovative analytical framework. Firstly, a few existing studies articulate ex-post and ex-ante analyses of changes of farms, specifically in the Amazonian pioneer fronts. Secondly, the combination of both approaches can support the exploration of sustainable futures.

The global systematic literature review provided a solid and comprehensive basis for identifying methodological and conceptual approaches for farms changes analysis. The strength of my analytical framework lies in its articulation between retrospective and prospective analyses, as well as the inclusion of sustainability using agroecological principles (Wezel et al., 2020). Although literature on agroecology and farm trajectories exists, the few existing studies focus on incremental changes in practices at the plot scale (Bakker et al., 2021; Mawois et al., 2019). They were generally based on the efficiency, substitution and redesign (ESR) framework of Hill and MacRae (1995). In our method we make emphasis on farm scale agroecological principles, However, principles such as fairness/connectivity, land governance and co-creation of knowledge play a key role in the articulation of agricultural production and food system whole dynamics (Gliessman, 2007).

In addition, our approach suggests a gender approach to make visible the underrepresentation of women in agricultural sectors and dynamics (Terrier et al., 2012).

This analytical framework is based on a combination of methods for data collection, including semi-structured interviews to understand individual experiences and knowledge in farm trajectories (Adams, 2015). The assessment of current sustainability is based on agroecological principles, using indicators identified in the agricultural Amazonian literature and scoring these indicators according to the range of responses from semi-structured interviews. Further on, focus groups are employed to support collective intelligence, valuing knowledge exchange in the process of envisioning future farms (Cradock-Henry et al., 2020).

The implementation of the method (in step 2, Chapter 3) highlighted that semi-structured interviews can be more complex and prolonged according to the length of the trajectory, with the result that some interviews exceeded three hours. To overcome this constraint for both the farmer and the interviewer, Moulin et al. (2005) in their methodological guide, proposes that two-person teams make two visits to the farmer, with one person taking notes and the other conducting the interview. Furthermore, it was found that territorial factors of the pioneer fronts, such as the geographic location of the farms, or social conflicts, affect farm trajectories. However, the cross-analysis with the JRC forest cover data turned out to be a significant challenge, given that we do not have the polygons of the farmers' farms to perform a finer analysis. In fact, issues of forest degradation and regeneration were difficult to capture during the semi-structured interviews. Although farmers had an accurate memory of when they cut the forest, they had more difficulty recalling the age of regeneration areas. They hesitated when providing regeneration dates during the recounting of the trajectory by the interviewer at the end of the interview. To address this, farms polygons could be cross referenced with the farmers' narratives.

The application of such methodology in pioneer fronts, where social conflicts still endure, has hindered the ability to capture the whole diversity of trajectories. This happened in Guaviare, where for security reasons it was not possible to work in the municipality of Miraflores, being the municipality with the largest area of 1116 hectares of coca as of 2022 (UNODC, 2023). However, data at the municipal scale show that production systems are based on cassava (700 ha), plantain (600 ha), corn (400 ha) and, to a lesser extent, cocoa (250 ha). In addition, cattle ranching also plays an important role with at least 18,000 animals, according to data from 2020. These elements allow us to consider the existence of trajectories of based on agroforestry, steady cattle, extensive cattle, cattle intensification through silvopastoral systems, the latter driven by Sinchi, following similar trajectory dynamics as in the rest of the department (Jimenez, 2017).

An important learning from the application of gender-differentiated focus groups (step 3, Chapter 4) was on the discrepancy between women discourse and their actual role in the farm: on the attendance form, where the profession was to be specified, all the women wrote “housemaker”. However, during the discussions, women said that they worked equally or more than men on their farms. This denotes a discrepancy between the dominant and normative discourses and the reality of women farmers that is happening not only in pioneer fronts but also worldwide (Galiè et al., 2013). Furthermore, the participation of each farmer and especially of women, is of major contribution to the sustainability of the farms and, to a certain extent, to the sustainability of the territories by involving farmers proactivity in building their futures farms. The farmers expressed their satisfaction at the end of the exercise, especially in Guaviare where, due to the conflict, they were not able to explore the future of their farms.

The second hypothesis of the thesis, which posits that in the Amazonian pioneer fronts, farm trajectories affect their current alignment of the farm with agroecological principles, was validated. The methodology allowed us to identify which type of trajectories were the most aligned with agroecological principles in their current phase. Therefore, the trajectory plays a role in the current sustainability of farms. This approach made it possible to assess whether agroecology is a potential response to the development of agriculture in the Amazon.

The trajectories that had a better score on agroecological principles were based on the one hand, on rotational cattle grazing and on agroforestry systems on the second hand. This result gives some orientations for the development of sustainable agriculture in the Amazonian pioneer front. This result highlights the complexity of the search for sustainable agriculture that lies in a differentiated approach considering the co-existence of diverse production systems within a given territory and promoting gender equity. Particularly for the two territories we studied, cattle farming was at the center of farm trajectories. In other words, supporting cattle-based systems is crucial for the transition towards sustainability in the former deforested areas, provided that sustainable management practices or grazing areas are promoted (Castro-Nunez et al., 2024).

Chapter 2 highlights six main farm trajectories in two Amazonian pioneer fronts, something that had not been previously analyzed in a single study. These trajectories are: (i) the progressive intensification of rotational cattle, (ii) the steady cattle, (iii) the agroforestry, (iv) the rapid shift to rotational cattle grazing, (v) the extensive cattle ranching, and (vi) the soybean cultivation combined with cattle ranching.

The first contribution is that no previous research study had examined farm trajectories in the Guaviare pioneer front. This provides relevant references at the departmental scale, while also revealing important patterns that can be extrapolated to other Amazonian departments in Colombia and even to areas of the Amazon where coca production takes place, such as in Peru and Ecuador.

In Guaviare, the role of coca within farms trajectories can be interpreted in multiple ways. First, coca may have provided an initial capital to farmers, but at a very high cost. The violence of the conflict, the illegality, and the uncertainty it created influenced their outlook and at the same time instability within trajectories. This uncertainty about the future during the coca boom prevented farmers from investing in other productions. Moreover, some farmers retained very little income from this activity. These results align with existing literature, which states that coca cultivation does not lift farmers out of poverty (Davalos et al., 2021).

Second, a simplistic interpretation of coca cultivation might suggest that these crops trigger a first stage of deforestation, as the boom could allow farmers to accumulate capital to invest in more coca crops and clear additional forest. While this interpretation is partially true, empirical data collected in the field indicates that coca cultivation occurs in small plots, with a maximum of one hectare. Farmers' rationale was to avoid detection by satellites. In other words, the instability of the context, primarily driven by violence and illegality, did not allow them to invest in legal agricultural systems. To some extent, coca cultivation helped maintain the forest. As Davalos et al. (2021) state, contrary to common belief, the expansion of legal agriculture is a more significant driver of deforestation than coca cultivation.

The analysis of Davalos et al. (2021) is based on statistical examination of secondary data on land cover, coca cultivation, socioeconomic variables, conflict, and anti-drug policies. My results align with their findings and further enrich the literature by supporting this claim through field-based research, drawing on farmers' histories and the trajectories of their farms.

Third, the existence of patterns in the sequences of agricultural trajectories in the two pioneer fronts of Paragominas and Guaviare provides lessons that transcend national borders within the Amazon. Specifically, identifying trajectories with a common pattern, starting with slash-and-burn agriculture and later shifting to cattle ranching, highlights a path dependency in the Amazon. This pattern is shaped by public policies that promoted cattle ranching during the colonization process, territorial characteristics (particularly infrastructure), cattle's role in savings and liquidity within the trajectory, and its function as a means of land appropriation and speculation. Identifying trajectories that follow this sequence within the complexity of a region like Guaviare, marked by violence and a history of illicit crops, is particularly striking. It highlights that in the Amazon, cattle ranching cannot be disentangled from broader territorial dynamics, regardless of the social challenges associated with it.

Fourth, and from an agronomic perspective, lies in the richness that emerges from combining farm trajectories with agroecology. This approach provides empirical insights into the relationship between the past trajectories of farms and their current level of agroecological alignment in pioneer fronts. While previous literature has analyzed farm trajectories (Carvalho et al., 2015; Cialdella et al., 2009a; Plassin, 2018) and emphasized the importance of agroecology (Caicedo-Vargas et al., 2023; Pizarro et al., 2025; Souza et al., 2021) in these regions, these aspects had been studied separately.

This approach allows us to identify which trajectories are more aligned with agroecology, enriching the literature by digging into the origins of observed trends. In other words, we built knowledge about where agricultural sustainability in the amazon comes from. Specifically, it demonstrates that the most sustainable trajectories are those associated with agroforestry and rotational grazing for cattle, highlighting a coexistence of sustainable trajectories. This suggests that there is not a single answer for sustainability issues.

The key point is that these sustainable trajectories in pioneer fronts exhibit what can be described as deterministic phases towards sustainability (e.g., transitions from extensive cattle ranching to more intensive cattle systems). These transitions are largely driven by exogenous factors, such as a combination of public policies and development projects promoting sustainability. However, it is also essential to acknowledge the remarkable capacity and willingness of farmers in these transitions, which could be explained by their strategic flexibility (Andrieu et al., 2015).

From a practical perspective, the combination of farm trajectory with agroecology analysis provides valuable knowledge for designing public policies or rural development initiatives in the Amazonian pioneer fronts. These insights can help to improve conditions for alternative systems, strengthening and expanding sustainable trajectories, such as rotational grazing for cattle production and agroforestry systems. Recognizing the diversity of trajectories, as well as the specific phases in which farms are situated, allows for the adaptation of strategies to each case. For example, strategies for addressing the slash-and-burn phase (which in some cases presents unsustainable characteristics, such as uncontrolled fires, and unregulated forest clearing, yet also plays a role in farms food supply and food security of territories), should differ from those targeting expansive cattle ranching phases. Tailoring interventions in this way enhances their effectiveness and ensures that sustainability actions from both public and private efforts are aligned with the realities of agricultural transitions in the Amazon.

A fifth key contribution lies in incorporating a gender perspective on farm trajectories. We give evidence on their fundamental role in farm long term perennity, particularly through their pluriactivity, which contributes to the stabilization of farm trajectories. Women's workload is significantly higher due to their triple role: agricultural labor, domestic work, and family responsibilities. While upgrade has been observed in these trajectories regarding women's autonomy and leadership, aligning with existing literature (Hodel, 2023), there is still much to be done to achieve full gender equity in these rural contexts.

The third hypothesis was partially validated. Although there were differences in the visions of ideal farms between women and men farmers, it cannot be affirmed that they envision completely different ideal farms. Both showed interest in agroforestry systems combined with rotational grazing of cattle systems or silvopastoral systems. The plausibility of the visions is linked to gender-specific tensions. Among these, inequalities in access to credit, higher workloads and lower presence in leadership positions within the associations were highlighted.

Women had a higher tendency to include diversification in their visions of the future compared to men. This was reflected in the tendency towards agroforestry and agroecotourism, including rotational grazing of cattle systems or silvopastoral systems. Women also envision to manage the farm on their own and to share the farm work with their husbands. As for men, although they also mentioned a desire to move towards agroforestry systems and rotational grazing for cattle, this was influenced by territorial factors such as better road infrastructure or closer markets.

The result of chapter 3 enriches the literature on anticipation, specifically in the foresight approaches. It shows that the combination of rotational grazing systems for cattle or silvopastoral systems and agroforestry is the dominant vision in two pioneering areas of the Amazon. This is highlighted at farm scale, an aspect not explored in the existing literature in the study sites. This result is interesting because it reveals a same vision in two pioneering areas at different pioneer front stages: one active and the other consolidated. It demonstrates that the dynamics of development projects and efforts by local governments influence not only their trajectories but also shape the visions of these ideal farms.

Compared to existing prospective studies on Amazonian agriculture (Camacho Peña, 2022; Osis et al., 2019), this work stands out for its participatory approach. Piraux et al. (2020) also involved farmers in shaping their own future, however, the originality of this study lies in its specific consideration of gender using exclusive women focus groups discussions, as well as the focus made on the ideal farm scale.

Finally, this thesis articulates the analysis of past trajectories (chapter 3) with the assessment of current sustainability through agroecological principles and the exploration of visions of ideal farms, with a gender perspective (chapter 4). The central question was to understand the extent to which past farm trajectories enable farmers to envision plausible sustainable farms. The findings suggest that past trajectories establish both the foundations and limitations to the current sustainability of farms. For instance, trajectories that historically involved higher levels of deforestation (e.g. extensive cattle trajectory) and reliance on external synthetic inputs (soybean-cattle trajectory) tend to be less aligned with agroecological principles today. The trajectories also influence the ideal visions of farmers. Indeed, from a local perspective captured through the patches, farmers largely envision ideal farms based on the existing trajectories within these patches.

Past trajectories heavily determine the current sustainability; this situation, along with gender-explicit experiences and aspirations, shapes the construction of ideal farm visions, and pathways to achieve them. To move toward more sustainable futures in the Amazon, I have demonstrated that it is crucial to understand the interconnection between the past, present, and future visions, taking into account the diversity of trajectories and gender perspectives.

5.2 Points of views on the smallholders' sustainable trajectories in the Amazon

- An interpretation of possible consequences within uncertainty

Sustainability based on the trajectories of rotation grazing and silvopastoral systems can be controversial in the Amazonian region. Cattle ranching, in many cases, is a means by which settlers access land, whether in public lands or within indigenous reserves. An example within this thesis is the *Naranjales vereda*, in Guaviare, where some farmers have settled within the *Nukak resguardo*. The Nukak are an indigenous group living in the forest situated between the Guaviare and *Inírida* rivers (Politis, 1996). What is sought to be highlighted here are the multiple possible consequences involved in silvopastoral systems or rotational grazing for cattle, if implemented in an uncontrolled manner. In fact, in the Amazonian context, the forest is still considered as potential land for appropriation and farming (crops or livestock) which implies cutting down the forest.

The literature highlights the possibility of the "rebound effect" (Nepstad et al., 2019), which occurs in intensive livestock systems that leads to an increase in the number of animals per hectare, helping to slow down the expansion of the agricultural frontier (Castro-Nunez et al., 2024). However, by making the activity more profitable (Pizarro et al., 2025), it can also encourage farmers to expand into remaining forested areas, especially in contexts where land suitable for this production is already occupied. This is even more likely when the demand for beef is high, as in Brazil, the world's largest beef exporter (zu Ermgassen et al., 2020) .

Although this phenomenon is more frequent in livestock intensification systems, due to their land-intensive nature (obviously less so than extensive livestock farming), it can also occur for agroforestry. Therefore, some authors suggest that the promotion of these systems should be accompanied by specific conditions, such as regulations for exhaustive use zoning, credit restrictions for actors with a history of deforestation, and market mechanisms promoted by private coalitions, such as the soybean moratorium in Brazil (Castro-Nunez et al., 2021; Nepstad et al., 2019). Beyond the conditions necessary to minimize these possible negative consequences, the core of the problem lies in the fact that most of these measures depend on the State, which, on the pioneering fronts, often has limited capacity.

The literature also points to a risk of leakage (Atmadja & Verchot, 2012), which refers to the possibility that forest conservation efforts such as policies in one specific region may result in increased deforestation or other negative environmental impacts elsewhere (states, departments, municipality). In this context, trajectories considered as sustainable (rotational grazing for cattle, Silvopastoralism and agroforestry) could develop and concentrate within sub-national territories having advanced conservation policies, displacing less sustainable trajectories (e.g. extensive cattle ranching) to sub-national territories where such policies do not exist. This could be considered as the classical reading of leakage. It has already been analyzed in other studies, especially in the timber and soy production in the Brazilian Amazon (Villoria et al., 2022; Wunder, 2008).

An additional interpretation of "leakage of the benefits of intensification" can be made at a finer spatial scale, within a subnational pioneer front, where conservation control policies do not operate under optimal conditions for enforcement and monitoring. This is where the patch as spatial scale plays a fundamental role in the discussion. The intensification of rotational grazing for cattle or silvopastoral systems reduces the need for large grazing areas withing farms, thereby "releasing land." This release of land may not systematically lead to forest regeneration (Ballon et al., 2016). Moreover, a key question is what those farmers would do with the land?

The release of land at the farm level may in turn reduce the local demand for pasture at the patch level, which can lead to a decrease in the price of grazing land, if it is not suitable for mechanization and grain cultivation. This cheaper land becomes more accessible to other farmers (who may have different trajectories, such as extensive cattle ranching). This process could be considered a "leakage of the benefits" within rotational grazing for cattle or silvopastoral intensification trajectories. This reflection depends on three assumptions (i) farmers in intensification trajectories want to sell the "released land" (ii) these same farmers can sell "released land" (iii) for farmers in extensive trajectories to settle on these lands, these lands must be continuous.

These possible consequences highlight the need for integrated approaches to the development of sustainable rotational grazing of cattle or silvopastoral and agroforestry trajectories, which consider the underlying dynamics of deforestation.

A focus on forest sustainability

The ideal visions of farms include elements that suggest greater sustainability, as they are based on a combination of rotational grazing for cattle or silvopastoral systems and agroforestry. From the perspective of agroecological principles, these practices are the most sustainable within the Amazonian context. This topic is explored in greater depth in the following section. Here, I emphasize the discussion on the forest area.

Forest cover still faces challenges that could compromise it, particularly regarding forest cover. It is noteworthy that smallholder farmers aim to maintain forest cover, which ranges from 5% to 50%, with a statistical median of 20% of the ideal farm visions.

Focusing on the visions on forest cover in ideal smallholder farms in Paragominas, Brazil, a median of 20% of the total area of the farm is mentioned, with values ranging from a minimum of 6% to a maximum of 50%. Environmental regulations establish that the percentage of Legal Reserve Area (ARL) must be 80% in the Legal Amazon (states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, Tocantins and Maranhão). In practical terms, this means that a farm located in the forest zone within the Legal Amazon should conserve 80% of its area with native forest vegetation. However, the new 2012 Forest Code (Law 12,651/2012) (Brasil, 2012) introduced the concept of “consolidated rural area”, defined as that part of the rural property with human occupation preexisting July 22, 2008, including buildings and agricultural and livestock productive activities.

This date is crucial, as it marks a turning point in the environmental control of the forest. For properties located in consolidated rural areas, the 2012 Forest Code allowed the percentage of Legal Reserve to be reduced to 50%, provided that the existing forest cover in 2008 was equal to or higher than that threshold. If the forest cover at that date was less than 50%, the owners were obliged to maintain the existing area and commit to its restoration until reaching the 50% level (Plassin, 2018).

The Forestry Code (low 12.651/2012) gave additional flexibility for smallholders owning less than four “fiscal modules”, which in Paragominas is equivalent to 220 hectares (one fiscal module equals 55 ha in Paragominas). In result, all focus group participants in Paragominas are in this category. The flexibility established means that these family farms are not required to reach the 50% Legal Reserve if their forest cover in 2008 was below this threshold. However, they must maintain at least the same area of forest cover that they had on July 22, 2008.

Given that smallholder farmers have more flexible regulation in terms of forest cover, the first aspect to consider is that keeping 6% of forest reserve area as they suggested in their vision of the ideal farm would be legal, if that area has been cleared prior to 2008. However, it is very likely that these farmers will face difficulties in complying with the requirements of Permanent Preservation Areas (APP), which correspond to naturally fragile areas where vegetation cover, preferably native (e.g. riverbanks), must be maintained. Failure to comply with these regulations could place them in a situation of environmental irregularity.

In the case of Colombia, in Guaviare, when analyzing the views on forest cover in ideal farms, an average of 19% was observed, with values varying between a minimum of 5% and a maximum of 25%. These results are consistent with those obtained in Paragominas. However, Colombian legislation regarding on-farm forest reserves is more complex. The legality of cutting the forest within a property is not determined by a percentage of the farmer's total area but depends on the zoning of the land according to environmental regulations and municipal management plans. In addition, land use conversion requires obtaining specific permits (Katz-Asprilla et al., 2024).

To comply with these regulations, it is essential to consider the role of the State. The State must not only provide the means for smallholders to comply with environmental regulations but also strengthen its institutional capacities to then control and monitor forest areas (Pacheco et al., 2008).

Given the above, the low percentages of forest reserve on ideal farms indicate that there is still a long way to go towards sustainability. Such a low forest reserve, between 6% and 10%, could have significant negative consequences for biodiversity, soil protection and ecosystem services.

Nevertheless, we can say that there is progress to the extent that farmers' visions maintain a part of forest: the median forest cover across groups on ideal farms is 20% in Brazil and 19% in Colombia. In the foresight exercise, we decided not to refer to the concept of sustainability to not bias the visions of the farmers. As a result, although the area of forest varies among the visions, all farmers expressed a desire to maintain an area of forest.

- Work dimensions in the farmer's ideal farm based on rotational grazing for cattle or silvopastoralism and agroforestry systems

A challenge in the way for achieving sustainable trajectories is the complexity of work, on and off farm. Considering its multiple dimensions, work it can be analyzed through the framework of work, profession or occupation, and employment Dedieu (2019) and Dedieu and Chauvat (2024) invited to consider the multiple dimensions of work through the framework of work, profession or occupation, and employment.

Regarding work, the implementation of systems that combine rotational grazing and agroforestry would alter farm work organization. While rotational grazing involves the dynamic management of fences, animal movement, and pasture management, agroforestry introduces additional tasks such as tree planting, pruning, and harvesting, as well as managing interactions between tree components and crops or pastures. This would result in a greater diversification of tasks compared to more specialized systems, whether exclusively agroforestry-based or solely focused on rotational grazing for cattle or silvopastoral systems. In this context, work organization, particularly workload distribution, which is already disproportionately higher for women, could be affected. The introduction of more complex systems may require a redistribution of responsibilities and the acquisition of new skills by family members (Pretty, 2018).

Furthermore, farmers' well-being and health are crucial aspects of work, especially difficult in Guaviare. The combination of activities may provide greater variety in daily tasks, potentially reducing monotony. However, it is also essential to assess the ergonomics of these new practices and determine whether they may generate new forms of physical hardship.

Regarding the profession, a key aspect lies in the meaning that farmers attribute to their work. Although agriculture is essential for food security, its value is not always properly recognized. To the extent that the "ideal farm" aligns with sustainability, this notion could play a role in the revaluation of the farming profession. A farmer whose farm is classified as sustainable may reconstruct the meaning of their profession based on this recognition. However, a pre requirement is the fulfillment of basic needs, including security and social needs (Janker et al., 2019). Currently, having large cattle herds in pioneer frontiers is still a symbol of prestige (Plassin, 2018), which falls within the dimension of profession. A key strategy to address this is to shift that paradigm and make sustainability a prestigious value in these pioneer fronts. However, for this to happen, sustainability must also contribute to people's well-being. The literature highlights examples such as the development of cocoa value chains in other parts of the Ecuadorian Amazon or cattle certification initiatives in Brazil, which have influenced local perceptions of prestige on forest, and, at the same time, has improved farm incomes (Alves-Pinto et al., 2015; Salazar et al., 2023). Nevertheless, these initiatives often rely on external factors beyond the farmers themselves and come with their own challenges, such as the vulnerability of producers to exporters, large processing companies, and international distributors (Salazar et al., 2023).

Regarding the employment dimension, the vision of ideal farms that combine rotational or silvopastoral grazing and agroforestry could have implications for the demand for hired labor. Depending on the scale and intensity of the system, there could be a greater need for workers with specific skills in livestock management, agroforestry, or even product processing. Consequently, the attractiveness of agricultural employment could increase if these farms provide fair and meaningful jobs aligned with agroecological principles such as equity (Wezel et al., 2020). However, it is essential to address issues such as remuneration, job stability, and training opportunities to make these jobs truly appealing, particularly in pioneer fronts where the informal economy prevails and there is still a long way to go.

Achieving the farmers vision of implementing more complex farming systems, requires not only technical innovations but also a comprehensive approach that considers the dimensions of work (work, profession, employment), both in farm organization and by ensuring well-paid jobs, adequate training, and the revaluation of smallholders' work, especially women.

In summary, the implementation of rotational grazing and silvopastoral systems, although potentially sustainable, presents risks such as the rebound effect and deforestation leakage. There may be a discrepancy between the vision of smallholders on the ideal forest cover (less than 50%) and environmental regulations, especially in Brazil (it depends on each case). The adoption of combined silvopastoral and agroforestry systems increases the complexity of agricultural work, affecting the organization and workload. For a successful transition towards more sustainable systems, integrated approaches with policy support, including regulations and market mechanisms, are required. In addition, the aim is to revalue the agricultural profession through sustainability, although this also depends on economic and social factors.

5.3 Does attaining agricultural sustainability require going through a phase of non-sustainability? Insights from the role of exogen factors and regulations

Farm trajectories in the pioneer fronts share the common characteristic of cutting down forest areas for the establishment of their production systems. This seems to be an inevitable phase of the trajectory, leading to ecosystem damage and biodiversity loss. The rationale behind forest cutting in Amazonian agriculture is twice: soil fertilization for planting crops and clearing for pasture. The "opening" for pasture is linked to the farm project to introduce cattle in the future but also for land appropriation (Carrero et al., 2022).

Understanding the complexity of forest conversion to farming lands in the Amazon shows that while forest opening and shifting to extensive farming systems have been historically common, the findings of this thesis showed that such conversion is not inevitable in the current context of the pioneer fronts studied. The trajectory of rapid shift to rotational grazing leaves us with valuable knowledge, proving empirically that sustainable intensification can be realized without the need for a prolonged extensive phase, which contributes to limiting forest opening, but with the risks mentioned in the previous section (rebound effect, leakage). This result was observed in the two pioneer fronts in different phases (active and consolidated), which makes it even more relevant. It shows that even in active pioneer fronts where there are unfavorable territorial factors such as armed conflict, relocation of farmer settlements, deficiency of basic services (e.g. water, electricity) and absence of marketing networks, it is possible to achieve a transition to rotational grazing of cattle in a short period of time under certain support conditions and on a limited scale.

This transition occurred under specific conditions and was mostly driven by exogenous that provided infrastructure and technical assistance, they aimed at strengthening the capacities of farmers in the implementation of rotational cattle grazing practices. This process was also reinforced by the coordination of local governmental institutions to promote these initiatives. It is also important to notice a key endogenous factor, such as the previous knowledge acquired within the family on livestock practices, which facilitated the adoption of these practices.

For example, in Guaviare, after the signing of the peace agreement in 2016, investments in sustainable agricultural systems increased. The European Fund for Peace stands out, with a total of 10,802,755 euros with 7,578,418 euros coming from the European Union and 3,224,337 euros from counterparts, including a significant participation of the Governorate of Guaviare, that permitted to finance the *Caminemos* project (Fondo Europeo para la Paz, 2019). The Sustainable Colombia Fund, with a current capital of US$57 million, is a key initiative for rural development and the reduction of deforestation in the country. Financed by the governments of Norway, Sweden and Switzerland and administered by the Inter-American Development Bank (IDB), this fund enabled the implementation of strategic projects in departments such as Guaviare. In fact, projects have been implemented in Guaviare, with an investment of more than US$4 million, focusing on the adoption of silvopastoral and agroforestry systems (Fondo Colombia Sostenible, 2022).

Additionally, among other initiatives, USAID investments stand out, which since 2020 have exceeded $40 million in programs in the Amazon, targeting sustainable agriculture, ecotourism and forest conservation (USAID Colombia, 2024). Following the same logic, Paragominas has received projects from the Amazon Fund, a financing mechanism led by Brazil and with contributions mainly from Norway and Germany, aimed at combating deforestation and promoting sustainable development in the region, which has approximately 600 million euros (de Oliveira & de Sá, 2024). It should be noted that together, these initiatives have facilitated the necessary conditions for the development of sustainable trajectories.

Although rapid shift intensification (in some cases 6 years) was not the conventional trajectory, in fact the conventional trajectory of the intensification of cattle breeding passes through an expansion phase of production systems, before starting the intensification process. This highlights the fact that the conventional trajectory of cattle intensification is not linear. However, it is possible to minimize the duration of this expansion phase, as well as limit the opening of the forest or plan agricultural activities only where forest has already been cut, while maintaining an alignment with agroecological principles, if the conditions are met.

An analysis of agroecological principles and farm trajectories leads us to discuss the origin of sustainability. It highlighted phases of slash and burn practices, which in some cases related to land appropriation and large people settlements, can have negative effects on biodiversity (including the forest), as well as reduced economic diversity (Bezerra et al., 2023, 2024; Martínez-Penados et al., 2024; Nhiuane et al., 2024). This suggests that, in pioneer fronts, the trajectories currently considered sustainable, those more aligned with agroecological principles would have previously gone through phases of “non-sustainability” in most of their agroecological principles, except for the use of synthetic inputs, which was initially low in initial phases due to farmers’ lack of resources to acquire them.

Given the existence of trajectories towards cattle intensification, fundamental questions arise: what will happen when the support projects come to an end? Will these intensification trajectories be maintained, and will they continue to follow agroecological principles? The ideal farms' vision shows that farmers do not desire to go back to extensive phases, at least not for smallholders. The ideal vision can be discussed theoretically from its agroecological principles.

The main ideal farm that emerged in Step 3 (Chapter 4), which combines silvopastoral systems/rotational grazing for cattle and agroforestry systems can potentially enhance alignment with several agroecological principles (Wezel et al., 2020) at farm-scale particularly the recycling and reducing synthetic inputs principles. The incorporation of trees from agroforestry into rotational grazing systems can also enhance soil health (Escribano Sánchez, 2014). Nutrient and biomass cycles can be improved within the farm: livestock consumes plant biomass and returns it to the soil as manure, enriching it with organic matter and nutrients (Stark et al., 2018). Additionally, trees contribute to nutrient cycles through leaf litter, further bolstering the recycling principle (De Almeida et al., 2013). Nitrogen fixation facilitated by the crop-livestock synergy can reduce the need for synthetic nitrogen fertilizers (Loker, 1994; Martin et al., 2016). The combination of agroforestry and cattle systems can also enhance the principle of biodiversity at farm scale. The diverse vegetation in these systems often includes fruit trees, timber species, nitrogen-fixing legumes, and forage plants, inherently increasing on-farm biodiversity (Kremen et al., 2012; Martin et al., 2016). This diversification of plant species can also favor income diversification, providing smallholders with greater resilience and market opportunities (Kremen et al., 2012; Puech & Stark, 2023). This same diversification can lead to the addition of value to agricultural products, which also support fair trade and fair employment, that are key agroecological principles. By integrating these systems, ideal farms align may improve their sustainability and resilience while offering economic and ecological benefits to farmers.

However, given the increased complexity associated to this ideal farm, the transition can be challenging for smallholders' trajectories that currently had low agroecological scores, such as the steady cattle trajectory, especially in contexts where exogenous factors, such as projects, do not reach these trajectories.

In the thesis I made emphasis on smallholder farmers. Large scale farmers with extensive cattle (between 300 ha and up to 8,151 ha) and soybean-cattle (between 400 ha and up to 1,100 ha) trajectories were interviewed in Paragominas but did not participate in the focus group. Indeed, I chose to focus on smallholder farmers in order to incentive them to project themselves into transitions toward sustainability, given that they are often excluded from such processes (Piraux et al., 2020). However, large farmers interviews gave some elements on their desired future. Farmers dedicated to extensive cattle raising, mentioned that their future project was oriented towards diversification to some extent, with the intention of allocating part of their land to a cycle of soybean and corn cultivation, followed by pasture and cattle, and then return to the soybean cycle. This practice is already used in the soybean-cattle trajectory, whose main difference lies in the fact that these farmers focus mainly on soybean production and diversify with cattle. Additionally, some women farmers within extensive cattle trajectory have expressed interest in growing açaí.

Farmers on the soybean-cattle trajectory envision even greater diversification than what they currently do, incorporating more cattle. Overall, soybean-cattle and cattle extensive trajectories were to some extent engaged in the dynamics of diversification that may strengthen their future alignment with some agroecological principles, such as biodiversity, economic diversification and synergy. However, at the Amazon scale soybean farmers continue to contribute indirectly to deforestation and degradation by displacing cattle pastures to areas less suitable for mechanized agriculture (Song et al., 2021). Cattle ranching remains the primary direct driver of deforestation in the Legal Amazon. Extensive cattle ranching practices are still predominant, leading to widespread pasture degradation, estimated at 30 million hectares in the Brazilian Legal Amazon (Garrett et al., 2021), which pushes these trajectories further away from agroecological principles such as biodiversity and soil health.

Additionally, these trajectories of large producers coexist with the trajectories of smallholder farmers. Empirical results show a conflict between these trajectories for the use of land. In the Brazilian federal state, in 2023, these conflicts, reached 49.4 million hectares according to the Pastoral Land Commission (Comissão Pastoral da Terra, 2023). Such conflicts do not depend on a specific territorial context but are rather common in rural Brazil. The Pastoral Land Commission also highlights additional conflicts related to water, rural slave labor, among others. The 2023 report on rural conflicts in Brazil by the Pastoral Land Commission, recorded 2,203 conflicts. This report emphasizes that these conflicts are connected to the expansion of agribusiness and the concentration of land among large scale farmers. This report also indicated that since 2014 these conflicts are rising and that between 2022 and 2023, they increased by 8%.

These facts reflect a worrisome trend that may be related to several factors. It highlights the absence or lack of actuation of the federal and state governments to resolve such conflicts. This underscores the importance of development projects, which, through the coordination of local governments, make efforts to stabilize trajectories for smallholder farmers.

However, it is also worth noting that there are also synergies and interdependencies between the trajectories of smallholder farmers and large landowners. From the empirical results, I was able to observe that landowners, to some extent, supported the stabilization of smallholder trajectories, for example, by providing initial livestock or training smallholder farmers to later manage their own cattle. Although these synergies may be minor in scale compared to the available conflict data, they still represent a notable dynamic. The literature highlights the coexistence of smallholders, medium-scale producers, and large farmers, where small farmers are often in a position of vulnerability and dependence on large farmers, and to some extent, also on medium-scale producers (Polge et al., 2018).

In any case, the agricultural sustainability of Amazonian territories depends on all these farmers, including smallholders as well as medium and large-scale landowners. But this is just one piece of the puzzle. The global food system plays a fundamental role in the sustainability of Amazonian agriculture. It is estimated that the European Union's consumption was responsible for 10% of global deforestation, associated with goods or services, including palm oil, soy, timber, and beef during the period that range from 1990 to 2020 (European Union n.o 995/2010, 2023). Although there have been advances in regulations, such as the European Regulation on Deforestation-free Products (EUDR) 2023/1115, which aims to prevent products linked to deforestation or forest degradation from entering its market, there are still risk of leakage toward other markets as long as there is no global regulation. This complicates the conditions for transitioning to agricultural sustainability without going through phases of unsustainability.

In summary, forest cutting for agriculture and cattle ranching has been a common practice in the Amazon, with negative consequences for the ecosystem. However, unsustainable conversion is not inevitable, as evidenced by the rapid shift to rotational grazing with external support. These transitions occur under specific conditions and often require the intervention of development projects, food system regulations and prior knowledge of farmers. Despite the possibility of rapid intensification, conventional trajectories often include an expansion phase, although its duration can be minimized by maintaining consistency with agroecological principles. Even if it is possible to avoid non-sustainability phases, this is not the reality of the pioneer fronts territories. Cases such as rapid shift trajectory may be more isolated if the whole picture is analyzed.

5.4 Research and development perspectives for agriculture in the Amazon and other pioneering fronts.

Our findings raise key points and new questions for Amazonian agriculture. It also provides some elements to reflect on policy makers with the objective of an inclusive agricultural development in the region.

- Supporting farm trajectories towards agroecological principles

It is crucial to investigate how to support the alignment of each type of trajectory with agroecological principles. Trajectories with agribusiness characteristics were farther from the principles. For this reason, research on how to progress towards sustainability in large-scale systems in the Amazon is fundamental to contribute to the sustainability of the territories. One entry point is the reduction of synthetic inputs, which, if productivity is maintained, would be of high interest to these farmers. Agroecology can provide knowledge and tools to manage an efficient use of natural ecosystem functionalities, so that dependence on external inputs of resources and particularly pesticides can gradually decrease along a trajectory of ecological intensification (Tittonell, 2020). Public policy can encourage transitions from large-scale agriculture with the example of Paragoclima which started in 2023 in search of carbon neutrality in the municipality of Paragominas. Although it is limited in the integration of smallholder farmers as most of them do not have a rural environmental register (CAR) (Nunes, 2022).

This also highlights the importance of supporting smallholder farmers in the transition towards a greater alignment with agroecological principles, the thesis opens an avenue for research: the in-depth study of unusual trajectories that are not reflected in the main trajectories described. These trajectories may present bifurcations (Grossetti, 2006) often caused by trigger events that, most of the time, are endogenous to the farm (Sutherland et al., 2012), such as the separation of the couple, deaths, illnesses, etc. The analysis of these atypical trajectories would allow a better understanding of the factors that influence the abandonment or permanence of agricultural activity, considering generational transmission. This would also teach us about possible strategies to mitigate the vulnerability of these moments and foster stability at the beginning of the transition to sustainability.

Another example of an unusual trajectory is the leasing of a significant part of a smallholder farm in Paragominas. This phenomenon occurred mainly for smallholder farmers who have land suitable for soybeans and lease their land to medium or large producers. Although the smallholder farmer can obtain income in the short term, this usually has an unfavorable effect on the smallholder farm's trajectory, limiting his capacity to continue in his farm trajectory, generating a stagnation that hinders his productive development and capacity building. This can lead to increased vulnerability and sale of the land.

- Scaling out and scaling up agroecology, innovations and leverage points as a strategy towards territorial sustainability on pioneering fronts

Climate change calls for urgent solutions for the Amazon which is facing a risk of tipping point towards its collapse (Chen et al., 2024). The analysis of the scaling out solutions from plot or farm scale, landscape to territorial, regional and even the food system (this one more scaling up solution) scales is part of the response. Transitions within these scales are at different levels, technical-productive, socio-ecological, political-institutional (Geels, 2002), involves a scaling up (Gliessman, 2018b; Tittonell, 2019). Additionally, leverage points are key areas where small changes can trigger transformative changes in social-ecological levels towards sustainability (Chan et al., 2020). With this framework, two points can be highlighted in research perspectives.

First, the typology of trajectories in the Amazonian pioneer fronts can allow us to discuss sustainability transitions through agroecological principles. In fact, each agroecological principle is related to one or even multiple scales, such as plot, farm or even the food system (Wezel et al., 2020). Therefore, each principle plays a role in the transitions occurring at these different levels. The thesis results offer valuable insights, particularly highlighting how principles like co-creation of knowledge and participation in farmer organizations are key to the dissemination of practices, essentially contributing to scaling out. However, these agroecological principles can also be analyzed from a scaling up perspective, examining how they contribute to political-institutional transitions. For instance, principles such as equity and the governance of land and natural resources are crucial in shaping broader systemic changes.

Second, identifying leverage points within sustainable trajectories, such as rotational grazing for cattle, silvopastoral systems, and agroforestry is necessary for understanding their role in scaling up and scaling out processes (figure 5.1). This means determining which points enable these trajectories to become embedded in policies and institutions (scaling up) and how they are disseminated across different scales (scaling out). Regarding the latter the thesis results already provide a preliminary insight into this analysis. Sustainable trajectories at the local level of patches influence farmers' visions, generating, to some extent, a scaling out effect. However, it is essential to assess the extent to which these trajectories contribute to scaling up, fostering more sustainable socio-ecological systems with a broader objective of redesigning the food system. This transformation would require a political-institutional transition to achieve deeper and more structural changes and consolidation of agroecology in pioneer fronts.

The analysis of the different levels of transitions, especially socio-ecological to political-institutional would help us to understand and provide key elements for scaling up such trajectories. It is essential to identify the social, technical and institutional innovations needed to break with dependency paths on the pioneering fronts (Rosenbloom et al., 2019). Additionally, the identification of leverage points of these transitions would allow the design of better strategies to achieve sustainability of territories, not only in the Amazon, but also in other pioneer fronts.

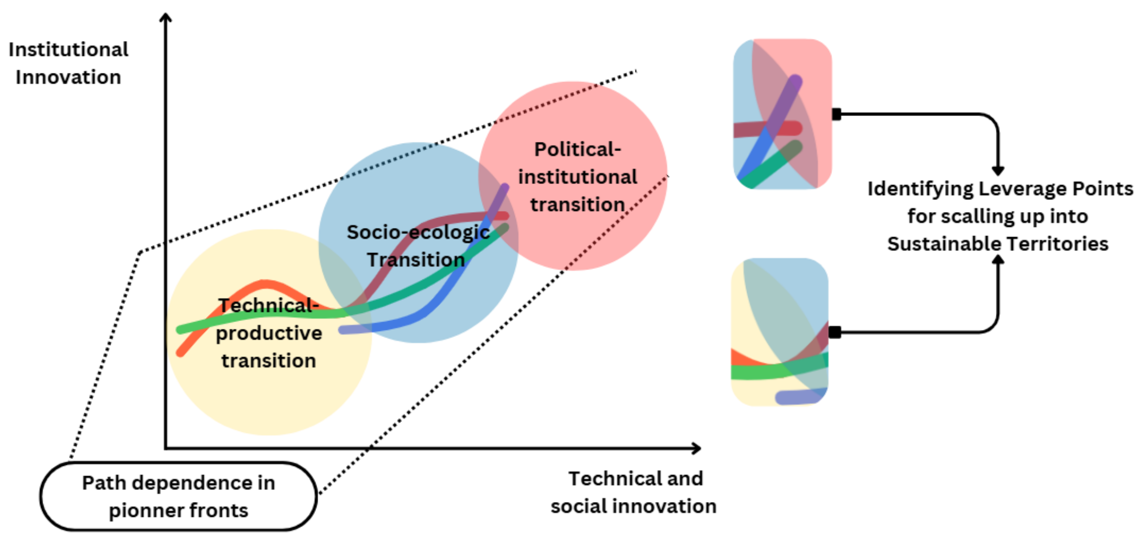

Figure 5.1 Transitions for Scaling agroecology up Adapted from, Geels (2002) Gliessman (2016). Tittonell (2019), this figure represents sustainable farm trajectories in lines, red one: progressive intensification based on rotational grazing or silvopastoral systems for cattle production, Green one: Agroforestry, Blue one: rapid shift to rotational grazing or silvopastoral systems for cattle production. Trajectories go through different levels of transition, each spanning a scale. These transitions include: Technical-productive: soil, plant, productive subsystems scales. Socio-ecological: farm, family, community scales. Political-institutional: landscape, territory, region scales. Emphasis is placed on the need to identify innovations and leverage points in critical moments within these transition processes. On the pioneer fronts, path dependence is driven by factors such as road infrastructure, lack of markets, land tenure and public policies, access to knowledge and technology, as well as social and gender factors.

- Settings to consider gender and farm realities within public policies and smallholders Amazonian farmers support services

A substantial contribution to the studied territories was the translation of agroecological principles into indicators, based on agricultural Amazonian literature. This allowed us to visualize an empirical gradient that can be useful for the use of NGOs, governmental organizations, facilitating a holistic reading of agroecology for Amazonian agriculture. This is also useful for farmers of these territories, offering them a broad vision of the main existing trajectories and their scores under agroecological principles that may be of interest to farmers. Public sectors should promote sustainable farm trajectories, with a gender focus. To this end, it is necessary to expand the identification and promotion of farm trajectories that balance productivity with environmental conservation. This implies adapting public policies to the diverse realities of the productive systems in the pioneering fronts, considering the different phases in the temporality of their development. In other words, agricultural policies should consider that some trajectories may be in the establishment phases, while others are in the consolidation or transition phases towards more sustainable agricultural systems.

In addition, recognizing the specific characteristics of farm trajectories considering the gender dimension, ensuring that support strategies are inclusive and equitable is at stake. This implies designing incentives that are differentiated according to the type of trajectory, but also according to the needs of women farmers. These can be economic and financial incentives, such as subsidies and/or preferential credits for types of trajectories and for women farmers. Investment funds can also be set up for ventures led by women farmers. Payments for environmental services (PES) can also be implemented to promote sustainable trajectories that consider their phases and temporality, such as the ecological intensification of livestock or PES that guarantee access to fair markets for agroforestry systems.

To strengthen farmers' capacities (capacity building), is crucial and should be gender-sensitive and adapted to overcome barriers such as women's high workloads that limit participation in such training. The empowerment of women has to be considered, so that they lead and manage agricultural projects. The empirical results show that a first step towards this empowerment is the recognition of their roles in the work of the farm and in decision-making. Understanding that they are the fundamental pillar for the development of their farms. To this end, such training and technical support programs should strengthen the leadership of women farmers through quotas or mechanisms that guarantee their active participation.

Existing challenges must be addressed, such as prioritizing the strengthening of territorial governance and legal security of land, combining land tenure regularization with strict enforcement of environmental regulations and monitoring to avoid undesired effects on forest conservation. Ensuring that access to this productive resource is facilitated for women. Additionally, developing infrastructure and commercialization channels is necessary to reduce the dependence of farmers on intermediaries, improving fair prices for their products.

Learning from the past is essential to project and build a sustainable and inclusive future. This pathway must integrate smallholder farmers, with an essential focus on women, who have been historically invisible in Amazonian agriculture. On this basis, the foundations are laid for the construction of gender-sensitive pathways from a political perspective, incorporating from the outset the opinions and visions of both male and female farmers in the construction of their future.

5.5 Conclusion

This thesis focused on understanding the extent to which farms' past trajectories enable farmers to envision plausible sustainable farms in two distinct contexts: Paragominas (Brazil), as a consolidated pioneering front, and Guaviare (Colombia), as an active one. To address this complex issue, the thesis combined a retrospective analysis of farm trajectories, an analysis of their current sustainability, assessed through agroecological principles, with a participatory prospective approach that explored smallholders' future visions. The methodology comprised three main steps.

A systematic literature review was conducted to identify the concepts and methods used in analyzing changes in farms. This review served to develop a relevant analytical framework for the thesis, but also for other pioneer fronts. Second, the empirical application of the retrospective component allowed for the study of various farm trajectories and an evaluation of their current sustainability, based on the contextualization of agroecological principles for the Amazon. Farmers interviews, coupled with a typology, allowed identifying the main farm trajectories in both pioneering fronts. These trajectories were primarily characterized by the presence of cattle within the configuration of production systems, which in turn is driven by territorial factors such as policies, geography, and markets. The agroecological assessment underscored rotational grazing for cattle or silvopastoral systems and agroforestry as trajectories most aligned with agroecological principles at present. Third, the prospective component used the Triangle of the Futures tool in gender-differentiated focus groups with smallholder farmers to explore their visions of ideal farms in the medium term (2034). A trend towards productive diversification emerged, with a strong preference for a combination of rotational grazing for cattle or silvopastoral with agroforestry systems in their future aspirations.

This overall methodology demonstrated that the past farm trajectories enabled to envision plausible sustainable farms to a greater extent. One of the crucial findings of the thesis is the influential role of these past trajectories on farmers' ideal visions. When envisioning their ideal farms, farmers rely mainly on three primary factors: (i) their accumulated experience and changes in their farms, i.e., their farm trajectory, (ii) on the production systems they know locally, (iii) on their perception of the challenges given current trends and historical inertias in the agricultural sector, which forge their plausibility.

The diversity of farm trajectories and their sustainability from an agroecology perspective provides a solid and contextualized basis for the design of pathways towards sustainability. This approach acknowledges the need to build pathways that allow the transition to more sustainable farms, considering the characteristics of each type of trajectory and its current sustainability. Such insights are valuable for public policy design as well as for stakeholders working towards more sustainable agriculture in the amazon. By articulating the specifies of each trajectory with the vision of the ideal farm, more precise, efficient, and targeted pathways can be designed, thus increasing the chances of success in building a more sustainable agricultural future for the region.

The research also highlighted the importance of considering gender differences in farm trajectories and visions of the futures. Women farmers, whose role is often invisible in normative discourses, play a fundamental role in agriculture, with a triple role, in farm work, in the domestic work and family farming care. Their visions often emphasize the importance of diversification, extending beyond traditional production systems to include activities such as agroecotourism. They also envision gender equity, seeing themselves as farm managers.

This research offers an innovative analytical framework for understanding farms and farmers' dynamics of change in Amazonian pioneer fronts and, to some extent, in other pioneer fronts. It interweaves the past, present and future of farms through a sustainability lens, while incorporating gender dimensions and territorial factors. The results contribute to a deeper understanding of the aspirations and challenges faced by farmers in this crucial region and provide a basis for developing strategies and policies that support inclusive and effective agricultural sustainable transitions in the Amazon.

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Annex A Supplementary material Chapter 2

Supplementary table 1: Documents included in the qualitative analysis (n=81)

Author	**Title**	**Year**	**Journal**
Egger, C.; Mayer, A.; Bertsch-Hörmann, B.; Plutzar, C.; Schindler, S.; Tramberend, P.; Haberl, H.; Gaube, V.	Effects of extreme events on land-use-related decisions of farmers in Eastern Austria: the role of learning	2023	Agronomy for Sustainable Development
Nishizawa, T.; Kay, S.; Schuler, J.; Klein, N.; Conradt, T.; Mielewczik, M.; Herzog, F.; Aurbacher, J.; Zander, P.	Towards diverse agricultural land uses: socio-ecological implications of European agricultural pathways for a Swiss orchard region	2023	Regional Environmental Change
Nishizawa, T.; Kay, S.; Schuler, J.; Klein, N.; Conradt, T.; Mielewczik, M.; Herzog, F.; Aurbacher, J.; Zander, P.	Correction to: Towards diverse agricultural land uses: socio-ecological implications of European agricultural pathways for a Swiss orchard region (Regional Environmental Change, (2023), 23, 3, (97), 10.1007/s10113-023-02092-5)	2023	Regional Environmental Change
Bakker, E.; Hassink, J.; van Veluw, K.	The 'inner' dimension of Dutch farmers' trajectories of change: drivers, triggers and turning points for sustained agroecological practices	2023	Agroecology and Sustainable Food Systems
Le Trouher, A.; Moulin, C.-H.; Huyen, L.T.T.; Blanchard, M.	Trajectories of crop-livestock integration in the context of specialization in Northwest Vietnam	2023	Journal of Agricultural Science
Thies, V. F.; Grisa, C.; Gazolla, M.	Trajectories of agricultural production and self-consumption in family farming in Salvador das Miss..es/RS: a longitudinal analysis between 2002 and 2017.	2023	Núcleo de Estudos Pesquisa Projetos de Reforma Agrária–NERA
Polge, E.; Pagès, H.	Relational drivers of the agroecological transition: An analysis of farmer trajectories in the Limagne plain, France	2022	Agricultural Systems
Alary, V.; Frija, A.	Crop-livestock systems transformation in the semiarid zones of North Africa over a decade: Approach and case-study in Southern Tunisia	2022	Journal of Agricultural Science
Song, B.; Robinson, G.M.; Bardsley, D.K.	Multifunctionality and path dependence: Farmer decision-making in the peri-urban fringe	2022	Journal of Rural Studies
Fischer, C.; Aubron, C.; Trouvé, A.; Sekhar, M.; Ruiz, L.	Groundwater irrigation reduces overall poverty but increases socioeconomic vulnerability in a semiarid region of southern India	2022	Nature-Scientific Reports
Dupé, Sandrine; Cardinal, Jérôme; Levain, Alix	Vers une agriculture sans ruralité ? La renégociation de la place de l'agriculture sur l'île de Bréhat (xxe-xxie siècle) »	2021	Norois

Pearson, L. J.; Dare, M.	**Farmer pathways to sustainability in the face of water scarcity.**	**2021**	**Environmental Science & Policy**
Tui, S.H.-K.; Descheemaeker, K.; Valdivia, R.O.; Masikati, P.; Sisito, G.; Moyo, E.N.; Crespo, O.; Ruane, A.C.; Rosenzweig, C.	Climate change impacts and adaptation for dryland farming systems in Zimbabwe: a stakeholder-driven integrated multi-model assessment	2021	Climatic Change
Rissing, A.; Inwood, S.; Stengel, E.	The invisible labor and multidimensional impacts of negotiating childcare on farms	2021	Agriculture and Human Values
Maccarthy, D.S.; Adam, M.; Freduah, B.S.; Fosu-Mensah, B.Y.; Ampim, P.A.Y.; Ly, M.; Traore, P.S.; Adiku, S.G.K.	Climate change impact and variability on cereal productivity among smallholder farmers under future production systems in west africa	2021	Sustainability
Bakker, T.; Dugué, P.; de Tourdonnet, S.	Correction to: Assessing the effects of Farmer Field Schools on farmers' trajectories of change in practices (Agronomy for Sustainable Development, (2021), 41, 2, (18), 10.1007/s13593-021-00667-2)	2021	Agronomy for Sustainable Development
Bakker, T.; Dugué, P.; de Tourdonnet, S.	Assessing the effects of Farmer Field Schools on farmers' trajectories of change in practices	2021	Agronomy for Sustainable Development
Rouget, N.; Boutry, O.; Fournier, A.	Agricultural dynamics: Trajectories vs. model(s)? The case of Douaisis	2021	BELGEO
Blanc, J	Social Change and Ecologic Modernization in Brazil	2021	Revista Pos Ciencias Sociais
Lanciano, Émilie; Saleilles, Séverine	Saisir l'agir entrepreneurial en agriculture : une analyse de l'apprentissage à la commercialisation en circuits courts par la trajectoire de projet	2020	Revue de l'Entrepreneuriat
Derrouch, D.; Chauvel, B.; Felten, E.; Dessaint, F.	Weed Management in the Transition to Conservation Agriculture: Farmers' Response	2020	Agronomy
Quénon, J.; Ingrand, S.; Magne, M.-A.	Managing the transition from purebred to rotational crossbred dairy cattle herds: Three technical pathways from a retrospective case-study analysis	2020	Animal
Nyberg, Y.; Wetterlind, J.; Jonsson, M.; Öborn, I.	The role of trees and livestock in ecosystem service provision and farm priorities on smallholder farms in the Rift Valley, Kenya	2020	Agricultural Systems
Cradock-Henry, N.A.; Blackett, P.; Hall, M.; Johnstone, P.; Teixeira, E.; Wreford, A.	Climate adaptation pathways for agriculture: Insights from a participatory process	2020	Environmental Science and Policy
Ahmad, I.; Ahmad, B.; Boote, K.; Hoogenboom, G.	Adaptation strategies for maize production under climate change for semi-arid environments	2020	European Journal of Agronomy
Oble Vergara, E.; Sandoval Garcia, A.; Almaguer Vargas, G.; Garcia Jimenez, R.	Techno-agricultural trajectory of orange cultivation in the northern area of Veracruz.	2019	Revista de Geografia Agricola

Jayne, T. S.; Muyanga, M.; Wineman, A.; Ghebru, H.; Stevens, C.; Stickler, M.; Chapoto, A.; Anseeuw, W.; Westhuizen, D. van der; Nyange, D.	**Are medium-scale farms driving agricultural transformation in sub-Saharan Africa?**	**2019**	**Special Issue: New mandates and new landscapes for agriculture.**
McGreevy, S. R.; Kobayashi, M.; Tanaka, K.; Cassidy, A.; Srinivasan, S.; White, B.	Agrarian pathways for the next generation of Japanese farmers.	2019	Cadanian Journal of Development Studies
Naqvi, S.A.A.; Nadeem, A.M.; Iqbal, M.A.; Ali, S.; Naseem, A.	Assessing the vulnerabilities of current and future production systems in Punjab, Pakistan	2019	Sustainability (Switzerland)
Huttunen, S.	Revisiting agricultural modernisation: Interconnected farming practices driving rural development at the farm level	2019	Journal of Rural Studies
Kongmanee, C.; Ahmed, F.	Detecting trajectories in rubber farms in southern Thailand	2019	International Journal of Recent Technology and Engineering
Bruce, A.B.	Farm entry and persistence: Three pathways into alternative agriculture in southern Ohio	2019	Journal of Rural Studies
Mu, J.E.; Antle, J.M.; Abatzoglou, J.T.	Representative agricultural pathways, climate change, and agricultural land uses: an application to the Pacific Northwest of the USA	2019	Mitigation and Adaptation Strategies for Global Change
Merot, A.; Alonso Ugaglia, A.; Barbier, J.-M.; Del'homme, B.	Diversity of conversion strategies for organic vineyards	2019	Agronomy for Sustainable Development
Mawois, M.; Vidal, A.; Revoyron, E.; Casagrande, M.; Jeuffroy, M.-H.; Le Bail, M.	Transition to legume-based farming systems requires stable outlets, learning, and peer-networking	2019	Agronomy for Sustainable Development
Kong, R.; Diepart, J.-C.; Castella, J.-C.; Lestrelin, G.; Tivet, F.; Belmain, E.; Bégué, A.	Understanding the drivers of deforestation and agricultural transformations in the Northwestern uplands of Cambodia	2019	Applied Geography
Revoyron, E.; Vidal, A.; Casagrande, M.; Jeuffroy, M. H.; Lebail, M.; Mawois, M.	Trajectories of legumes insertion in farms: methodological framework for the analysis of long-term changes.	2018	Aspects of Applied Biology
Zollet, S.	Towards sustainability transitions in Japanese agri-food systems: the role of new entrant organic farmers in rural areas of Hiroshima Prefecture, Japan.	2018	13th European International Farming Systems Association (IFSA) Symposium,

			Farming systems: facing uncertainties and enhancing opportunities, 1-5 July 2018, Chania, Crete, Greece
Mellisse, B.T.; van de Ven, G.W.J.; Giller, K.E.; Descheemaeker, K.	Home garden system dynamics in Southern Ethiopia	2018	Agroforestry Systems
Valdivia, R.O.; Antle, J.M.; Stoorvogel, J.J.	Designing and evaluating sustainable development pathways for semi-subsistence crop–livestock systems: lessons from Kenya	2017	Agricultural Economics (United Kingdom)
Ameur, F.; Kuper, M.; Lejars, C.; Dugué, P.	Prosper, survive or exit: Contrasted fortunes of farmers in the groundwater economy in the Saiss plain (Morocco)	2017	Agricultural Water Management
Brédart, D.; Stassart, P.M.	When farmers learn through dialog with their practices: A proposal for a theory of action for agricultural trajectories	2017	Journal of Rural Studies
Vall, E.; Marre-Cast, L.; Kamgang, H.J.	Intensification pathways and sustainability of crop-livestock systems in Sub-Saharan Africa: Crop-livestock interaction contribution	2017	Cahiers Agricultures
Miranda, D. L. R.; Gomes, B. M. A.	National program of fortification for family farming: trajectories and challenges at the Ribeira Valley, Brazil.	2016	Soc. & Nat.
Bathfield, B.; Gasselin, P.; García-Barrios, L.; Vandame, R.; López-Ridaura, S.	Understanding the long-term strategies of vulnerable small-scale farmers dealing with markets' uncertainty	2016	Geographical Journal
Mulwa, R.; Rao, K.P.C.; Gummadi, S.; Kilavi, M.	Impacts of climate change on agricultural household welfare in Kenya	2016	Climate Research
Sutherland, Lee-Ann; Toma, Luiza; Barnes, Andrew P.; Matthews, Keith B.; Hopkins, Jon	Agri-environmental diversification: Linking environmental, forestry and renewable energy engagement on Scottish farms	2016	Journal of Rural Studies
Rapey, Hélène	L’agrandissement-spécialisation des élevages en montagne. Une dynamique inégale	2015	Économie rurale
Veysset, Patrick; Lherm, Michel; Roulenc, Marielle; Troquier, Christophe; Bébin, Didier	Analyse et déterminants de l’évolution des performances d’élevages bovins et ovins allaitants en zones défavorisées de 1990 à 2012	2015	Économie rurale
Plassin, S.; Poccard-Chapuis, R.; Tourrand, J. F.; Gritti, E. S.; Wery, J.	Linking landscape patterns and farm trajectories: a prerequisite to design eco-efficient landscapes in agricultural frontiers of Brazilian Eastern Amazon.	2015	Proceedings of the 5th International Symposium for Farming Systems Design (FSD5), Montpellier,

			France, September 7-10, 2015
Carvalho, S. A. de; Poccard-Chapuis, R.; Tourrand, J. F.	Opportunism and persistence in milk production in the Brazilian Amazonia.	2015	Revue d'Elevage et de Medecine Veterinaire des Pays Tropicaux
Falconnier, G.N.; Descheemaeker, K.; Van Mourik, T.A.; Sanogo, O.M.; Giller, K.E.	Understanding farm trajectories and development pathways: Two decades of change in southern Mali	2015	Agricultural Systems
Chantre, E.; Cerf, M.; Le Bail, M.	Transitional pathways towards input reduction on French field crop farms	2015	International Journal of Agricultural Sustainability
Cialdella, Nathalie; Navegantes Alves, Livia	La ruée vers l'açai : trajectoires d'un fruit emblématique d'amazonie	2014	Revue Tiers Monde
Bredart, D; Dorothée, D.; Mormont, M.; Aenis, T.; Knierim, A.; Riecher, M. C.; Ridder, R.; Schobert, H.; Fischer, H.	Toward redesigning the relationship between farming systems and biodiversity conservation.	2014	11th European IFSA Symposium, Farming Systems Facing Global Challenges: Capacities and Strategies, Proceedings, Berlin, Germany, 1-4 April 2014
Ryschawy, J.; Joannon, A.; Gibon, A.; Aenis, T.; Knierim, A.; Riecher, M. C.; Ridder, R.; Schobert, H.; Fischer, H.	Evaluating innovative scenarios to enhance mixed crop-livestock farm sustainability: a partnership methodology based on farmers' longterm strategies.	2014	11th European IFSA Symposium, Farming Systems Facing Global Challenges: Capacities and Strategies, Proceedings, Berlin, Germany, 1-4 April 2014
Madelrieux, S.; Terrier, M.; Borg, D.; Dobremez, L.; Aenis, T.; Knierim, A.; Riecher, M. C.; Ridder, R.; Schobert, H.; Fischer, H.	Development trajectories of mountain dairy farms in the globalization era. Evidence from the Vercors (French Northern Alps).	2014	11th European IFSA Symposium, Farming Systems Facing Global Challenges: Capacities and Strategies, Proceedings, Berlin, Germany, 1-4 April 2014

Alavoine-Mornas, F.; Madelrieux, S.; Streith, M.; Cresson, C.	Transitions to organic farming: a diversity of processes.	2014	Economie Rural
Bernard, C.; Boutonnet, J. P.; Garnier, A.; Lerin, F.; Medolli, B.; Baumont, R.; Carrere, P.; Jouven, M.; Lombardi, C.; Lopez-Francos, A.; Martin, B.; Peeters, A.; Porqueddu, C.	Quality labels: a way to support the development of pastoral resources? Methodological insights based on the monographic analysis of Hasi region - Northern Albania.	2014	Options Mediterraneennes
Gonzáleza, I.V.; Garcíaa, F.S.; Arias, A.I.G.	Growth pathways in Northern Spain's farms	2014	Economia Agraria y Recursos Naturales
Chantre, E.; Cardona, A.	Trajectories of French Field Crop Farmers Moving Toward Sustainable Farming Practices: Change, Learning, and Links with the Advisory Services	2014	Agroecology and Sustainable Food Systems
Barrio de pedro, José Carlos	Caractérisation et diagnostic de familles paysannes andines au sein de leurs communautés, selon une méthode typologique (haute vallée du Cañete, province de Yauyos, Pérou)	2013	Les Cahiers d'Outre-Mer
Hirczak, Maud; Dedeire, Marc; Razafimahefa, Lala; Chevalier, Pascal	Systèmes de qualité et trajectoires agricoles : une approche spatiale des disparités et des convergences en France, Italie et Espagne	2013	Revue d'Économie Régionale & Urbaine
Ryschawy, J.; Choisis, N.; Choisis, J.P.; Gibon, A.	Paths to last in mixed crop-livestock farming: Lessons from an assessment of farm trajectories of change	2013	Animal
Rosenzweig, C.; Jones, J.W.; Hatfield, J.L.; Ruane, A.C.; Boote, K.J.; Thorburn, P.; Antle, J.M.; Nelson, G.C.; Porter, C.; Janssen, S.; Asseng, S.; Basso, B.; Ewert, F.; Wallach, D.; Baigorria, G.; Winter, J.M.	The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies	2013	Agricultural and Forest Meteorology
Terrier, M.; Madelrieux, S.; Dedieu, B.	Understanding the diversity of farm pathways as a co-evolution between the family organization and the farming system.	2012	Producing and reproducing farming systems. New modes of organisation for sustainable food systems of tomorrow. 10th European IFSA Symposium, Aarhus,

			Denmark, 1-4 July 2012
Malaquin, I.; Waquil, P.; Morales, H.	Social sustainability of livestock farms. The case of the Basalt region-Uruguay.	2012	Sustentabilidad social de explotaciones ganaderas. El caso de la region del Basalto-Uruguay.
Navegantes-Alves, L.; Poccard-Chapuis, R.; Huguenin, J.; Ferreira, L.; Moulin, C.H.	Grassland deterioration linked to farm trajectories in the eastern Amazon	2012	Outlook on Agriculture
Silvestri, N.; Pistocchi, C.; Sabbatini, T.; Rossetto, R.; Bonari, E.	Diachronic analysis of farmers' strategies within a protected area of central Italy	2012	Italian Journal of Agronomy
Benoit, M.; Laignel, G.	Long term analysis of meat sheep farming systems in France. Which dynamics of evolution and which factors can explain the economical performance?	2011	Productions Animales
Moreno-Pérez, O.M.; Arnalte-Alegre, E.; Ortiz-Miranda, D.	Breaking down the growth of family farms: A case study of an intensive Mediterranean agriculture	2011	Agricultural Systems
Kenny, G.	Adaptation in agriculture: Lessons for resilience from eastern regions of New Zealand	2011	Climatic Change
Lamine, C.	Transition pathways towards a robust ecologization of agriculture and the need for system redesign. Cases from organic farming and IPM	2011	Journal of Rural Studies
Valbuena, D.; Verburg, P. H.; Bregt, A. K.; Ligtenberg, A.; Houet, T.; Verburg, P. H.; Loveland, T. R.	An agent-based approach to model land-use change at a regional scale.	2010	Landscape Ecology
Rueff, C.; Gibon, A.; Darnhofer, I.; Grotzer, M.	Using a view of livestock farms as social-ecological systems to study the local variety in their trajectories of change.	2010	Building sustainable rural futures: the added value of systems approaches in times of change and uncertainty. 9th European IFSA Symposium, Vienna, Austria, 4-7 July 2010
Cots-Folch, R.; Martínez-Casasnovas, J.A.; Ramos, M.C.	Agricultural trajectories in a mediterranean mountain region (Priorat, Ne Spain) as a consequence of vineyard conversion plans	2009	Land Degradation and Development
Dedieu, B.	Qualification of the adaptive capacities of livestock farming systems	2009	Revista Brasileira de Zootecnia
Iraizoz, B.; Gorton, M.; Davidova, S.	Segmenting farms for analysing agricultural trajectories: A case study of the Navarra region in Spain	2007	Agricultural Systems

Sharma, T.; Carmichael, J.; Klinkenberg, B.	Integrated modeling for exploring sustainable agriculture futures	2006	Futures
Paquette, S.; Domon, G.	Agricultural trajectories (1961-1991), resulting agricultural profiles and current sociodemographic profiles of rural communities in southern Quebec (Canada): A typological outline	1999	Journal of Rural Studies
Perrot, C.; Pierret, P.; Landais, E.	Farm trajectories analysis: a way of updating farm typology and of studying local agricultural changes.	1995	L'analyse des trajectoires des exploitations agricoles: une methode pour actualiser les modeles typologiques et etudier l'evolution de l'agriculture locale.

Annex B Supplementary material Chapter 3

Supplementary Figure 1

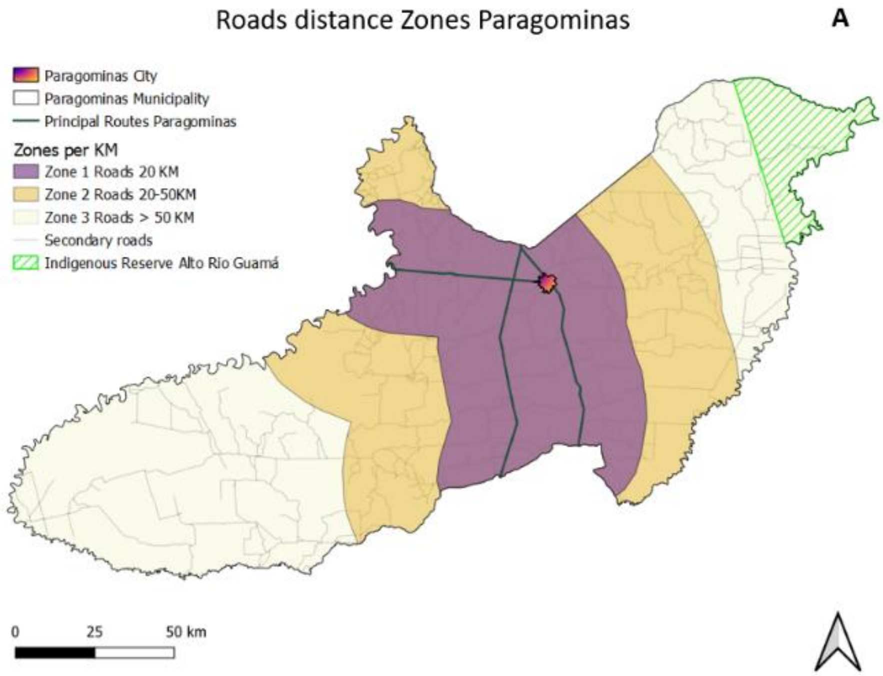

Figure 1A: Paragominas map zones created by the author.

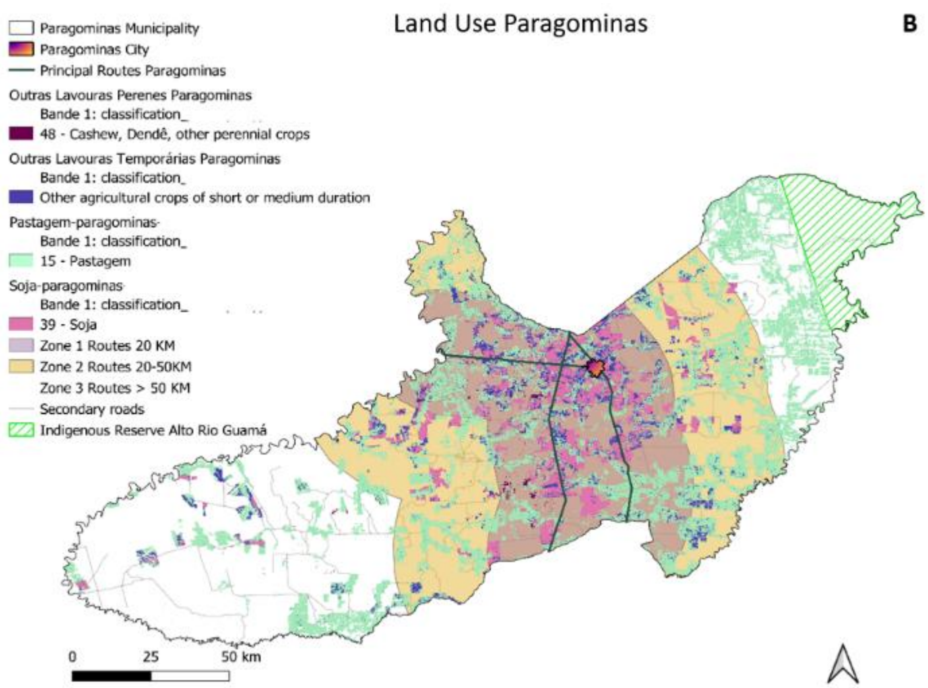

Figure 1B: Paragominas Land Use created by the author based on data from MapBiomas 2022.

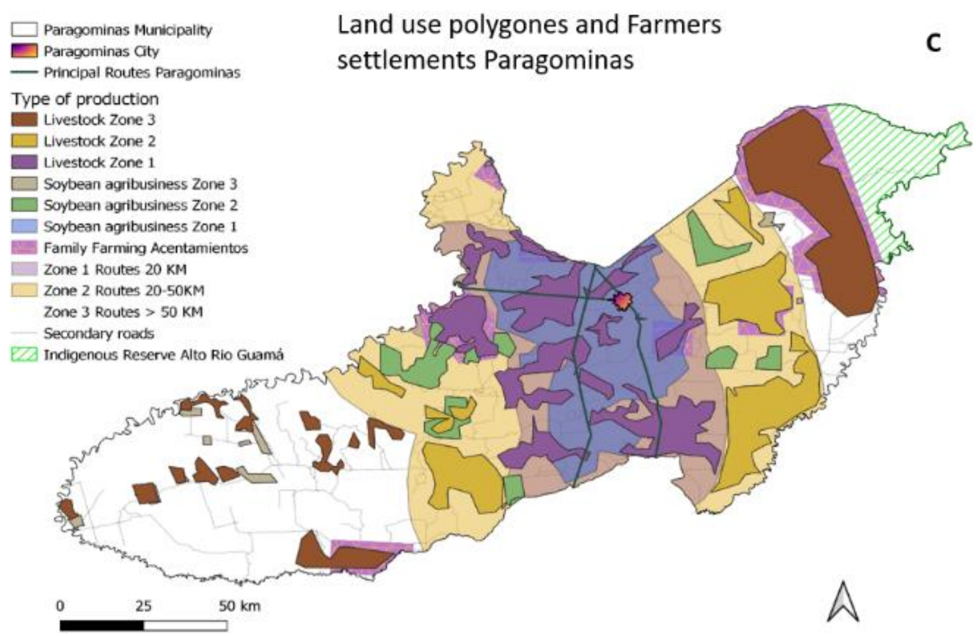

Figure 1C: Paragominas Land use and Farmers Settlements created by the author.

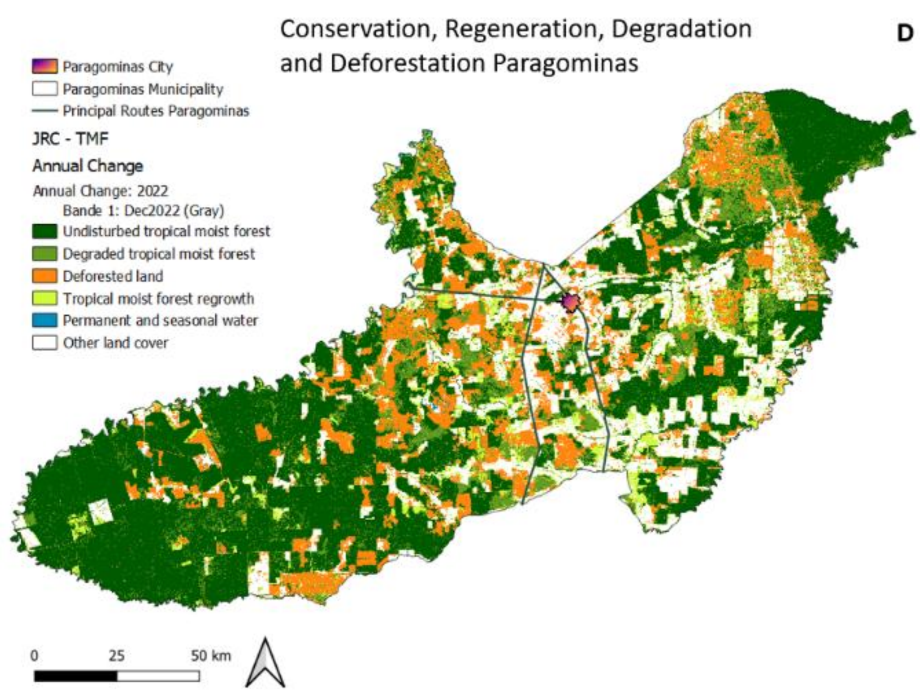

Figure 1D: Paragominas map created by the author based on data from JRC TMF Moist 2022.

Supplementary figure 2 (maps of levels of deforestation, degradation and regeneration per zone roads created by the author based on data from JRC TMF Moist Forest 2022)

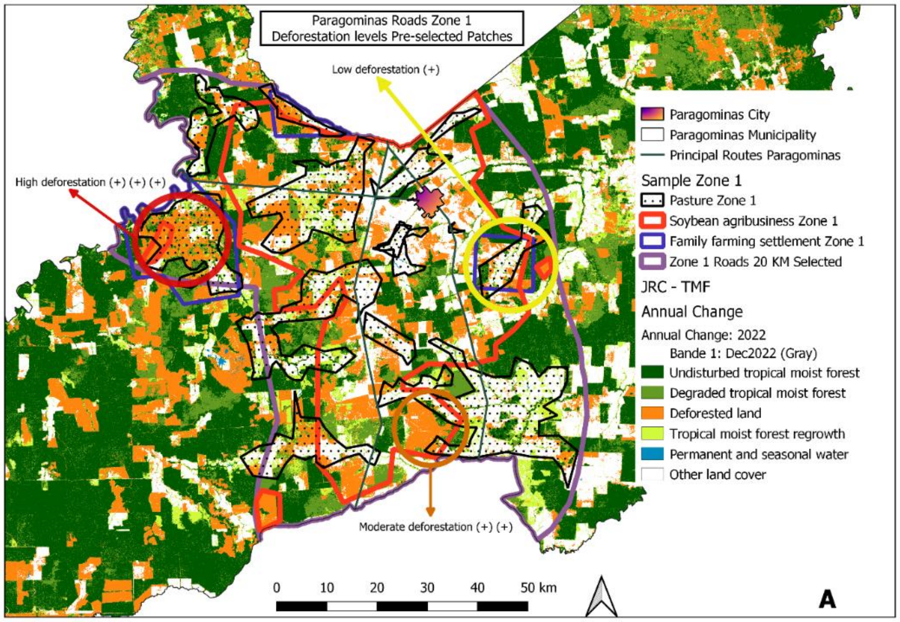

Figure 2A: Paragominas map roads zone 1 deforestation levels created by the author based on data from JRC TMF Moist Forest 2022.

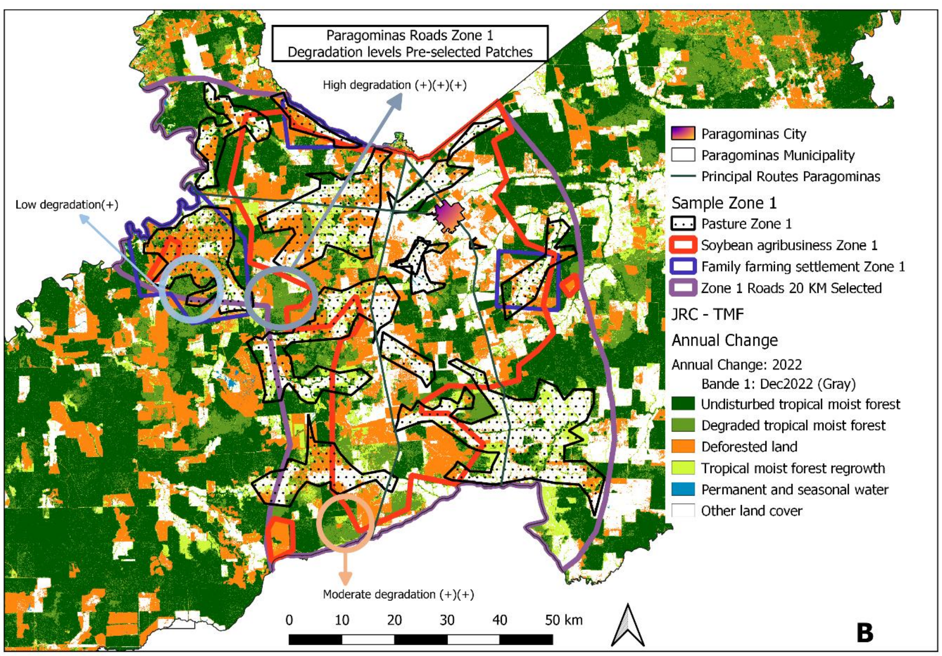

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Figure 2B: Paragominas map roads zone 1 degradation levels created by the author based on data from JRC TMF Moist Forest.

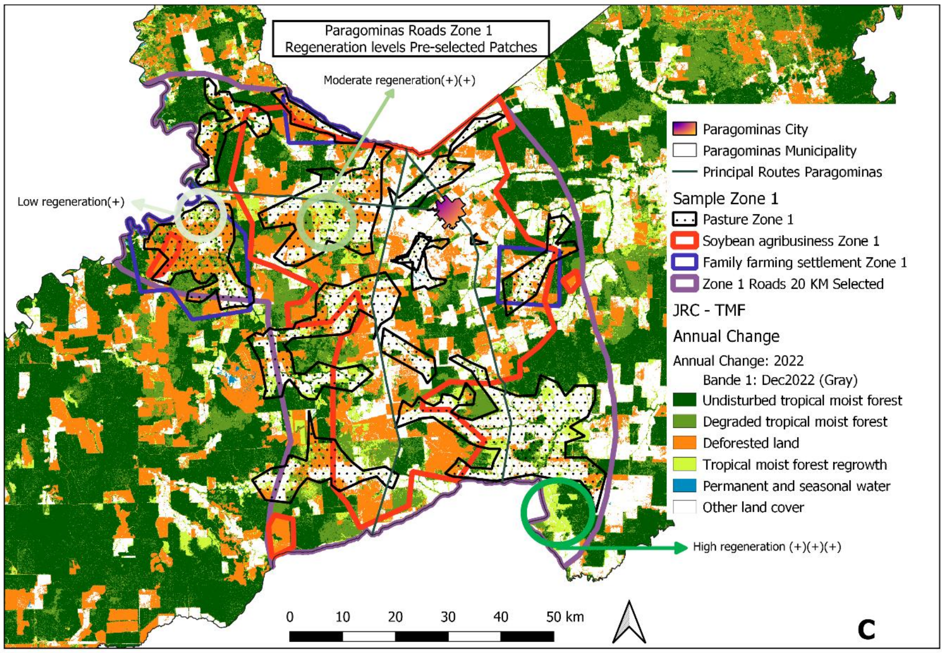

Figure 2C: Paragominas map roads zone 1 regeneration levels created by the author based on data from JRC TMF Moist Forest 2022.

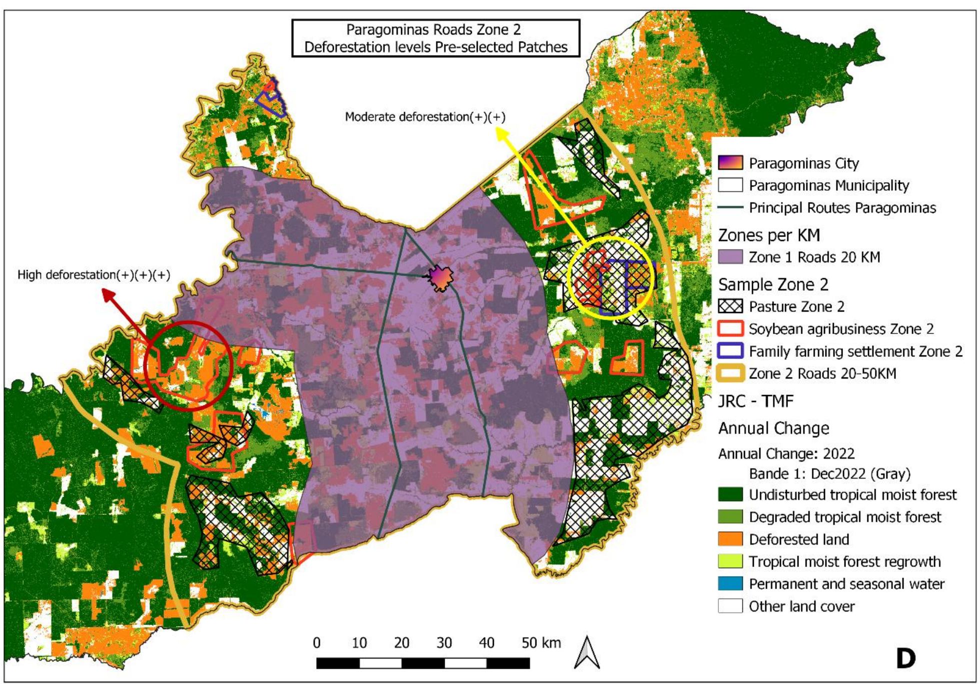

Figure 2D: Paragominas map roads zone 2 deforestation levels created by the author based on data from JRC TMF Moist Forest 2022.

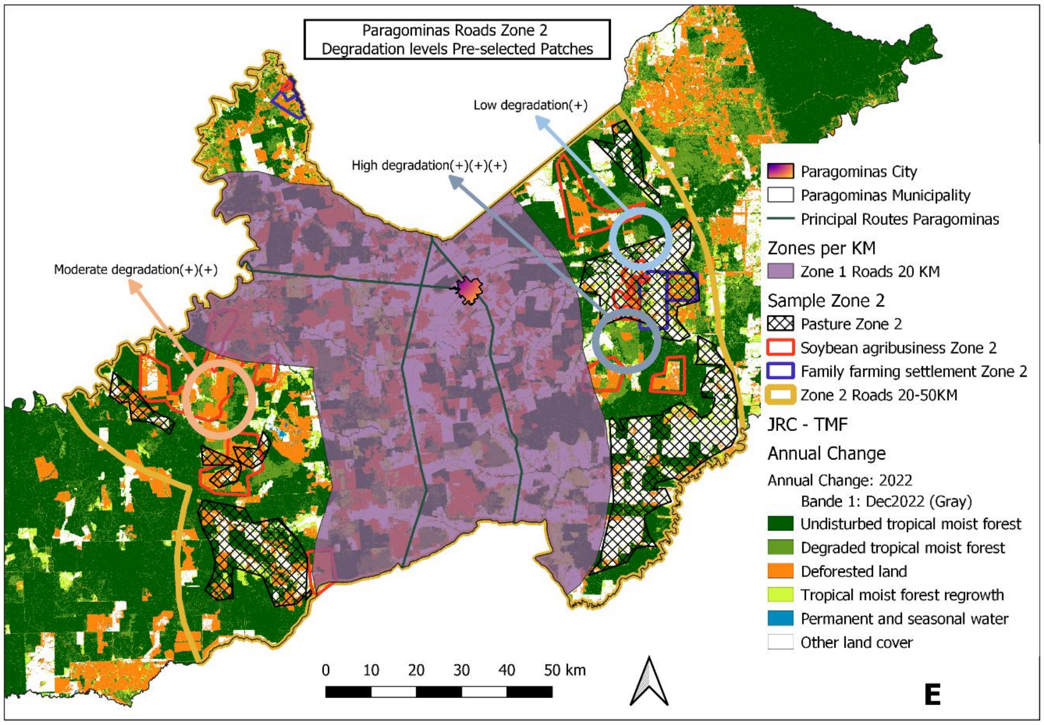

Figure 2E: Paragominas map roads zone 2 degradation levels created by the author based on data from JRC TMF Moist Forest 2022.

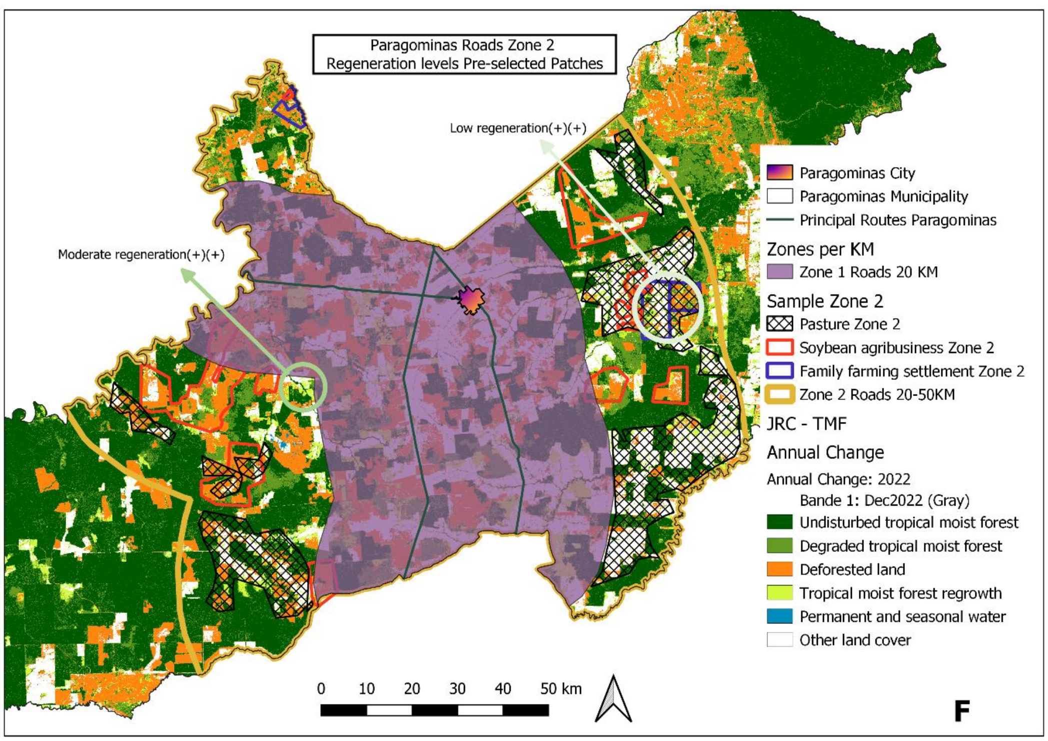

Figure 2F: Paragominas map roads zone 2 regeneration levels created by the author based on data from JRC TMF Moist Forest 2022.

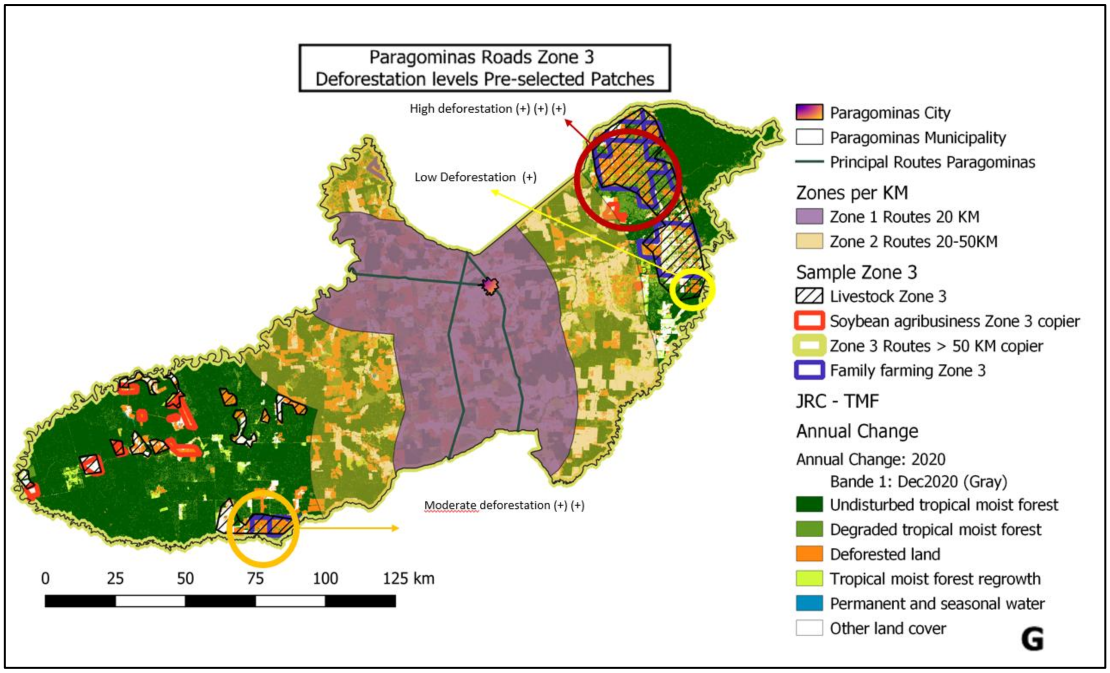

Figure 2G: Paragominas map roads zone 3 deforestation levels created by the author based on data from JRC TMF Moist Forest 2022

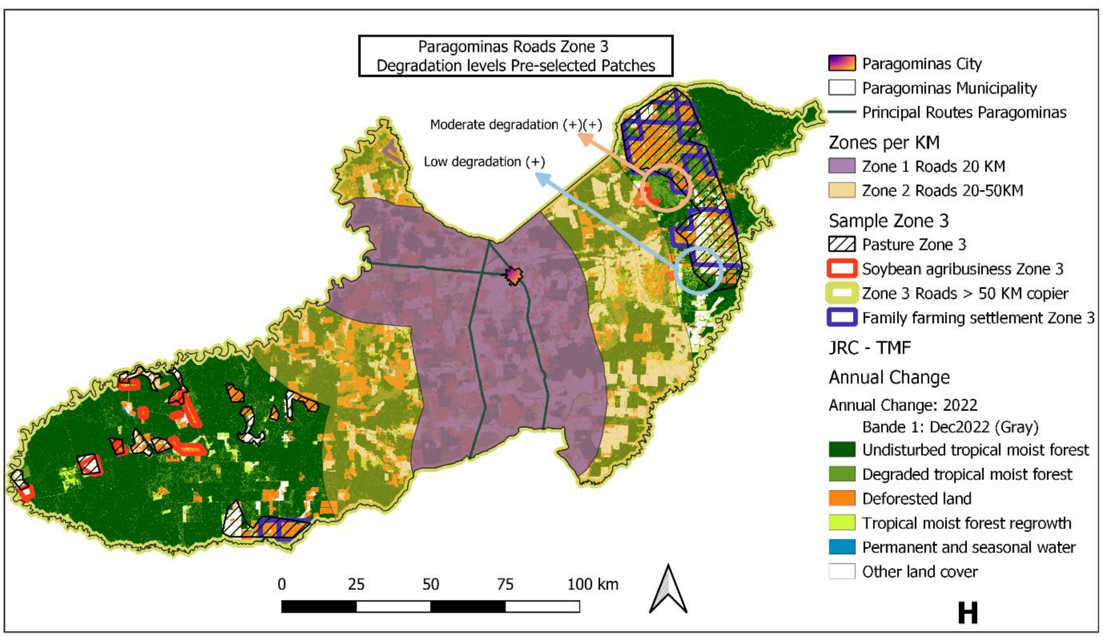

Figure 2H: Paragominas map roads zone 3 degradation levels created by the author based on data from JRC TMF Moist Forest 2022

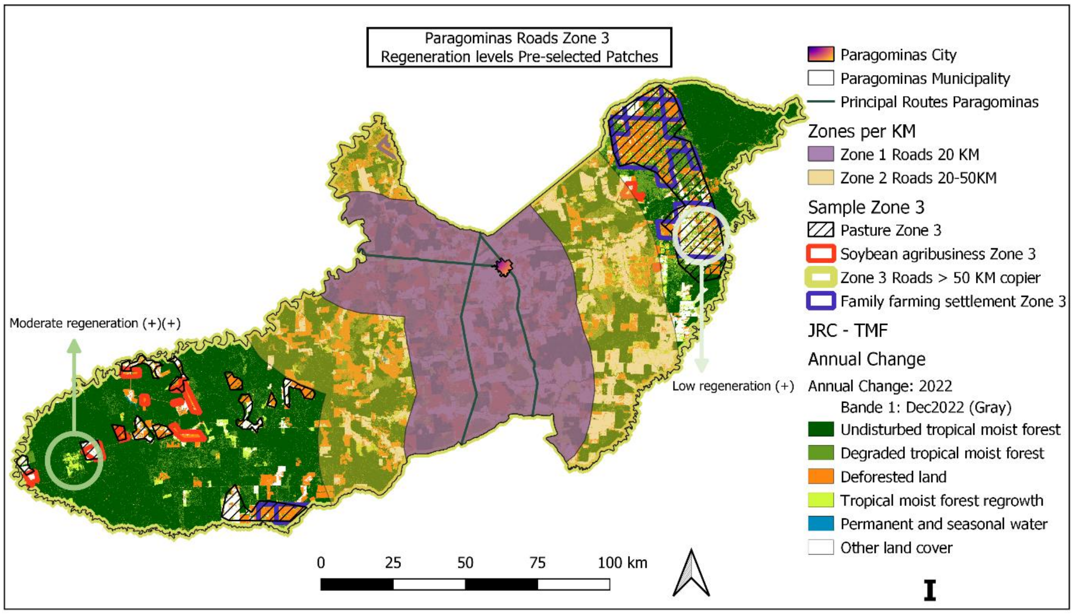

Figure 2I: Paragominas map roads zone 3 regeneration levels created by the author based on data from JRC TMF Moist Forest 2022.

Supplementary figure 3 (diagrams used for construction of farm trajectories)

Figure 3: Farmers constructed their trajectory phases through these diagrams, in a first step describing the current phase of the farm, then the beginning phase. The intermediate phases then were made. Farmers could use as a background the primary or secondary forest depending on what they had the most at that moment of their trajectory. They placed the house at the beginning as a reference to guide them and then the crops or animals they worked with.

Supplementary Material: Semi-structured interview guide

Nombre de la persona: Vereda:

Nombre de la finca: Fecha:

Guía de entrevista de trayectorias del sistema productivo de la finca y agricultor.a

En itálico notas del entrevistador.

Explicar en pocas, quien soy, que hago aquí, en sí, mi objetivo consiste en estudiar las trayectorias de los agricultore.as y sus fincas, es decir la historia desde su instalación en la finca hasta el día de hoy.

1. Historia y origen de la familia

¿Puede contarme como, cuando llego a esta finca, cual fue el proyecto inicial?, ¿sus padres de dónde vienen, son agricultores?

1.1 Cambios radicales

Estamos estudiando los cambios radicales en sus actividades productivos, como cultivos o ganadería que pudieron ocurrirle en la historia de su trayectoria, para comprender cómo, en una época de grandes cambios, consiguieron mantener una actividad agrícola y cuáles fueron las consecuencias para la organización de su finca y el bosque.

Esto es importante para comprender qué margen de maniobra tienen y qué ayudas necesitarían para preservar sus condiciones de producción y el bosque.

¿Piensa que tuvo cambios radicales en su trayectoria?

¿Qué cambio? ¿Como? ¿Por qué?

1.2 Construcción da trayectoria

El objetivo es que a partir de las figuras cada agricultor-a construya su trayectoria. Aquí se construye la fase actual, luego la inicial y después las fases intermedias

¿Podría contarme cuáles son sus actividades en la actualidad en esta finca? ¿Puede utilizar estos dibujos para describir como está la finca?

¿Podría contarme cuales fueron sus actividades cuando llego a esta finca? ¿Con que actividades inicio? ¿Puede utilizar estos dibujos para describir la finca en el inicio?

Desde la fase inicial a la fase actual que describió con las figuras, puede contarme lo que paso entre ellas, ¿qué cambios hubo?

Para comprender de cambios entre fases desde la perspectiva del agricultor.a se pregunta:

¿Cuáles fueron las principales razones de esos cambios entre fases? ¿Se debió al contexto externo o familiar?

¿Puede decirme qué le impulsó a orientar su finca en esta dirección? ¿Quién estaba detrás de esta idea de cambio?

1.2.1 Configuración de grupos de trabajo familiares

(a construir en paralelo con la evolución del sistema productivo)

Miembros de la familia que trabajan en la finca en cada fase

Membro	Edad
Esposo	
Esposa	
Hijo 1	
Hijo/a 2	
Hijo/a 3	
Hijo/a 4	
Hijo/a 5	

1.2.2 Configuración de los sistemas de producción

(a construir en paralelo con la evolución del sistema productivo)

Total	Fase x	Fase x	Fase x
Bosque en HA			
Rastrojo en HA			
Pastos en HA			
Cultivos anuales en HÁ			
Cultivos perenes en HÁ			
Número de cabezas de ganado			
Tamaño de los corrales			
Uso de productos forestales no maderables			

Preguntar se no viene en la conversación ¿Con que herramientas inicio, esto cambio a lo largo del tiempo en las fases?

¿Quien decidió sobre la compra de esas herramientas?

Sabemos que a veces la actividad fuera de la finca permite asegurar los gastos de la familia

¿Usted podría decirme qué actividad dio para los gastos diarios en la fase X, X,X ?

En caso que usted tuvo que gastar mucho dinero de una vez (ej. salud) ¿Ud. que hacía? para la fase X?

¿Ud. como consiguió invertir en esta actividad? ¿Basado en las actividades de las fases, Quien lo decidió? *(Decisiones estratégicas de la finca)*

1.2.3 Organización del trabajo

Quisiera saber quién trabajaba en cada fase de la trayectoria

¿Trabajan todos en la propiedad?

¿Alguno de los miembros tenía un trabajo ocasional fuera de la finca? ¿Qué trabajo? ¿Quien?

¿Alguno de los miembros tiene o tuvo trabajo fijo fuera de la finca? ¿Quién? ¿Cuál trabajo?

¿En las diferentes fases puede explicarme si ustedes contrataron jornaleros? ¿contrataron trabajadores fijos? ¿Para qué trabajos?

A- Papel de las mujeres y los hombres

A.1 Percepción y contribución de la mujer dentro y fuera de la finca. Gestión y toma de decisiones

Ahora vamos conversar sobre las responsabilidades de la familia, de la producción y de la comunidad sobre toda la trayectoria – intentar identificar si tuvo cambios y cuando

Para cada fase de la trayectoria, será peguntado

¿En las actividades que Ud. no participa/trabaja dentro de la finca?

¿Ud tiene responsabilidades especificas en la finca?

Decisiones estratégicas de la finca, Horizonte temporal de la finca

¿Quién se encargar de la de las cuentas, la contabilidad? ¿Qué hacía Ud. dentro de esto?

¿Tiene un dinero propio que puede gastar? ¿Con que actividad?

¿Quien decide sobre la contratación de jornaleros, o sobre quien trabaja qué?

¿Ud. Participa en las ventas, negociaciones de productos de la finca? *Por ejemplo, si la mujer no trabaja con ganado podría no estar en la gestión de venta del mismo.*

Decisiones para organizar los procesos de producción en la finca. Horizonte anual

¿Quién decide sobre los lugares donde se colocan los cultivos, como es tomada la decisión?

¿Utiliza algún tipo de abono para sus cultivos o pastos? ¿lo produce usted o lo compra? ¿Si lo produce, como lo hace? ¿En que cultivos o áreas lo aplica? ¿cuáles utiliza y con qué frecuencia o en qué cantidades por hectárea aproximadamente? ¿Desde cuándo lo usa?

Si responde que lo produce preguntar si es orgánico (e.g., compost o estiércol de sus animales)

¿Utiliza algún producto para matar bichos o enfermedades en los cultivos o en pastos?

Si es así, ¿cuáles utiliza y con qué frecuencia o en qué cantidades por hectárea?

¿Desde cuándo lo hace?

Decisiones para la puesta en marcha los procesos de producción, Horizonte infra anual

¿Como son tomadas las decisiones del día a día, para que funcione la finca?

¿Como considera que ha evolucionado su papel a lo largo del tiempo, antes era diferente? ¿Qué ha cambiado, por qué?

Como mujer, ¿cree que su opinión se tiene en cuenta en la finca, si para qué?

Trabajo no remunerado

¿Qué trabajos no remunerados realizan las mujeres, cuales los hombres?

A.2 Preguntas más generales, enfoque mujeres y principios agroecológicos

Ahora voy a pasar a unas preguntas más generales

¿Cuáles son los desafíos que enfrentan las mujeres en las fincas? ¿existen desafíos específicos (diferente al de los hombres) para las mujeres, en termino de acceso a recursos, económicos, mercados, negociaciones, acceso a proyectos, documentos de la finca o de gestión de la misma, etc.?

¿Tienes el título de propiedad de tu tierra? ¿Este título te da alguna forma de seguridad adicional?

¿La finca está a nombre de quién?

¿A dónde Venden? ¿A quién? es el consumidor final? ¿Desde cuándo venden a ellos?

¿Ud. considera que recibe una remuneración justa por sus productos agrícolas?

¿En su entorno existen espacios para empoderar las mujeres agrícolas en la actualidad, si, cuáles?

¿Forma parte de alguna asociación de agricultores, cooperativa u otro tipo de organización local? Si es así, ¿participa activamente en sus actividades y toma de decisiones?

Si es así, ¿Cuál es su objetivo? ¿Desde cuándo?

¿Intercambia información técnica con otras personas? ¿Con quién? ¿Esto como lo ayuda?

¿Desde cuándo?

¿Como Ud se siente ahora y como siente el bien estar de su familia?

¿Cuál considera que es la diversidad de la dieta de su familia? Además de lo que produce para la venta, ¿cultiva o cría una variedad de alimentos para el consumo de su propia familia? ¿La calidad de los alimentos que compra es buena? ¿qué es un alimento de buena calidad?

1.2.4 Comprensión del a función de regeneración del bosque

Preguntar sobre la regeneración y/o plantación de árboles.

¿Por qué se regenero esa área x o por que se plantaron arboles? ¿Como ocurrió? ¿Que será del futuro de esa parte de bosque regenerado?

1.2.5 Políticas Publicas

Aquí presentaré un soporte gráfico (cronograma) de los mandatos de los últimos 30 años de cada alcalde, gobernador y presidente.

¿Tuvo alguna ayuda o apoyo del gobierno municipal/departamental/nacional, con qué programa, cómo se produjo?

¿en qué medida las políticas públicas locales han influenciado el papel de las mujeres en la agricultura? ¿qué incentivos o programas locales han impactado positivamente el empoderamiento de la mujer?

2. Futuro

Información esencial para los talleres

¿Cómo Ud. se ve en 10 años, como ve a su familia? ¿Qué planes tiene para el futuro?

¿Cuáles son los planes de sus hijos? ¿Piensa transmitir la propiedad a sus hijos? ¿Continuarán con la finca?

2.1 Desafíos

¿Cuál son los desafíos a los que se enfrenta en el futuro?

Tener en cuenta que el futuro hace referencia a los 10 años de la pregunta anterior.

Annex C Supplementary material Chapter 4

Supplementary Table 1 Ideal farm visions Paragominas

Ideal farm vision	Ideal farm description	Number of participants	Patch	Focus group Gender
A-*Bom Jesus* Rotational grazing with a complement of Agroforestry based on açai	Land Use: Pasture: 60%, Roça: 10%; Agroforestry (Açai, Cupuaçu, banana, graviola, barbados cherry and peach-palm): 5%; Fishing farming 4% Other land use: vegetable garden, housing: 1%.	7	Potirita	Mixed
	Forest Coverage**:** 20%			
	Farmer Goals: to initiate the agroforestry system, fishing farming, divide the paddocks			
	Working group configuration: Women manages finance and commerce, share work in all farm.			
B- *Nova Uniao* Agroforestry system with annual crops and pisciculture, Hens, pigs	Land Use: Agroforestry (Cocoa, Açai, banana Brazil Nut): 60%; Roça: 9%, Chocolate factory 1% Other land use: Housing, pigs and hens coop: 1%.	5		
	Forest Coverage**:** 29%			
	Farmer Goals: to add value to cocoa and transform into chocolate, start/improve agroforestry system.			
	Working group configuration**:** Couple + day workers			
C-*Boa Vista* Cattle rotational grazing with a complement of annual crops (roça), açai in monoculture and pisciculture	Land Use: Pasture: 60% Roça: 10%; Pisciculture: 9%, Açai: 10% % Other land use: housing: 1%.	5		
	Forest Coverage**:** 10%			
	Farmer Goals: to divide paddock into 100x100 mts			
	Working group configuration: Couple + day workers, children will not continue with farm.			

D-*Alta Floresta* Agroforestry, pisciculture and cattle rotational grazing	Land Use: Agroforestry (Banana, açai, cocoa and copuaçu): 40%; Pasture: 30% Pisciculture: 8%, % Other land use: housing and fruits garden: 2 %. **Forest Coverage:** 20% Farmer Goals: to install/improve agroforestry, diversify agroforestry, learn how to do it, divide paddocks. Working group configuration**:** Couple + children but not sure about children.	6		
E-Movimento de Mulheres Agricultoras CAIP Região -diversified agroforestry system with a complement rotational grazing cattle for meat production, Hens and Pigs	Land Use: Agroforestry (Açai, Banana, Cocoa, Orange, peach-palm, Gaviola; Cupuaçu and Andiroba, Magno, Ipe): 2%; Pasture: 40%, *Roça*: 1%, vegetable garden: 1%, Other land use: Fishing farming, housing, breeding of small animals (beekeeping, pigs and hens): 6%. Forest Coverage: 50% Farmer Goals: to initiate the agroforestry system, divide the paddocks Working group configuration**:** Couple Woman + Husband, 2- or 3-day workers in high workload period.	6	CAIP	Women Only
F-Sitio do futuro, Agroforestry based on açai with a complement of rotational grazing cattle for meat production, apiculture	Land Use: Agroforestry (Açai, Cupuaçu and cocoa): 28%; Pasture: 20%, *Roça*: 12%, Other land use: vegetable garden, Fishing farming, housing, beekeeping: 16%. Forest Coverage**:** 24% Farmer Goals: to improve the agroforestry system and beekeeping, divide the paddocks Working group configuration**:** Couple Woman + Husband and children but they are not sure about children	6		
G-*Sitio Nova Uniao*-rotational grazing cattle for meat with a complement of an	Land Use: Agroforestry (Açai and Cupuaçu and cocoa): 16%; Pasture: 68%, Fishing farming 9% Other land use: vegetable garden, housing: 1%. Forest Coverage: 6%	5		

agroforestry system and fishing farming	Farmer Goals: to initiate the agroforestry system, fishing farming, divide the paddocks			
	Working group configuration**:** Women manages finance and commerce, all farm work shared by the couple + children if possible			

Supplementary Table 2 Ideal farm visions Guaviare

Ideal farm vision	**Description**	**Number of Participants**	**Patch**	**Focus group Gender**
H-Nuevo Horizonte Silvopastoral system cattle dual purpose	Land Use (average): Pasture: 74 %; *Pancoger*(self-consumption crops): 5%; Other uses (housing, orchards, fish pits, fodder banks, corral): 2%.	13	Unilla	Both
	Forest Coverage (average): 19 %; Range: 3%–35%.			
	Farmer Goals: Genetic improvement and continued division of paddocks with tree fences.			
	Working group configuration: Couple + 1 to 2 children but farmers are is not sure that they stay. 1-to-3-day workers.			
I-*Tierra Esperanza* Silvopastoral system specialized in meat	Land Use (average): Pasture: 83 %; Pancoger: 2%; Other uses (housing, orchards, fodder banks, corral): 1%.	2		
	Forest Coverage average: 14 %; Range: 11%–26%.			
	Farmer Goals: Improving genetics and fattening practices, divide paddocks and have watering troughs for cattle			
	Working group configuration: Couple + 2 children but farmers are is not sure that they stay. 1 Permanent worker.			
J-Integral farm: Diversified farm of cattle dual purpose with agroforestry	Farm Size (HA) Range: 25-35HA	2		
	Land Use (average): Pasture: 59 %; Pancoger: 1.9%; Agroforestry based on peach palm and cocoa: 13.7 % Other uses (orchards, fish pits, fodder banks, housing.): 0.8 %.			
	Forest Coverage average: 24.6 %; Range: 19.8%–29.4%.			

	Farmer Goals- To realize all the paddocks of 1ha and livestock aqueduct. Have a forage bank, buy a milking machine, add value to cocoa and peach-palm. Looking for better genetics of milking cows. Working group configuration: Couple + 2 children but farmers are is not sure that they stay. 2 to 5 Day workers.			
K-*Tierra bella* Agroecoturism farm with a Silvopastoral system of dual-purpose livestock and agroforestry	Land Use: Pasture: 50 %; Pancoger: 10%; Agroforestry based on peach palm and cocoa:20% Other uses (housing, orchards, fish pits, fodder banks, hens coop): 5%. Forest Coverage**:** 15% Farmer Goals: improvement of tourist trails, division of paddocks with aqueducts, better management of cocoa and peach palm, installation of fish ponds. Working group configuration**:** Day workers would be employed, with the woman managing the farm and the man farming. They do not know if the children will continue on the farm.	5 (1 children)	Guacamayas	Women only
L-*Finca del Ganado sostenible* Silvopastoral system cattle dual purpose	Land Use: Pasture: 60 %; Pancoger: 5%; Big paddock with corral 5%; fishing farming: 5%. Other uses (housing): 5% Forest Coverage**:** 20% Farmer Goals: reduce paddocks and get better milk cow genetics Working group configuration**:** The woman managing the farm and the man farming. They do not know if the children will continue on the farm. 1-to-3-day workers.	5 (1 children)		
M-*Finca del manana* Agroforestry farm based on peach palm complemented by dual-purpose silvopastoral system.	Land Use: Pasture: 55 %; Agroforestry based on peach palm and some cocoa :10%, Pancoger: 10%, Corral: 5% Other land uses (housing, orchards, fish pits, hens coop): 5%. Forest Coverage: 5% Farmer Goals: increasing peach palm production and divide the paddocks. Working group configuration**:** Couple + children but farmers are is not sure that they stay. Youngs in the group stated that they do not want to stay in farms	5 (1 children)		

N-*El futuro del campo* dual-purpose silvopastoral system with Agroforestry farm based on peach-palm	Land Use: Pasture: 60 %; Agroforestry based on peach palm: 10%, Pancoger: 2%, Other land uses (housing, orchards, vegetable garden, fish pits, hens coop): 3%. Forest Coverage: 25% Farmer Goals: to make paddocks with drinking troughs, to enlarge the peach palm crop, Working group configuration: Couple + children, present children said that they do not want to stay in the farm.	4 (1 children)		

Supplementary Table 3 Traversal pushes and weights Paragominas

Push of the present	**Weight of the past**
PTP1- Farm structure and new practices: • PTP1A Paddocks division • PTP2B Rotational cattle grazing practice • PTP1C Seedlings for AFS and first crops on AFS PTP2- Knowledge and experience: • PTP2A Experience on cattle and crops management PTP3-NGO's support: • PTP3A Tractor lending from (not NGO but Cirad) • PTP3B Imazon courses AFS, composting. PTP4-Local and federal Government support: • PTP4A Maintenance of bridges and roads • PTP4B School transportation • PTP4C Seedling's provision for AFS • PTP4D Tractor lending for plowing • PTP4E New health post and one health agent for community PTP5: Farmer Association: • PTP5A Communities represented by the forum • PTP5B strong associations, **particularly in Potirita**	PTW1 Lack of knowledge and technical assistance: • PTW1A in cattle rotational grazing • PTW1B in agroforestry systems PTW2 Credit access PTW3- Role of government: • PTW3A Roads in poor condition • PTW3B Lack of school transportation • PTW3C The lack of land title PTW4-Externalities of farm neighborhood: • PTW4A Pesticides from agribusiness affect our crops, bushes and water. PTW5- Health: • PTW5A Workforce reduction due to illness • PTW5B Lack of health posts PTW6- Political representation: • PTW6A Lack of coordination among associations at municipality level that results on absence on political representation

PTP: Potirita transversal push; PTW: Potirita transversal weight

Supplementary Table 4 Specific pushed and weights Paragominas

	Specific push of the present	**Specific weight of the past**
Potirita	SPP1-Farm structure and new practices: • SPP1A no-fire roça pact SPP2- Government support: • SPP2A Technical assistance and courses from local government with agronomists in cocoa and provide cacao seeding since 2022 • SPP2B Provision of water and electricity SPP3- Association of farmers: • SPP3A Strong organization for Land regularization • SPP3B Lending tools for cultivation, seed exchange	SWP1 Lack of knowledge and technical assistance: • SWP1A lack of knowledge in cocoa • SWP1B lack of technical assistance for seedling maintenance (cocoa, açai) SWP2 Role of government: • SWP2A Lack of water for consumption and production • SWP2B Lack of electricity SWP3 Market: • SWP3A Lack of transportation to the market SWP4 -Externalities of farm neighborhood: • SWP4A large landowners have the political power to block the land regularization process and pressure us to sell our land. SWP5-Pest: • SWP5A- Crop pests, ticks, flies on cattle SWP6- Climate change:

		• SWP6A Strong droughts
Ciap	SPC1-Farm Structure and new practices: • SPC1A women managing the farm (more and more women working on the farm) SPC2- Educational support: • SPC2A Women participation in courses on plowing tractors, SENAR (for women only) • SPC2B Courses on beekeeping, control pests of the roça, cooking for pluriactivity (SENAR). SPC3-Government support: • SPC3A Provision of fish tanks, with a breeding course by the local government • SPC3B The local government organizes market for sales but it's small • SPC3C PNAE (Federal policy) help to develop market of vegetable garden • SPC3D a Women health agent per community SPC4-Women in Associations: • SPC4A Women's participation on the communities' forum (young also participate) • SPC4B Women's participation on CONTAG and FETAEG, take on leadership positions in CAIP, to make demands that affect women (e.g support in separations and agroecological projects/food security	SWC1 Women Credit access: • SWC1A Women have less access to credit because they say they are less connected than men (most associations are run by men for men, plus they don't have time available because of their triple role, home, farm and family) • SWC2B PRONAF and FNO projects focused on cattle, without technical assistance and for men. At that time, it was more difficult for women because they didn't have the knowledge to work with cattle SWC2 Role of government: • SWC2A Lack of support for women-only initiatives, such as the community vegetable garden employing women's labor. • SWC2B Policies and projects badly planned, e.g. municipal government project on pineapples that had no market. Lack of communication between political representatives and the community about the community's real problems, such as markets and schools SWC3 Market: • SWC3A Lack of market for crops SWC4-Pest: tapirs eat crops, bush pigs too SWC5-Workforce is scarce and getting more expensive every day SWC6-Schools are being closed SWC7- The associations are manly led by men: • SWC7A There has never been a women's cooperative. • SWC7B Lack of unity between the associations in CAIP, sometimes it's political. SWC8 - Lack of access to health care for women

SPP: Specific Push Potiria; SWP: Specific Weight Potirita; SPC: Specific Push Caip; SWC: Specific Weight Caip

Supplementary Table 5 Traversal pushes and weights Guaviare

Push of the present	Weight of the past
GTP1-Farm structure and new practices: • Silvopastoral systems are being established with elevated tanks, corrals, paddocks division, fodder banks, cattle drinking trougs. GTP2-Knowledge and experience: • GTP2A Farmers have cattle and diary production, annual crops and vegtable gardering experince • GTP2B Since 2019, they have lerned how to rotate cattle GTP3-ONG's support: • GTP3A The farmers expressed that the Caminemos project played an essential role in the division of pastures and aqueduct for cattle, they also received rotational credits (rotation b/t farmers) • GTP3B Training on good dairy practices and SPS (Teat Washing, Drying and Sealing) by Caminemos(in unilla) and Terramaz, executed by ONF • GTP3C The GEF Amazon project helped them with support to cattle rotational grazing (seeds, fertilizers and training) GTP4-Government support: • GTP4A Farmers have been trained in cattle fodder banks and veterinary by the departmental government • GTP4B Projects to convert to sustainable livestock farming based on a silvopastoral rotational grazing system, including live fences by CDA • GTP4C Gov. improved some roads GTP5-Associations: • GTP5A Strong associations in each patch that allow them to organize and attract projects/financial resources. These associations are involved in productive alliances with the departmental government, which allowed them to obtain tanks and wire for the fences. • GTP5B Associations have improved some roads GTP6 Environmental Conservation: • GTP6A Farmers expressed having forest conservation practices, supported mainly by SINCHI and CDA, which include preserving water resources, having a forest reserve area, climate change awareness and a commitment to care for the environment • GTP6B Farmers who want ecotourism claim to have sufficient forest areas for this practice GTP7- Market: Lácteos del Guaviare buys milk from us and is a safe commercial partner, they are some buyers of peach palm	GTW1-Lack of knowledge: • GTW1A Farmers had no training on livestock, no knowledge of silvopastoral systems • GTW1B no training on cocoa or peach palm, and no training on how to transform these crops GTW2-Lack of vision: • GTW2A Lack of vision due to illicit coca crops • GTW2B In the beginning we focused on traditional slash-and-burn crops for self-consumption GTW3-Role of government: • GTW3A Roads in poor condition • GTW3B There was a lack of aid from public entities for electricity and health • GTW3C Lack of credibility in government institutions, non-compliance by PNIS on illicit crops GTW4-Market: • GTW4A 15 years ago there was no trade for products, cattle, for milk • GTW4B The local markets for the crops are quickly saturated and the price goes down, this happens until today GTW5-Day worker are expensive and harder to find GTW6-Lack of machinery Lack of tractors for plowing the land GTW7-Armed conflict • GTW7A Forced displacement, Separation of families, money to be paid, Fear of recruiting their children • GTW7B Women left without their husbands because of the conflict GTW8-Soil Quality: • GTW8A Land unsuitable for cultivation due to soil acidity • GTW8B Soil degraded by coca glyphosate fumigation • GTW9 Land title, overlapping indigenous land

GPT8-Farmers have electricity and health post access GPT9-Peace agreement Post conflict GPT10-Electricity on both since 2019-2020	

GTP: Guaviare Transversal Push; GTW: Guaviare Transversal Weight

Supplementary Table 6 Specific pushes and weights Guaviare

	Specific push of the present	Specific weight of the past
Unilla	SPU1-Rotational fonds (*Camimemos* and *Terramaz*) SPU2-Sena Risk Training	SWU1-Lack credit access SWU2-Investment loss risk SWU3-No training in cocoa crops and cocoa processing SWU4-The farmers remarked that they are not clear about what type of cattle genetics they are looking for. SWU5-Low incomes of agricultural activity
Guacamayas	SPG1 Knowledge and experience • SPG1A Farmers have received training from SENA for peach palm crops and soil fertilization. They have training on organic fertilizers by SINCHI. • SPG1B GEF Amazonia training in peach palm production SPG2-Women participate on local cattle markets SPG3-Peach-palm has a commercial market outlet: National federation of peach-palm (FENACHO) and inclusion of the productive line of peach-palm in the Guaviare government SPG4-There is a new association (2022) focused on developing farms ecotourism in farms	SWG1-Lack of machinery for peach palm transformation SWG2-No training in peach palm crops and cocoa processing SWG3-Lack of markets for peach palm SWG4-Climate change: Strong Rainfall that affects roads and access to markets for peach palm SWG5-Heavier workload for women who have to support the house, family and farm SWG6-Lack of confidence to establish an agricultural project without men SWG7-Lack of Agroecotourism infrastructure SWG8-Pests and diseases in peach-palm crops, *cucarron picudo*, fungi, parrots and monkeys eat it

SPU: Specific Push Unilla; SWU: Specific Weight Unilla; SPG: Specific Pushes Guaviare; Specific Weights Guaviare

Supplementary Table 7 Transversal Tension Paragominas

Transversal Tensions	Lever
PTT1- (PTW1) Lack of knowledge, technical assistance (PTW1A cattle rotational grazing, PTW1B AFS) assistance VS (PTP1) Farm structure and new practices, (PTP2) Knowledge and experience (PTP3) NGO's, (PTP4C, PTP4D) Local and federal Government support	N/A
PTT2-(PTW2) Credits Access vs Nothing 🛇	PTL1 Negotiate with credit institutions
PTT3- (PTW3) Role of government (PTW3A poor roads-PTW3B school transportation) vs (PTP4) Local Government support (PTP4A and PTP4B) (△ for CAIP)	N/A
PTT4 – PTW3 Role of government, (PTW3D) Land titling Vs (PTP5B) Association Potirita and CAIP △	N/A
PTT5- (PTW4) Externalities of farming neighborhood (PTW4A pesticides) vs Nothing 🛇	PTL2.1 Potirita Negotiate from association PTL2.2 CAIP Evidence of pesticide damage, raise community awareness
PTT6 - (PTW5) Health: (PTW5B lack of health post, PTW5A reduce workforce) vs PTP4 Local Gov (PTP4E Health post and agents) △	N/A
PTT7-(PTW6) Political representation(PTW6A) vs PTP5 Paragominas rural community's forum △	N/A

Transversal tensions in Paragominas two ideal farms in Potirita (Pot_RG_ASF and Pot_AFS). CAIP has only one ideal farm (CaipRG_AFS). Tensions are classified: Partially Resolved Tension: △ , Unresolved Tension: 🛇 . PTT: Paragominas transversal Tension, PTW: Paragominas transversal Wight, PTP: Paragominas transversal push. N/A: not applicable.

Supplementary Table 8 Specific Tension Paragominas

Patch	Specific Tensions	Specific Lever
Potirita	STP1- (SWP1) Lack of knowledge and technical assistance (SWP1A and SWP1B) vs SPP2 Local gov. support (SPP2A), (SPP1A) No fire roça pact, (SPP3B) lending tools for cultivation, seed exchange b/t farmers.	N/A
	STP2-(SWP2) Role of Gov (SWP2A) lack of water and (SWP2B) electricity VS (SPP2B) gov. support △	N/A
	STP3- SWP3 (SWP3A) Market transport vs Nothing ⊘	SLP1 Negotiate with the municipality gov. via the rural community's forum
	STP4- (SWP4) Externalities of the agribusiness, (SWP4A) land pressure vs (SPP3A) association for get land title △	N/A
	STP5-(SWP5A) Pest vs Nothing ⊘	SLP2 Organize a course for control pest at the settlement
	STP6-(SWP6) Climate change, (SWP6A) Strong droughts vs Nothing ⊘	SLP3 Respect the Forest reserve at farms level
CAIP	STC1-(SWC1) Women Credits Access (SWC1A, SWC2B) credits for women vs Nothing ⊘ ♀	SLC1: Negotiate with credit institution via the rural community's forum
	STC2-(SWC2) Role of Gov, (SWC2A) lack of support women initiatives vs (SPC3C) PNAE, (SPC1A) women managing the farm (SPC2A SPC2B) Women on SENAR courses △ ♀	N/A
	STC3- SWC2 (SWC2B) Policies bad planned vs Nothing ⊘	SLC2 Dialog with the municipality gov. via the rural community's forum
	STC4-(SWC3A) lack of market for crops vs SPC3 (SPC3B) Local gov. organize markets △	N/A
	STC5-(SWC4) pest (Tapirs, bush pigs) vs Nothing ⊘	SLC3 Find a biologist through association
	STC6- SWC5 workforce scarce vs nothing ⊘	SLC4 Find with SENAR educational programs with technology to motive young to stay
	STC7 (SWC6)-School being closed vs Nothing ⊘ ♀	SLC5 Dialog with the municipality gov. via the rural community's forum
	STC8-(SWC7) Association for men (SWC7A) vs SPC4-(SPC4A) Women on associations △ ♀	N/A
	STC9-SWC7 (SWC7B) Lack of unity between the associations in CAIP vs SPC4 Women on associations leadership positions and on rural community forum (SPC4A and SPC5B) △ ♀	N/A
	STC10- (SWC8) Lack health access women vs (SPC3D) women health agent for a community △ ♀	N/A

Potirita ideal farms (Pot_RG_AFS and Pot_AFS). CAIP has only one ideal farm (CaipRG_AFS). Tensions are classified: Partially Resolved Tension: △ , Unresolved Tension: ⊘. STP: Specific Tension Potirita, SLP: Specific Lever Potirita, STC: Specific Tension Caip, SLC: Specific Lever Caip, N/A: not applicable

Supplementary Table 9 Transversal Tension Guaviare

Transversal Tensions	Lever
GTT1-(GTW1A, GTW1B) Lack of knowledge on cattle **VS** (GTP3B) Training on good dairy practices, (GTP3C) GEF training on rotational grazing management practices. (GTP4A) Training in cattle fodder banks and veterinary by departmental gov, (GTP2A, GTP2AB) experience on cattle rotational grazing, and diary production, annual crops and vegetable garden	N/A
GTT2-(GTW2A) Lack of vision due to illicit coca crops and (GTW2B) subsistence slash and burn farming **VS** a model of farm (GTP1, GTP3A) farm infrastructure for this system (paddocks division, fodder banks, cattle drinking trougs) and (GTP3A) support of projects *Caminemos* and (GTP4B) CDA for SPS. (GTP6A GTP6B) Forest reserve area for climate change (preserve water) and (GTP5A) strong associations	N/A
GTT3-(GTW3A) Roads in poor condition **VS** (GTP5B GTP4C) Associations and Gov have improved some roads△	N/A
GTT4-(GTW3B) Lack of electricity and health **VS** (GPT8 GPT10) access to electricity and health post service△	N/A
GTT5-(GTW4A-GTW4B) Lack of markets and then saturation of markets (volatility of prices) **VS** (GPT7) Commercial alliances for milk and markets for peach-palm△	N/A
GTT6-(GTW7A) Armed conflict: Forced displacement, money to be paid, separation of families, Fear of recruiting their children **VS** (GPT9) Peace agreement Post conflict△	N/A
GTT7-(GTW3C) Lack of credibility in government **VS** Nothing	GTL1 Negotiation tables
GTT8-(GTW5) Workforce scarce **VS** Nothing	GTL2 Purchase tractors through associations and projects
GTT9-(GTW6B) Lack of tractors for plowing the land **VS** Nothing	GTL2 Purchase tractors through associations and projects
GTT10-(GTW9) Land title **VS** Nothing	GTL3 Negotiate with the National Land Agency
GTT11-(GTW7B) Women alone because of the conflict **VS** (GPT9) Peace agreement△ ♀	N/A

The transversal tensions have the same weight per patch regardless of the different ideal farms. Tensions are classified: Partially Resolved Tension: △ , Unresolved Tension: . 1.GTT: Guaviare Transversal Tension, GTW: Guaviare Transversal Weight, GTP: Guaviare Transversal Push, GTL: Guaviare Transversal Lever, N/A: not applicable

Supplementary Table 10 Specific tensions Guaviare

Patch	Specific Tensions	Specific Lever
Unilla	ST1-(USW1) Lack credit access and risk of losing investments vs (USP1, USP2) Rotational fonds and SENA risk training △	N/A
	STU2-(USW3) No training for cocoa vs Nothing 🛇	SLU1-Seeking cocoa training through the National Training Service (SENA) via the association.
	STU3-(USW4) The farmers expressed uncertainty on the specific type of cattle genetics they seek vs Nothing 🛇	SLU2-Financing an expert in cattle genetics through the association
	STU4-(USW5) Low income in agricultural activity vs Nothing 🛇	SLU3 Create a green seal for meat cattle through the association
Guacamayas	STG1-(SWG1) Lack of machinery for peach palm transformation vs Nothing 🛇	SLG1 Financing peach palm machine through an association
	STG2-(SWG2) No training in peach palm crops vs (SPG1A and SPG1B) training Peach palm, SENA and Sinchi △	N/A
	STG3-(SWG3) Lack of markets for peach palm vs (SPG3) FENACHO and productive line of Peach-palm △	N/A
	STG4-(SWG4) Climate change: Strong Rainfall vs Nothing 🛇	SLG2 Preserve Forest reserve
	STG5-(SWG5) Heavier workload for women vs Nothing 🛇 ♀	SLG3 Create women's associations to strengthen their empowerment.
	STG6-(SWG6) Lack of confidence to establish an agricultural project without men vs Nothing 🛇 ♀	SLG3 Create women's associations to strengthen their empowerment.
	STG7-(SWG7) not agroecoturism infrastructure vs Nothing 🛇	SLG4 Obtain financing projects through the association to invest in tourism infrastructure.
	STG8-(SWG8) Pests and diseases in peach-palm crops vs (SPG1B) training in peach palm by SINCHI △	N/A

Resolved Tension: △ , Unresolved Tension: 🛇. STU: Specific Tension Unilla, SLU: Specific Lever Unilla, STG: Specific Tension Guacamayas, SLG: Specific Lever Guacamayas. N/A: not applicable.