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Unravelling the diversity and the temporal dynamics of inter-row management in smallholder immature rubber plantations in Thailand

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A R T I C L E I N F O

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A B S T R A C T

Today, enhancing the sustainability of rubber-based cropping systems is crucial to ensure sufficient production to meet the growing demand for natural rubber while limiting negative impacts. Inter-row management during the immature period of rubber is particularly important to establish a viable and productive plantation in the long term while starting production as soon as possible. Two main inter-row management options exist in smallholder rubber plantations in Thailand, mono-cropping and intercropping systems. Inter-row management is usually characterized and assessed based on the choice of the crop while the associated technical operations remain poorly considered in the literature. We undertook the detailed characterization of inter-row management including the diversity of technical operations used during the immature period of rubber systems in three contrasted provinces in Thailand. Semi-directive interviews were conducted on 137 plantations intercropped with cassava in Buriram, pineapple in Rayong, upland rice in Trang or with rubber grown as a mono-crop in these three provinces. The 'Typ-iti' method, combining multivariate analysis, clustering and association rules was used to explore the diversity of technical management routes (TMRs). A wide range of inter-row TMRs was observed in each cropping system. The clusters were distinguished according to several management steps along the TMR, making them more complex to characterize than with a single management step or an overall gradient of intensification, especially in cassava and upland rice systems. In the mono-cropping systems, the diversity of inter-row management concerned the technical operations used to control weeds, and differences were identified both within and between provinces. No temporal changes in the TMRs were observed either in the same plot for cassava, upland rice, or in the mono-cropping systems in Rayong, whereas some adjustments over time were identified in pineapple systems in Rayong, i.e. a reduction in the use of chemical fertilizers and herbicides. In mono-cropping systems, the number of weeding operations was reduced in Buriram while in Trang, changes in weeding methods were observed from one year to the next. Among the technical operations identified, those used for pineapple cultivation were the most intense, although there was considerable variability among pineapple growers. This study highlights the wide range of technical operations currently used for managing the inter-rows during the immature period of rubber systems in different contexts in Thailand that may result in varying sustainability performances at plot level. Any evaluation of systems used during the immature period of rubber should thus include management diversity, with both the choice of the intercrop and associated technical operations, to better understand performance variability.

1. Introduction

The rubber tree (*Hevea brasiliensis*) is a major cash crop tree in the tropics, particularly in Thailand, where in 2022, rubber plantations accounted for 3.9 million ha, i.e. 14 % of the total agricultural area (Wang et al., 2022; OAE, 2023). The rapid expansion of rubber

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producing areas in recent decades, in addition to large surface areas replanted with mono-cropping systems have raised questions about the sustainability of current rubber systems. Recent studies have highlighted the long-term negative effects of rubber cropping systems on environmental components including the soil (Panklang et al., 2022), water resources (Häuser et al., 2015) and biodiversity (Ahrends et al., 2015), coupled with new economic and social challenges (Häuser et al., 2015; Tongkaemkaew and Chambon, 2018; Lehoux et al., 2019). Today, designing and promoting more sustainable rubber-based systems is crucial to ensure sufficient production while limiting negative impacts.

Throughout the lifespan of the rubber tree, the immature period is rarely included in questions linked to the sustainability of rubber systems, despite its potential impacts (Bessou et al., 2013; Simon et al., 2017). During this initial period, which generally lasts 6–7 years, farmers have two objectives: (1) to establish a viable and productive plantation in the long term and (2) to start natural rubber production as soon as possible to obtain an income from natural rubber. Management practices used in both the rubber rows and the inter-rows are key to achieving these objectives (Vrignon-Brenas et al., 2019; Burgos and Ortuoste, 2020). In standard rubber plantations (i.e. a single row of rubber trees planted at a mean density of 500 trees.ha^{-1}), inter-rows represent around 75 % of the surface area. Due to the availability of resources in the inter-rows, especially during the first four years before closure of the rubber canopy, managing the inter-rows is crucial not only to ensure the viability and productivity of the plantation but also to increase the provision of other services (Schroth and Ruf, 2014; Simon et al., 2024).

When designing sustainable cropping systems, a diagnosis including characterization followed by an assessment helps identify the strengths and weaknesses of existing systems (Simon et al., 2017; Perrin et al., 2023). The three specific aims of characterization are to (1) understand the range of different management options that result from strategic and tactical decisions taken by farmers depending in their objectives, perceptions and production context (Cittadini et al., 2008; Therond et al., 2017); (2) acquire key information for the assessment, since the management, functioning and performances of a cropping system are intrinsically linked (Meynard et al., 2001); (3) identify how opportunities for innovation or adaptation have already been grasped by the farmers. Characterizing cropping systems involves first identifying the crops and then identifying the 'technical operations' (TOs; i.e. the actions taken or choices made by the farmer concerning the plot for each and every crop (Akakpo et al., 2021)). According to Wezel et al. (2014), a cropping system is characterized by five management steps: (1) the choice of the crop and of the variety, the spatial distribution of the crops, and crop successions over time; (2) tillage; (3) fertilization; (4) irrigation; and (5) weed, pest and disease management. Also, since technical operations are linked and are scheduled by farmers in a logical sequence, their description should include this sequence in what we call a 'technical management route' (TMR) (Renaud-Gentié et al. 2014; Sébillotte 1974).

The use of different cropping systems in the inter-rows of immature rubber plantations has already been documented, with systems ranging from mono-cropping with intense control of weeds to diversified rubber-based cropping, with a wide range of possible crop associations (Simon et al., 2024). All the systems are usually characterized based on the first management step, i.e. the choice of the crop and of the variety, the spatial distribution including the planting density, and crop successions. Studies of the technical operations linked to the other management steps are rare in the literature. Yet, a range of different technical operations can be used for a given crop, in the same or in different plantations, due to multiple agricultural factors. Firstly, in Thailand, the fact that 90 % of the total area under rubber is managed by smallholders, may have led to a wide diversity of TOs, due to structural differences between farms, the farmers' objectives and their know-how (Sail and Muhamad, 1994; Cheyns and Rafflegeau, 2005). Secondly, most rubber plantations in Thailand are located in three regions (North-East, Central and South) in which the socio-historic contexts of rubber development and the pedo-climatic conditions are contrasted (Fox and Castella, 2013; Gohet et al., 2015). Finally, the temporal dynamics of the above- and below-ground biophysical conditions in the same plot linked to the development of rubber trees (Pagès et al., 1995; Sahuri, 2017) may lead farmers to adjust their inter-row management over time. Based on these factors, we assume that designing more sustainable systems for the immature rubber period first requires in-depth characterization of existing TMRs, including the possible diversity of technical operations used, for different crops grown in the inter-rows.

This aim of the present study was to thoroughly understand management of the inter-rows in immature smallholder rubber plantations in three contrasted provinces in Thailand. To this end, we tackled the following questions: 1) How are inter-rows managed during the first four years of the immature rubber period, considering the whole TMR? 2) Does the TMR within a single plot change over time? 3) Which inter-row cropping system requires the most intense and variable technical operations?

2. Materials and methods

2.1. Case studies and farmers' selection

2.1.1. Study sites

The present study was conducted in the three main natural rubber producing regions in Thailand: North-East, Central and Southern, which, in 2022, represented respectively, 26 %, 10 %, and 58 % of the total surface area of rubber plantations in the country (OAE, 2023). In each region, we chose to work in one province. To select these provinces, we preliminary consulted researchers specializing in rubber-based systems in Thailand, as well as the government institution overseeing rubber production in Thailand (Rubber Authority of Thailand). We also took into account the extent of the area under immature rubber, the replanting dynamics and the representativeness of the pedo-climatic and socio-economic contexts in each region. Buriram was selected in the North-East where, in 2022, rubber plantations covered 48 603 ha, i.e. 5 % of the total agricultural area of the province. Despite the fact immature plantations represented only 5 % of the total surface area under rubber, Buriram had seen a marked increase (i.e. 36 %) in its rubber cultivation area between 2013 and 2022 (OAE, 2014, 2023; LDD, 2019). Buriram has a mean annual mean temperature of 27.7°C, total annual rainfall of 1 352 mm and around four dry months (monthly rainfall < 50 mm) (data averaged from 2013 to 2022 (TMD, 2023)). Consequently, Buriram can be considered as a marginal rubber cultivation area (Gohet et al., 2015). Rayong was selected in the Central region, where rubber plantations covered 92 277 ha in 2022, i.e. 71 % of the total agricultural area. In 2022, immature rubber plantations represented 11 % of the total area under rubber which, between 2013 and 2022, had decreased by 22 % (OAE, 2014, 2023; LDD, 2019). Rayong has a mean annual temperature of 28.8°C, total annual rainfall of 1 752 mm and around three dry months (TMD, 2023). Trang was selected in the South where on 2022, rubber plantations covered 190 847 ha, i.e. 43 % of the total agricultural area in the province and immature plantations represented 11 % of the total rubber area. The total area under rubber decreased by 13 % between 2013 and 2022 (OAE, 2014, 2023; LDD, 2019). Trang has a mean annual temperature of 28.4°C, total annual total rainfall of 2 391 mm and around two dry months (TMD, 2023). Unlike Buriram, Rayong and Trang are considered to provide optimum climate conditions for the growth of rubber trees (Gohet et al., 2015).

2.1.2. Immature rubber systems

Among systems based on immature rubber, we selected systems with a single row of rubber trees and a planting pattern of 2-to-3 × 6-to-7 m, which is a standard planting pattern in Thailand. We focused on two systems based on their inter-row management: (1) intercropping systems and, (2) rubber mono-cropping systems with only weeds (i.e. no intercropping or cover cropping at any age of the rubber stand). We selected the most widely used intercropping system in each province based on information provided by the provincial offices of the Rubber Authority of Thailand (RAOT). This meant Rubber + Cassava was selected in Buriram, Rubber + Pineapple was selected in Rayong, and Rubber + Upland rice was selected in Trang (Fig. 1).

2.1.3. Farms and plots

We selected farms that had at least one immature rubber plot aged between one and four years at the time of the interview (September to December 2022). To be selected, the plot had to have been managed as a rubber intercropping or mon-cropping system. Concerning the intercropped plots, the intercrop selected in each province had to have been cultivated at least once since rubber was planted, and one whole

Fig. 1. Photos showing immature rubber-based systems selected. From top-left to bottom-right: Rubber + cassava in Buriram, Rubber + pineapple in Rayong, Rubber + upland rice in Trang, and mono-cropping system (Photo credits: C. Simon).

cultivation cycle had to have been completed. Other intercrops may have been grown before or after the cultivation cycle concerned. The selected farms were located in several districts across all three provinces to better account for the spatial diversity of the technical operations (Fig. 2). We interviewed 137 farmers who owned the plots, 45 of which were located in Buriram ($N_{cassava} = 24$; $N_{mono\text{-}cropping} = 21$), 47 plots in Trang ($N_{rice} = 24$; $N_{mono\text{-}cropping} = 23$), and 45 plots in Rayong ($N_{pineapple} = 24$; $N_{mono\text{-}cropping} = 21$).

2.2. Data collection

Data were collected during individual interviews with the people in charge of the plot management on the selected farms. In most cases, this was the owner of the farm or another member of the household. As the immature plantations with Rubber + Pineapple in Rayong were mostly managed by contractors, the interview was conducted with the farmer or manager under contract in addition to the owner of the farm whenever possible. The interviews were mostly face-to-face at the interviewee's house. When required, additional information was obtained later by phone.

In cases where the farmers owned or managed more than one plot that met our criteria, we first chose the plot with the oldest rubber trees to maximize coverage of the initial four-year period and gather the most information possible regarding the technical operations after tree planting. We then selected the largest plot possible, and finally the plot that was easiest to access at the time of the interview. Additionally, in cases where farmers managed multiple plots, with some under intercropping systems with the selected intercrop and others as mono-cropping systems, we considered the overall distribution of the samples between intercropping and mono-cropping systems.

To characterize plot management, we asked for details on all the technical operations applied to the inter-rows, from the preparation of the soil for rubber planting until the day of interview, using a list of possible technical operations drawn up before the interviews (see Supplementary material 1). We used a timeline to guide the interview and to collect the information provided by the farmers (see Supplementary material 2). To ensure the quality of the data collected, we checked the consistency of the information in a visit to the plot following the interview and occasionally examined the packages of products used.

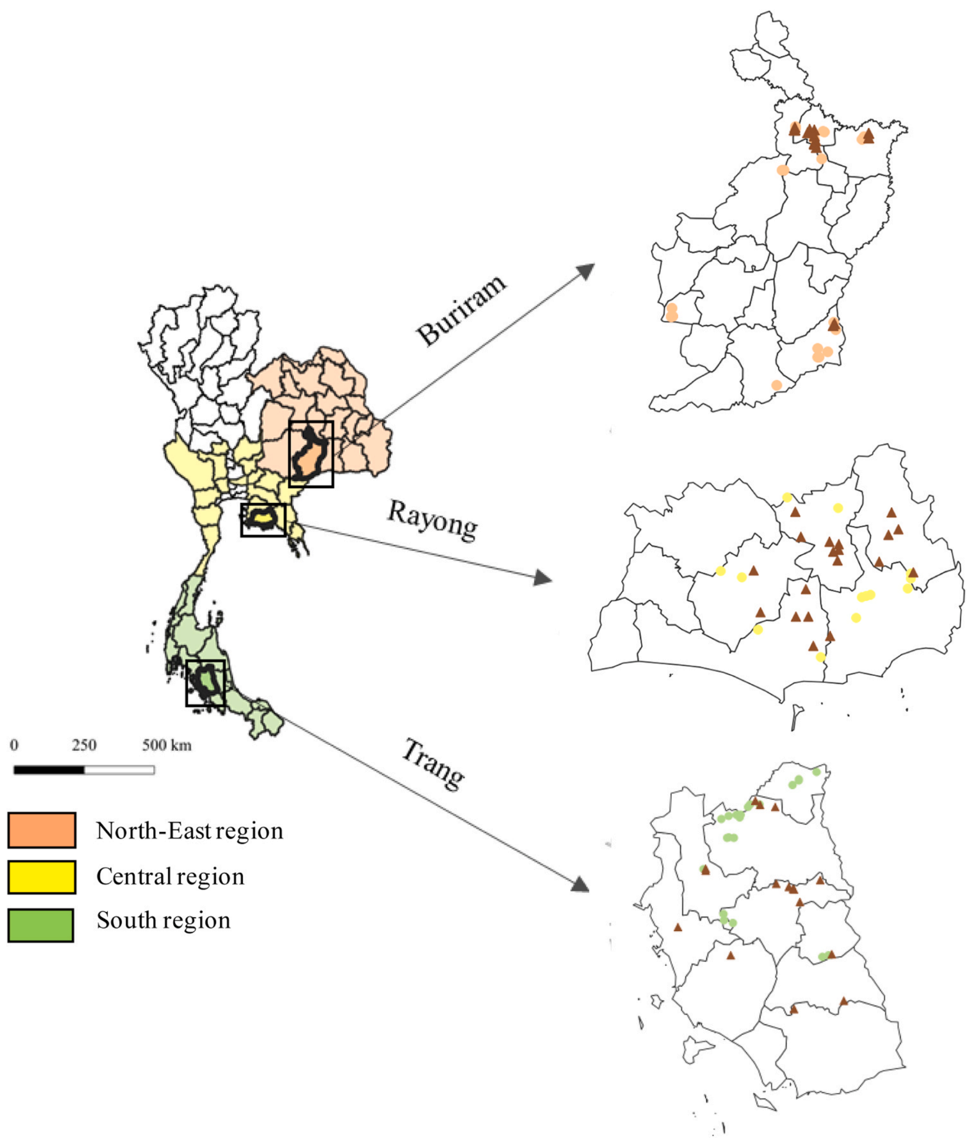

Fig. 2. Location of the plots selected for interviews in Buriram, Rayong and Trang. For each province, the different colored dots represent plots with intercropping systems while the brown triangles represent plots with mono-cropping systems. (Only plots that were visited after the interview are shown.).

2.3. Data analysis

The different steps associated with data preparation and data analysis are summarized in Fig. 3. All statistical analyses were conducted in R (v. 4.1.3). Statistical significance for all analyses was set at $p \leq 0.05$, highly significant at $p \leq 0.01$.

2.3.1. Preparation of the database

From raw data collected during the interviews, we prepared the database for analysis according to four main steps: (1) segmentation of timelines in cultivation cycles; (2) raw data processing; (3) variables aggregation from monthly information; and (4) transformation of variables into modalities.

Segmentation in cultivation cycles. For each plot, we segmented the timelines drawn with the farmers into cultivation cycles. For the intercropping systems, we considered the technical operations applied to cassava in Buriram, pineapple in Rayong and upland rice in Trang, with varying cultivation cycle lengths depending on the crop. Cultivation cycles for cassava and upland rice covered the period from soil preparation to harvest and included management of crop residues, with an average duration of nine and six months, respectively. For pineapple, we defined two cycles, both lasting 17 months. The first one covered the period from soil preparation to the first harvest (i.e. management of the plant crop). The second one started after the first harvest and lasted until the second harvest (i.e. management of the ratoon crop). For mono-cropping systems, cultivation cycles were based on the technical operations used in the inter-rows, covering a period of 12 months from the month in which the rubber trees were planted (between May and August in 120 out of the 137 plantations).

Only completed cultivation cycles were retained, giving a total of 279 cycles for 137 plots, with $n = 39$ cycles for cassava in Buriram, $n = 35$ for pineapple in Rayong, $n = 44$ for upland rice in Trang, and $n = 161$ for mono-cropping in the three provinces combined. In other words, between one and four cultivation cycles were associated with each plot.

Raw data processing. This step included the conversion of certain data (e.g. nitrogen, phosphorus, and potassium amounts based on the commercial composition of chemical fertilizers and the quantity applied), the estimation of some applied product quantities, as well as the management of missing data. Missing data could concern product information (e.g. chemical fertilizer composition), the amount of product applied or specific details related to other technical operations (e.g. *Distance of planting from the rows of rubber trees)*. All raw data processing procedures are summarized in Supplementary Material 3.

Variables aggregated from monthly information. To summarize the information on the management at the cultivation cycle level, we aggregated all similar technical operations. Thus, aggregated variables per cycle corresponded to either the frequency of application (e.g. *number of deep soil tillage operations*; *number of hand weeding operations*) or the quantities of products applied per hectare (e.g. *Total quantity of N*

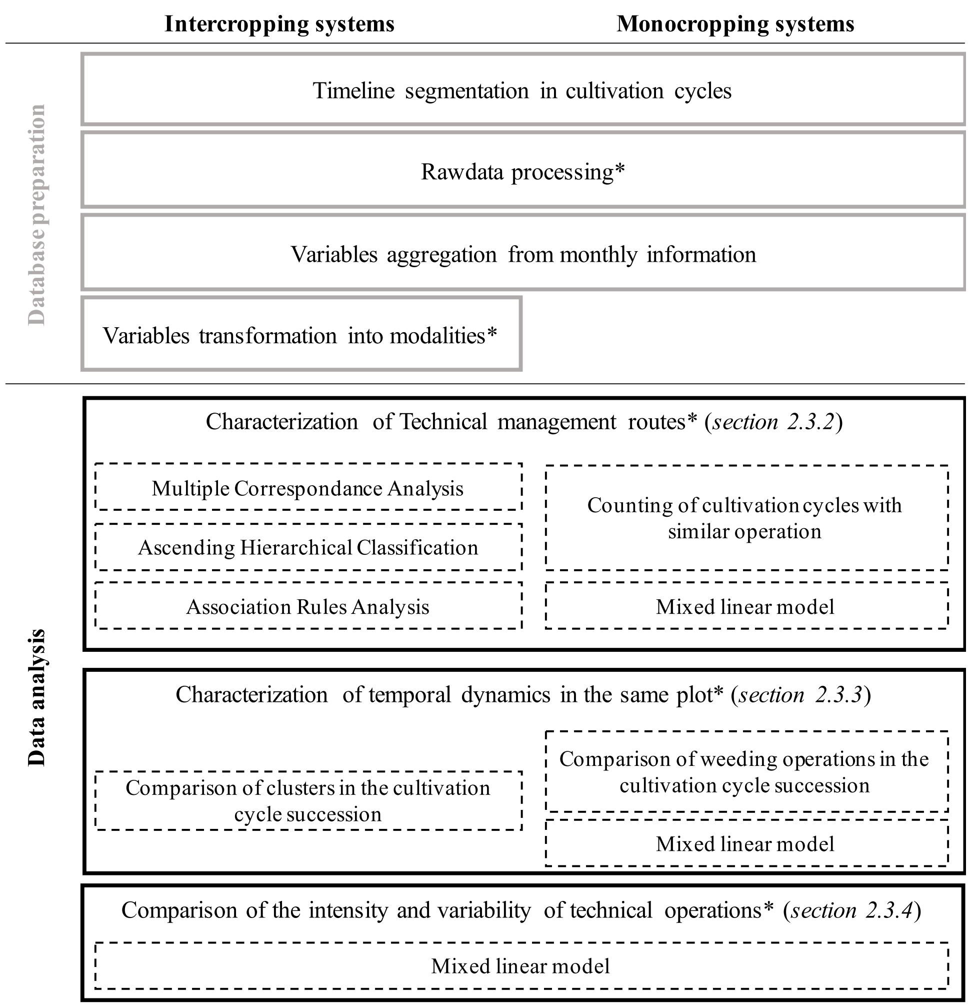

Fig. 3. Methodological steps from database preparation (in grey) to data analysis (in black). For each step outlined with a solid frame, the main objective is presented. The steps relying on statistical tools are marked with a "*". Each sub-step outlined with a dashed frame, the immature rubber-based systems (i.e. intercropping or mono-cropping systems) involved are specified.

per ha; Total Herbicide Index). We also calculated synthetic indexes for chemical weeding and pineapple flower induction. A herbicide index (HI) was calculated for herbicide and a flowering index (FI) for the plant growth regulator used to induce flowering (only *Ethephon)* (Gravesen, 2003; Lechenet et al., 2017). All data calculations are summarized in Supplementary material 3.

Transformation of variables into modalities. For the intercropping systems only, we transformed the aggregated variables into modalities representative of the diversity observed during the interviews. These modalities were built differently depending on the type of variable. Qualitative and discrete quantitative variables were handled similarly, by determining relevant modalities according to the histograms of the distribution of observations ('naturally occurring division', Husson et al., 2017). Continuous quantitative variables were split into four equal modalities based on the median and quartiles. We also considered the potential effects of modalities in further statistical analyses: (1) rare modalities contribute more to inertia; (2) variables with many modalities contribute excessively to the inertia; (3) a large majority of variables with only two modalities might bias the clustering (Chavent, 2015; Husson et al., 2017). We did not keep variables for which at least 80 % of the TMRs used the same technical operation because, in this case, the variables did not distinguish between situations (Renaud-Gentié et al. 2014). In addition, when two or more variables provided similar information after modality transformation, we reduced the number of variables. These choices were made on a case-by-case basis, considering the overall variability across cultivation cycles and the need to retain either variables with the highest level of detail or those encompassed more information.

2.3.2. Characterization of the technical management routes

Intercrops in diversified systems characterized using the Typ-iti method. The "Typ-iti " analytical method (Renaud-Gentié et al. 2014; Akakpo et al., 2021) was used to study management diversity in the three intercropping systems, with one analysis per system. This method computes a typology of TMRs by considering the specific associations of technical operations and is based on three statistical tools: a multiple correspondence analysis (MCA), an ascending hierarchical classification (AHC), and a data-mining analysis to generate association rules between technical operations (Renaud-Gentié et al. 2014).

MCA was performed to summarize the relationship between individuals (i.e. between TMRs) and the modalities of the variables selected (i.e. the technical operations), with the *FactoMineR* R package (Lê et al. 2008). A qualitative supplementary variable was added to describe the TMR number in the temporal succession in the same plot. Only the MCA dimensions with inertia greater than 1/number of variables were retained (Husson et al., 2017).

Next, AHC was performed to create clusters of TMRs using the Ward method. The number of clusters was determined according to the clustering dendrogram and consolidated using the Elbow method. The AHC identified the variables that contributed significantly to clustering, i.e. "*discriminating variables*" according to chi2 correlation tests ($p \leq 0.05$). We also identified specific modalities for each cluster, i.e. '*discriminating technical operations',* linked to discriminating variables. A TO was considered to be discriminating when 1) it was present in the TMRs of more than 50 % of the cluster, or 2) if at least 50 % of all TMRs that included this TO were present in the cluster.

We performed a data-mining analysis based on association rules, defined as a succession of '*common technical operations*', i.e. shared by a predefined minimum of TMRs in the same cluster. This data-mining analysis allowed us to identify additional technical operations that could complete the description of TMRs in a cluster but not revealed by the previous MCA and AHC analyses, since they were not specific to a cluster. According to (Renaud-Gentié et al. 2014; Akakpo et al., 2021), we used the following parameters: the minimum support *Sm*, found by calculating the ratio of the number of TMRs in the smallest cluster to the total number of TMRs for a given cropping system, the adjusted support Sa equal to 0 (i.e. at least 50 % of TMRs in the cluster should comply with the rule), and the confident C equal to 1. The analysis was performed with the R *arules* package (Hahsler et al., 2023). For each cluster, the rules with the highest number of common technical operations, i.e. the longest rules, were retained, with a minimum of one rule and a maximum of four rules (Renaud-Gentié et al. 2014). The length of longest rules retained together with the total number of rules indicated the homogeneity between TMRs in a given cluster.

Finally, TMRs were characterized for each cluster according to *descriptive technical operations*, corresponding to *discriminating technical operations* resulting from the AHC step, together with *common technical operations* resulting from the data-mining step.

Inter-row in mono-cropping systems characterized using mixed linear models. Only a few technical operations linked to weed control were used in the inter-rows in mono-cropping systems. We selected six variables to characterize the TMRs in mono-cropping systems: *Total number of weeding operations*, *Number of weeding methods*, *Number of weeding operations using a plow*, *Number of weeding operations using a knife, grass cutter or mower*, *Number of chemical weeding operations*, and the associated *Herbicide Index* (HI) (Burgos and Ortuoste, 2020). For each variable and each province, we assessed management diversity separately by counting the number of TMRs that used each modality. We then compared mean values of the variables between provinces using mixed linear models with the R *lme4* package (Bates et al., 2015). Plot was used as a random effect to check for the possible dependency of successive TMRs over time in the same plot. The normality of the residuals and the homoscedasticity of the variance residuals were also checked. When we observed a significant effect ($p \leq 0.05$), Tukey HSD multiple comparison of means (post-hoc test) was implemented using the R *emmeans* package (Lenth, 2024).

2.3.3. Characterization of temporal dynamics in the same plot

We selected only plots that had undergone at least two complete cultivation cycles (intercropping systems: $N_{cassava}$=11, $N_{pineapple}$=10, $N_{upland\ rice}$=8; mono-cropping systems: $N_{Buriram}$=13, N_{Rayong}=17, N_{Trang}=19). For intercropping systems, we reported the succession of TMRs over time, using the previously attributed clusters, and considered possible changes in clusters between TMRs in the same plot. For mono-cropping systems, we recorded the total number of weeding operations and the methods used for each TMR and studied possible changes in the same plot over time. We compared the average number of total weeding operations in the different TMRs in the temporal succession using mixed linear models, as described in 2.3.2.

2.3.4. Comparison of the intensity and variability of technical operations

We selected five variables common to all the cropping systems studied: *Total quantity of N per ha, Total quantity of P per ha, Total quantity of K per ha, Herbicide Index,* and *Number of tillage operations* (i.e. sum of all the technical operations carried out using a tractor during a cultivation cycle that may include soil preparation, weeding using a plow, and in the case of intercrops, planting and harvesting).

Depending on the cropping system studied, the average length of a cultivation cycle varies: six months for upland rice, nine for cassava, 12 for the inter-rows in mono-cropping systems and 17 months for pineapple. To compare variables using the same duration, we chose the longest cultivation cycle as a reference, i.e. 17 months, and estimated the equivalence for the different crops. In this way, in real field conditions, 17 months corresponds to a complete cycle in pineapple, to 1.5 cycles for the inter-rows in mono-cropping systems over 17 months, to 1.5 cycles for cassava over 13 months plus four months that remain uncultivated between the two cycles, and two complete cycles over six months for upland rice plus around five months that remain uncultivated between the two cycles. It should be noted that we did not include any technical operations between two successive cultivation cycles in cassava and upland rice systems, because most of the farmers did not conduct technical operations in their plot during this period.

We compared the mean values of each variable between the four cropping systems using mixed linear models with the *lme* function in the R *nlme* package. In the models, we indicated the difference in variance between cropping systems, due to the heteroscedasticity of the variance residuals (Pinheiro et al., 2023). Plot was used as a random effect to account for the possible dependency of successive TMRs over time in the same plot. The normality of the residuals was checked. When a significant effect ($p \leq 0.05$) was observed, Tukey HSD multiple comparison of means (post-hoc test) was used, with the R *emmeans* package (Lenth, 2024). The mixed linear models also allowed us to estimate the standard error (SE) for each cropping system, which we then used to explore variability in the same cropping system. It should be noted that mono-cropping systems were not included in the mixed linear models on fertilization variables since no fertilizer was applied to the inter-rows in these systems.

3. Results

3.1. Inter-row management in intercropping and mono-cropping systems

3.1.1. Cassava in Buriram

From the 28 variables originally calculated from raw data on the 39 TMRs used for cassava (see Supplementary material 4), 15 variables were selected for the analysis, divided into four management steps: Soil preparation and planting (four variables), Fertilization (6), Weed control (4) and Management of crop residues (1) (Table 1). Five dimensions were selected for the MCA, explaining 58 % of the total inertia (see Supplementary materials 5 A and B). The AHC step resulted in five clusters, that explained 76 % of the total variability after consolidation with Kmeans (see Supplementary material 5 C). Overall, 13 out of 15 variables contributed highly significantly to the clustering ($p \leq 0.01$); the three first discriminating variables were *Number of applications of chemical fertilizer, HI and Number of chemical weeding operations* (see Supplementary material 5D). *Number of applications of organic fertilizer* and *Number of applications* of *hormones or micronutrients* were the only variables that did not significantly contribute to clustering. Each cluster was distinguished from the others according to six discriminating technical operations. The last step of data-mining analysis resulted in a total of 30,528 rules. After specific attribution of rules to the five clusters, the clusters were unequally homogeneous: the number of rules varied from five to 1 375, and the longest rules varied from four to 10 common technical operations (see Supplementary material 5E). After combining the three analysis steps, the diversity of cassava TMRs was characterized by all 15 variables retained, with from six to 11 descriptive technical operations, depending on the cluster (Fig. 4).

TMRs in Cluster 1 (C1), were primarily characterized by the lack of chemical or organic fertilizer, but also by reduced soil preparation before planting cassava, with only one or two preparations of the surface soil, and moderate occupation of the inter-rows, i.e. three to four rows of cassava planted at a distance of 2–2.5 m from the rows of rubber trees. After cassava was harvested, some cassava stems were kept for the following cultivation cycle while the residues of the other cassava plants were left in the plot, either on the surface of the soil between the rubber trees or incorporated into the soil in the inter-rows.

Cluster 2 (C2) could be considered as more intensive in terms of occupation of the inter-rows than the other clusters, with three to four rows of cassava planted close (at a distance of 1–1.5 m) to the rubber rows. In this cluster, weeding only consisted of applying moderate doses of herbicide once during the cassava crop cycle ($1.4 < HI \leq 3$). TMRs in C2 were also characterized by reduced soil preparation before cassava was planted, with only one or two preparations of the surface soil, and a few applications of chemical fertilizers.

Cluster 3 (C3) was characterized by the very high frequency of applications of chemical fertilizer, which included a very large quantity of K (50–70 kg.ha^{-1}) as well as a large quantity of P (5–7 kg.ha^{-1}). Most of the TMRs in this cluster were also associated with intensive weed control, with four weeding operations including one hand weeding during the cassava crop cycle. Finally, C3 was characterized by reduced soil preparation before cassava was planted, with only one or two preparations of the surface soil, and by moderate occupation of the inter-rows, with three to four rows of cassava planted at a distance of from 2 to 2.5 m from the rows of rubber trees.

Cluster 4 (C4) differed from the other clusters by intensive soil preparation before cassava was planted, with three to four preparations including both deep and surface soil. The cluster was also characterized by a low amount of P (1.5–5 kg.ha^{-1}) applied and by the combination of hand and chemical weeding using small amounts of herbicide ($0 < HI \leq 1.4$). Like C1, after harvest, some cassava stems were kept for the following cassava cycle while the other cassava residues were left on the surface of the soil in the plot.

Cluster 5 (C5, $n = 7$) were firstly characterized by a reduced soil preparation before cassava was planted, with only one or two preparations of the surface soil, and reduced occupation of the inter-rows, with only one to two rows of cassava planted as a distance of from 3 to 3.5 m from the rows of rubber trees. This cluster also differed from the others by the very high frequency of applications of chemical fertilizer, but containing only a small amount of K (5–20 kg.ha^{-1}), and no chemical weed control.

3.1.2. Pineapple in Rayong

Among the 33 variables originally calculated from raw data on the 35 TMRs on pineapple (see Supplementary material 6), 17 variables were

Table 1
Technical operations (i.e. Variables and associated modalities) selected to perform the multiple correspondence analysis (MCA) on cassava management in intercropping systems in Buriram.

Management step	Variable code	Variables	Modality 1	Modality 2	Modality 3	Modality 4
Soil preparation and planting	*SP*	Total number of soil preparations	[1; 2]	[3; 4]		
	Deep_SP	Number of deep soil preparations	0	[1; 3]		
	Distance	Planting distance from row of rubber trees (m)	[3; 3.5]	[2; 3[	[1; 2[	
	Nb_row	Number of rows planted	[1; 2]	[3; 4]		
Fertilization	*Chemf*	Number of applications of chemical fertilizer	0	1	[2; 4]	
	N_tot	N *(kg.ha^{-1})*	[0; 8]	]8; 20]	]20; 33]	]33; 60]
	P_tot	P *(kg.ha^{-1})*	[0; 1.5]	]1.5; 5]	]5; 7]	]7; 21]
	K_tot	K *(kg.ha^{-1})*	[0; 5]	]5; 20]	]20; 50]	]50; 150]
	Orgf	Number of applications of organic fertilizer	0	[1; 5]		
	Horm	Number of applications of hormones or micronutrients	0	[1; 3]		
Weed control	*Weed*	Total number of weeding operations	[0; 1]	2	3	4
	Herb	Number of chemical weeding operations	0	1	2	3
	HI	Herbicide Index	0	]0; 1.4]	]1.4; 3]	]3; 11]
	Handw	Number of hand weeding operations	0	1	[2; 3]	
Management of crop residues	*Residue*	Management of crop residues	Left in the plot	Exported		

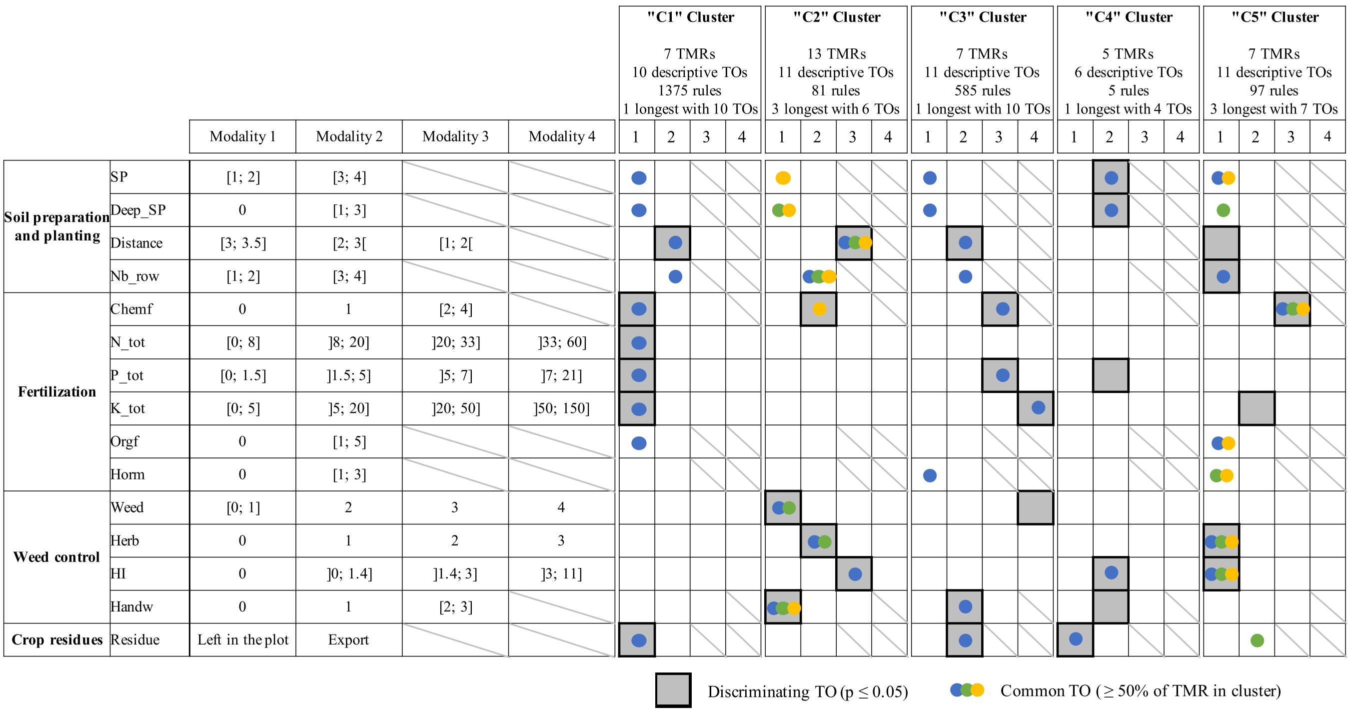

Fig. 4. Description of the clusters based on the diversity of technical management routes (TMRs) used for cassava in intercropping systems in Buriram. On the left, variables and modalities correspond to the technical operations (TOs) selected to perform the Typ-iti method (see details in Table 1). On the right, the five clusters retained are presented. In the upper part, each cluster is described based on the number of TMRs involved, the number of descriptive TOs, the total number of association rules, and the number of longest rules retained (between one and four) with the number of TOs in each rule. In the lower part, each cluster is characterized by its descriptive TOs, including discriminating TOs from ascending hierarchical classification (boxes outlined in bold) and common TOs from data mining (identified by colored dots). In the case of TOs common to a given cluster, one color is attributed to one associated rule, with one to three different rules, depending on the cluster.

selected, divided into five management steps: Soil preparation and planting (six variables), Fertilization (5), Weed control (3), Flower induction (2) and Harvest (1) (Table 2). Five dimensions were selected for the MCA that explained 51 % of total inertia (Supplementary material 7 A and B). AHC resulted in four clusters that explained 69 % of total variability after consolidation with Kmeans (Supplementary material 7 C). In all, 13 out of the 17 variables contributed highly significantly to clustering ($p \leq 0.01$); the four first discriminating variables were the *Number of soil preparations*, *Number of deep soil preparations*, *Number of applications of Ethephon* and *Pineapple crown cut off* at harvest (Supplementary material 7D). Depending on the cluster, three to 11 technical operations discriminated between them. The last step of data-mining analysis resulted in a total of 9 025 rules. After specific attribution of rules to the clusters, the clusters were unequally homogeneous, with a number of rules varying from 23 to 385 and the longest rules varying from four to eight common technical operations (Supplementary material 7E). After combining the three analysis steps, pineapple TMRs were characterized according to 15 out of the 17 variables, with seven to 13 descriptive technical operations depending on the cluster (Fig. 5).

Cluster 1 (P1) was primarily characterized by the production of pineapple for industry meaning farmers can sell the fruits without their

Table 2
Technical operations (i.e. Variables and associated modalities) selected to perform the multiple correspondence analysis on pineapple management in intercropping systems in Rayong.

Management step	Variable code	Variables	Modality 1	Modality 2	Modality 3	Modality 4	Modality 5
Soil preparation and planting	*SP*	Total number of soil preparations	0	1	2	3	Non app
	Deep_SP	Number of deep soil preparations	0	1	2	Non app	
	Distance	Planting distance from row of rubber trees (m)	]1; 1.4]	[0.6; 1]			
	Nb_row	Number of rows planted	[8; 9]	10			
	Material	Planting material	Crowns	Suckers			
	RT_age	Rubber trees age at planting *(month)*	]6; 14]	[0; 6]	Before RT planting	Non app	
Fertilization	*Chemf*	Number of applications of chemical fertilizer	[2; 3]	4	5	6	[7; 9]
	N_tot	N *(kg.ha^{-1})*	[22; 70]	]70; 150]	]150; 250]	]250; 410]	
	P_tot	P *(kg.ha^{-1})*	[0; 4]	]4; 19]	]19; 30]	]30; 80]	
	K_tot	K *(kg.ha^{-1})*	[3; 55]	]55; 136]	]136; 260]	]260; 656]	
	Micront	Number of applications of micronutrients	0	1	2	3	[4; 6]
Weed control	*Herb*	Number of chemical weeding operations	[0; 1]	2	[3; 4]		
	HTI	Herbicide Index	[0; 3]	]3; 4]	]4; 5]	]5; 12]	
	Handw	Number of hand weeding operations	0	[1; 4]			
Flowering induction	*Flower*	Number of applications of Ethephon	1	[2; 3]			
	FTI	Flowering Index	[8; 24]	]24; 37]	]37; 58]	]58; 100]	
Harvest	*Crown*	Pineapple crown cut off	No	Yes			

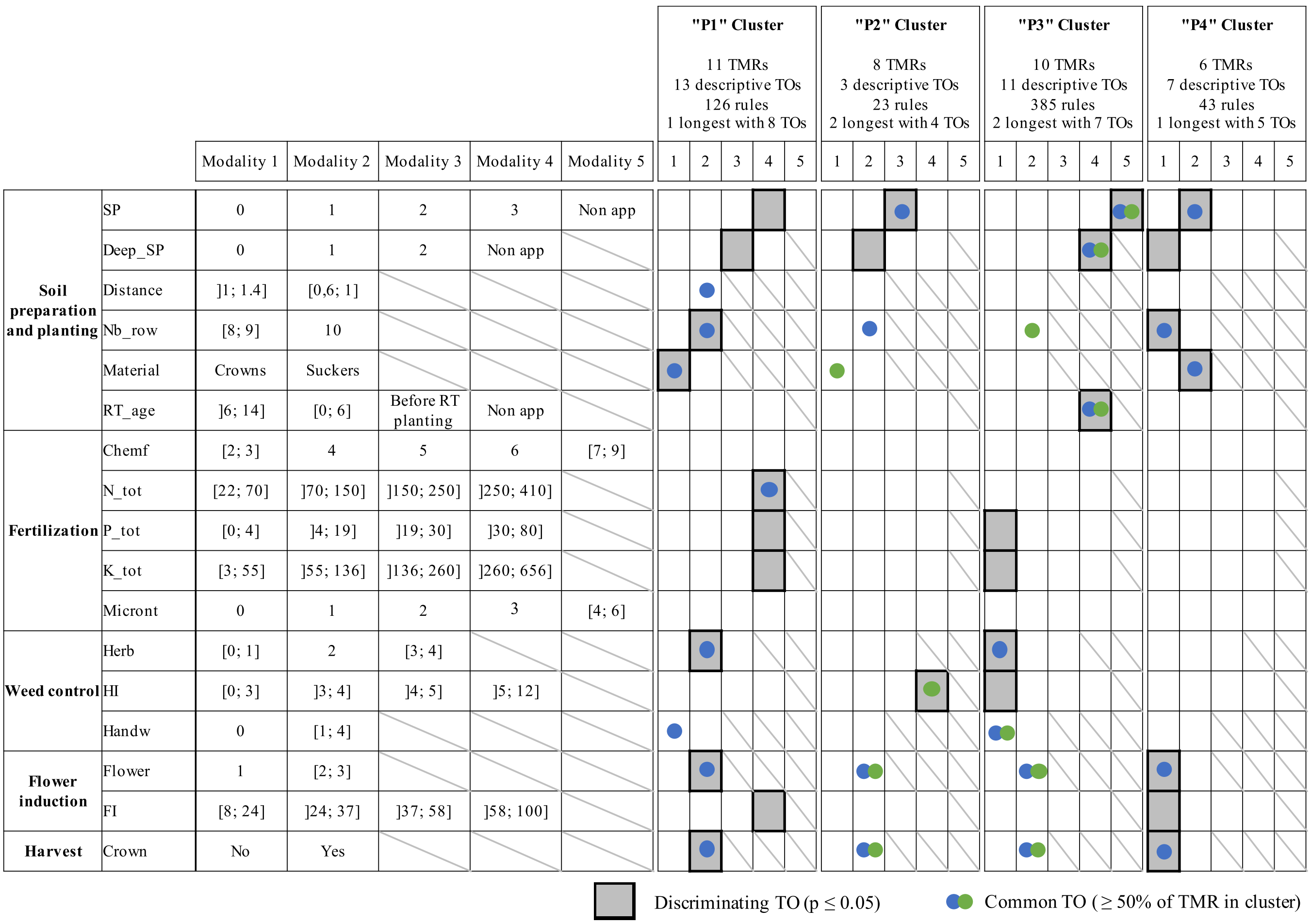

Fig. 5. Description of the clusters based on the diversity of technical management routes (TMRs) used for pineapple in intercropping systems in Rayong. On the left, variables and modalities correspond to the technical operations (TOs) selected to perform the Typ-iti method (see details in Table 1). On the right, the four clusters retained are presented. In the upper part, each cluster is described based on the number of TMRs involved, the number of descriptive TOs, the total number of association rules, and the number of longest rules retained (between one and four) with the number of TOs in each rule. In the lower part, each cluster is characterized by its descriptive TOs, including discriminating TOs from ascending hierarchical classification (boxes outlined in bold) and common TOs from data mining (identified by colored dots). In the case of TOs common to a given cluster, one color is attributed to one associated rule, with one to three different rules, depending on the cluster.

crowns since the pineapple fruits are processed. After harvest, the fruit crowns were cut and used as planting material in other plots. This cluster was consequently intensive in terms of occupation of the inter-rows thanks to easy access to planting material, with 10 rows of pineapple planted close to the rows of rubber trees (at a maximum distance of 1 m). P1 was also intensive in terms of soil preparation, with three soil preparations including two deep soil tillages before planting. Cluster 1 was also characterized by very high use of chemical fertilizer, the highest average amount of N (250–410 $kg.ha^{-1}$), P (30–80 $kg.ha^{-1}$) and K (260–656 $kg.ha^{-1}$) being applied. Finally, these TMRs were mostly associated with intensive flower induction, in both the frequency and the dose applied ($58 < FI \leq 100$).

Like P1, Cluster 2 (P2) was primarily characterized by the production of pineapple for industry. Consequently, the fruit crowns were cut after harvesting for use as planting material in other plots and so possible intensive occupation of the inter-rows, i.e., 10 rows of pineapple planted in the inter-rows. Nevertheless, TMRs in P2 differed from TMRs in P1 through moderate soil preparation, with two soil preparations including one deep tillage before planting. P2 also involved the highest average use of herbicide for weed control, with a HI between 5 and 12, but was moderate concerning the flower induction, usually involving only one application.

Cluster 3 (P3) was an atypical cluster because it comprised only TMRs used after the first harvest (i.e. the TMRs applied to the ratoon crop). Since pineapple plants were kept for a second harvest, there was no soil preparation or planting during these TMRs (soil preparation and planting variables were considered *Non-applicable)*. This cluster also differed from the others in the use of chemicals, with comparatively very low amounts of P and K applied as fertilizer, and reduced use of herbicide, with at the most one application along the TMR and in the low dose applied ($0 \leq HI < 3$). Regarding induction of flowering and harvest variables, the TMRs in P3 were quite similar to those in P2, generally including only one induction of flowering and fruit crowns cut after harvest.

Cluster 4 (P4) was primarily characterized by pineapples sold in markets for fresh consumption, meaning the fruits are sold with their crown. Since these crowns were not available for planting, the farmers generally used plant suckers, which are less accessible than crowns. P4 was classified as moderate in terms of occupation of the inter-rows, with 8–9 rows of pineapple mainly grown from suckers, planted further away (at least 1.2 m) from the rows of rubber trees. This cluster also mainly corresponded to TMRs with few flower inductions (one flower induction; $0 \leq FI < 24$). It should be noted that no technical operations linked to fertilization and weed control appeared as a key descriptor in this cluster. P4

3.1.3. Upland rice in Trang

Out of the 28 variables originally calculated from raw data on the 44 TMRs used for upland rice (see Supplementary material 8), 14 variables were selected, divided into five management steps: Soil preparation and planting (three variables), Fertilization (4), Weed control (3), Harvest (3), and Pest control (1) (Table 3). Five dimensions were selected for the MCA that explained 58 % of the total inertia (Supplementary material 9 A and B). AHC resulted in six clusters that explained 59 % of the total variability after consolidation with Kmeans (Supplementary material 9 C). All in all, nine out of the 17 variables contributed highly significantly to clustering ($p \leq 0.01$), the amount of *N*, *P* and *K* applied being the three first discriminating variables. In addition, three other variables (i.e. *Period between harvest and removal of residues*, *Management of crop residues* and *Number of soil preparations*) contributed significantly to clustering ($0.01 < p \leq 0.05$) (Supplementary material 9D). The method of harvesting upland rice was the only variable that did not significantly contribute to clustering. Depending on the cluster, four to seven variables discriminated between them. The last step of mining association rules resulted in a total of 51,248 rules in the upland rice TMRs before specific attribution to the four clusters. The clusters varied in homogeneity, the number of rules varying from 72 to 750 and the longest rules varying from six to 10 common technical operations depending on the cluster concerned (Supplementary material 9E). After combining the three analysis steps, upland rice TMRs were characterized by all 14 variables selected, with nine to 11 descriptive technical operations depending on the cluster (Fig. 6).

Cluster 1 (UR1) was primarily characterized by a very large quantity of P and of N applied, but with no K applied via chemical fertilization. In UR1, upland rice was generally planted close (0–0.8 m) to the rows of rubber trees with no soil preparation beforehand. Finally, the rice plants were removed one to three months after the rice grains were harvested, the plant residues being left in the plot.

Cluster 2 (UR2) was firstly characterized by a reduced occupation of the inter-rows, with rice planted both by hand and by machine at least 1 m from the rows of rubber trees. UR2 also differed from the others in the large number of interventions on intercropped rice, with at least two applications of fertilizer and two hand weeding operations. Despite the frequent applications of fertilizer, the TMRs in UR2 were characterized by the low doses of N and P applied (respectively, 0–7 $kg.ha^{-1}$ and 0–2 $kg.ha^{-1}$). After the rice was harvested by hand, the plant residues were generally left in the plot.

TMRs in Cluster 3 (UR3) were firstly characterized by frequent applications of chemical fertilizer, with the largest average amounts of N (21–50 $kg.ha^{-1}$), P (6–13 $kg.ha^{-1}$) and K (8–56 $kg.ha^{-1}$) applied. UR3 was also characterized by the large number of manual interventions for planting, weed control and harvesting operations.

Cluster 4 (UR4) was firstly described by frequent applications of chemical fertilizer but using rather small quantities of N (7–14 $kg.ha^{-1}$), P (2–4 $kg.ha^{-1}$) and K (0–8 $kg.ha^{-1}$). In this cluster, after at least one soil preparation, upland rice was usually planted near the rows of rubber trees (at a maximum distance of 0.8 m) using a combination of hand and machine planting. Weeds were mainly controlled by cutting, especially between the rubber trees and rows of the upland rice. After the rice was harvested by hand, plant residues were generally cut and left in the plot.

TMRs in Cluster 5 (UR5) were firstly characterized by the minimum use of chemical inputs for fertilization, weed control and pest control. After rice was planted (only by machine), chemical fertilizers were applied once only, using only a small amount of N (0–7 $kg.ha^{-1}$) and no K. Rice was usually harvested by hand, the plants were removed just after harvesting, and the residues taken out of the plot.

Cluster 6 (UR6) was primarily distinguished by the use of chemical products to control rice pests. However, no herbicide was used and weeds were mainly controlled by cutting between the rows of rubber trees and the rows of upland rice. In UR6, after at least one soil preparation, upland rice was usually planted by machine at a distance of 1–1.25 m from the rows of rubber trees. Chemical fertilizers were generally applied once, and contained a very large quantity of N (21–50 $kg.ha^{-1}$), a large quantity of P (4–6 $kg.ha^{-1}$) and a moderate quantity of K (0–8 $kg.ha^{-1}$).

3.1.4. Mono-cropping systems in the three provinces

In Buriram, 41 out of the 43 TMRs were primarily characterized by at least one weeding operation (Fig. 7A). Only two TMRs involved no weeding operations. In the 41 TMRs, the number of weeding operations ranged from one and six, with two operations in 13 TMRs and three in 17 TMRs. In Buriram, plowing was almost the only weeding method, with 40 out of 41 TMRs including at least one plowing operation and 36 of TMRs characterized by plowing alone. Mowing and chemical methods were rarely used, but when they were then alone (one TMR with only two mowing operations) or combined with plowing (two TMRs combining plowing and mowing or plowing and chemicals).

In Rayong, 39 out of the 51 TMRs were primarily characterized by at least one weeding operation (Fig. 7B). Twelve TMRs included no weed control at all. In the 39 TMRs, the number of total weeding operations varied between one and four, with one operation in 13 TMRs and two in 18 TMRs. In this province, plowing and mowing methods were used to the same extent, with 17 TMRs including at least one plowing operation and 14 TMRs including at least one mowing operation. Chemical method was used to a lesser extent, applied in 10 TMRs. In these TMRs, the HI was between 1.4 and 11.9. However, a single method was used in almost all the TMRs. Only two TMRs combined plowing with mowing or applications of herbicides.

Table 3
Technical operations (i.e. Variables and associated modalities) selected to perform the multiple correspondence analysis on upland rice management in intercropping systems in Trang.

Management step	Variable code	Variables	Modality 1	Modality 2	Modality 3	Modality 4
Soil preparation and planting	*SP*	Total number of soil preparations	0	[1; 3]		
	Distance	Planting distance from row of rubber trees (m)	]0.8; 1.25]	[0; 0.8]		
	Planting	Planting method	Hand	Hand & Machine	Machine	
Fertilization	*Fert*	Total number of applications of fertilizer	[0; 1]	[2; 3]		
	N_tot	N *($kg.ha^{-1}$)*	[0; 7]	]7; 14]	]14; 21]	]21; 50]
	P_tot	P *($kg.ha^{-1}$)*	[0; 2]	]2; 4]	]4; 6]	]6; 13]
	K_tot	K *($kg.ha^{-1}$)*	0	]0; 8]	]8; 56]	
Weed control	*Herb*	Number of chemical weeding operations	0	[1; 2]		
	Handw	Number of hand weeding operations	0	1	[2; 3]	
	Grass	Number of weding operations using a grass cutter	0	[1; 2]		
Pest control	*Pest*	Number of pest control operations	0	[1; 2]		
Harvest and Management of crop residues	*Harv*	Harvesting method	Hand	Hand & Machine		
	Residue	Management of crop residues	Left in the plot	Exported		
	Remov	Period between harvest and removal of residues *(month)*	]3; 6]	]0; 3]	0	

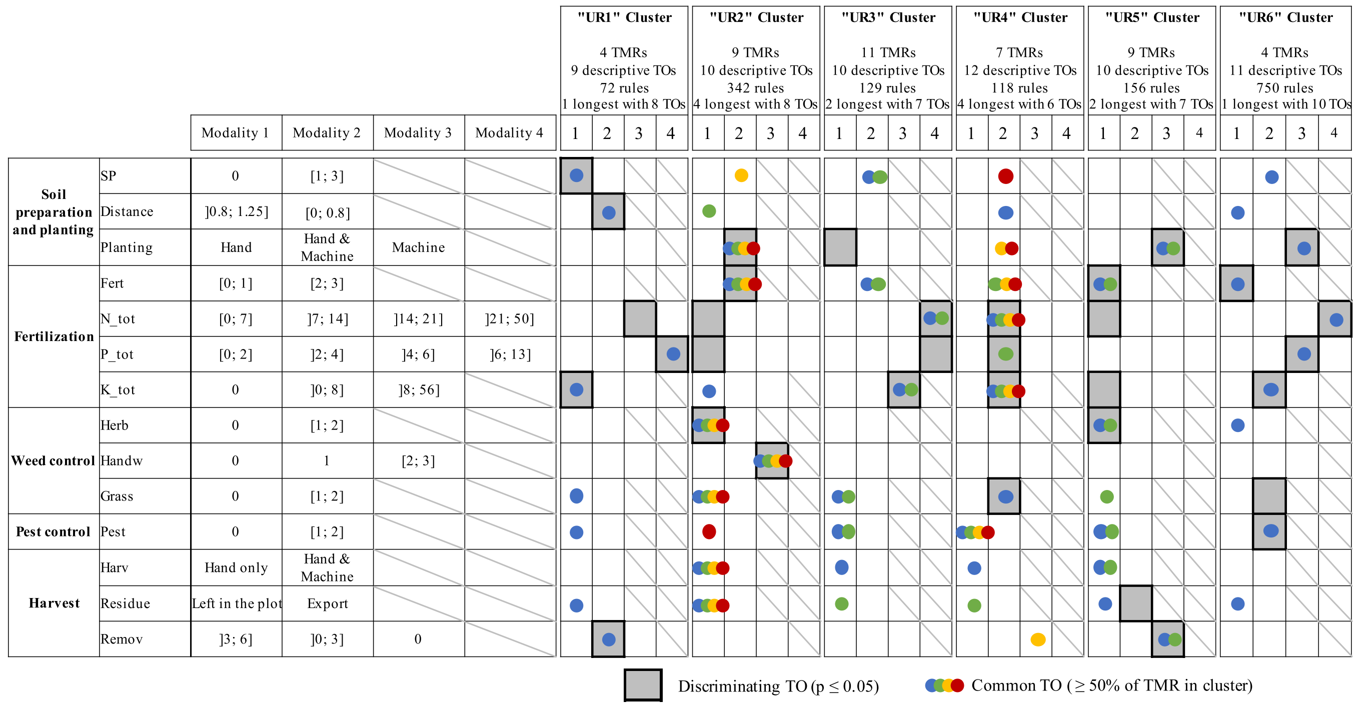

Fig. 6. Description of the clusters based on the diversity of technical management routes (TMRs) used for upland rice in intercropping systems in Trang. On the left, variables and modalities correspond to the technical operations (TOs) selected to perform the Typ-iti method (see details in Table 1). On the right, the six clusters retained are presented. In the upper part, each cluster is described based on the number of TMRs involved, the number of descriptive TOs, the total number of association rules, and the number of longest rules retained (between one and four) with the number of TOs in each rule. In the lower part, each cluster is characterized by its descriptive TOs, including discriminating TOs from ascending hierarchical classification (boxes outlined in bold) and common TOs from data mining (identified by colored dots). In the case of TOs common to a given cluster, one color is attributed to one associated rule, with one to three different rules, depending on the cluster.

In Trang, 59 out of the 67 TMRs were primarily characterized by at least one weeding operation (Fig. 7C). Only eight TMRs included no weed control at all. In the 59 TMRs, the number of total weeding operations varied from one to five, with one operation in 26 TMRs and two operations in 13 TMRs. In this province, the most common weeding method was mowing, with 31 TMRs including at least one mowing operation and 26 TMRs using this method alone. Plowing was the second most common method, and 21 TMRs included at least one plowing operation. Chemical weeding was the least used method, but was nevertheless applied at least once in 13 TMRs. In these TMRs, the HI varied between 1.2 and 8.8. A single method was used in almost all the TMRs. A combination of two weeding methods was observed in only six TMRs; three TMRs combined mowing and the use of chemicals, two TMRs combined plowing and mowing, and one combined plowing and chemicals.

3.2. *Temporal dynamics of inter-row management in the same plot*

In intercropping systems in Buriram, 11 farmers cultivated cassava for several years, the majority used two successive cassava cycles. No temporal effect was observed for this intercrop, with 10 out of 11 farmers using the same TMR in successive cassava cycles (Fig. 8). For upland rice, six out of the eight farmers we interviewed had implemented three successive upland rice cycles in their plantation. Like for cassava, we observed no temporal changes in upland rice management, with seven out of eight farmers using the same TMR throughout successive cycles of upland rice in Rubber + Upland rice systems in Trang. However, in most cases, the pineapple TMR changed over time. Of the 10 farmers interviewed that had harvested pineapple twice in their plot, nine farmers changed their management between the first and the second harvest, all converging to P3 for the second TMR.

Concerning the mono-cropping systems, the total number of weeding operations decreased significantly over the first four years in Buriram, with around three operations in year 1 but only one or two in year 4 (Fig. 8). The same weeding method (i.e. plowing) was used during this period in 11 out of 13 plots in Buriram. In Rayong and Trang, we observed no significant changes in the total number of weeding operations over time but farmers were likely to change their weeding methods from one year to another, especially in Trang where 10 out of 19 farmers alternated between plowing, mowing and the use of chemical herbicides.

3.3. *Intensity and variability of technical operations in the inter-rows in the different cropping systems*

Concerning fertilization, significantly higher quantities were applied to pineapple than to the other intercrops, especially of N and K (Fig. 9A and C). The amount of N applied in pineapple systems averaged 169 kg.ha^{-1} over 17 months (Standard Error = 19.2), i.e. around five times more than in cassava systems (29.9 kg.ha^{-1}, SE = 5.2) and upland rice systems (32.9 kg.ha^{-1} month^{-1}, SE = 5.3). Similarly, the amount of K applied in pineapple systems averaged 177 kg.ha^{-1} over 17 months (SE = 27.1), i.e. around 8.5 times more than in upland rice (20.8 kg.ha^{-1}, SE = 9.29) and four times more than in cassava systems (45.3 kg.ha^{-1}, SE = 9.1). No significant difference in the doses of N, P and K was observed between cassava and upland rice. The amounts of N and K in the chemical fertilizers applied varied more in pineapple systems than in cassava and upland rice systems. Consequently, some pineapple clusters, especially P3 and P4, received similar or even smaller quantities of chemical fertilizer than cassava and upland rice clusters. For example, quantities of K averaged 69 kg.ha^{-1} and 79 kg.ha^{-1} in respectively P4 and P3 versus 137 kg.ha^{-1} in C3 (Fig. 9 C).

Regarding herbicides, we observed significantly higher HI in pineapple over 17 months (4.60) than in the other crops, particularly

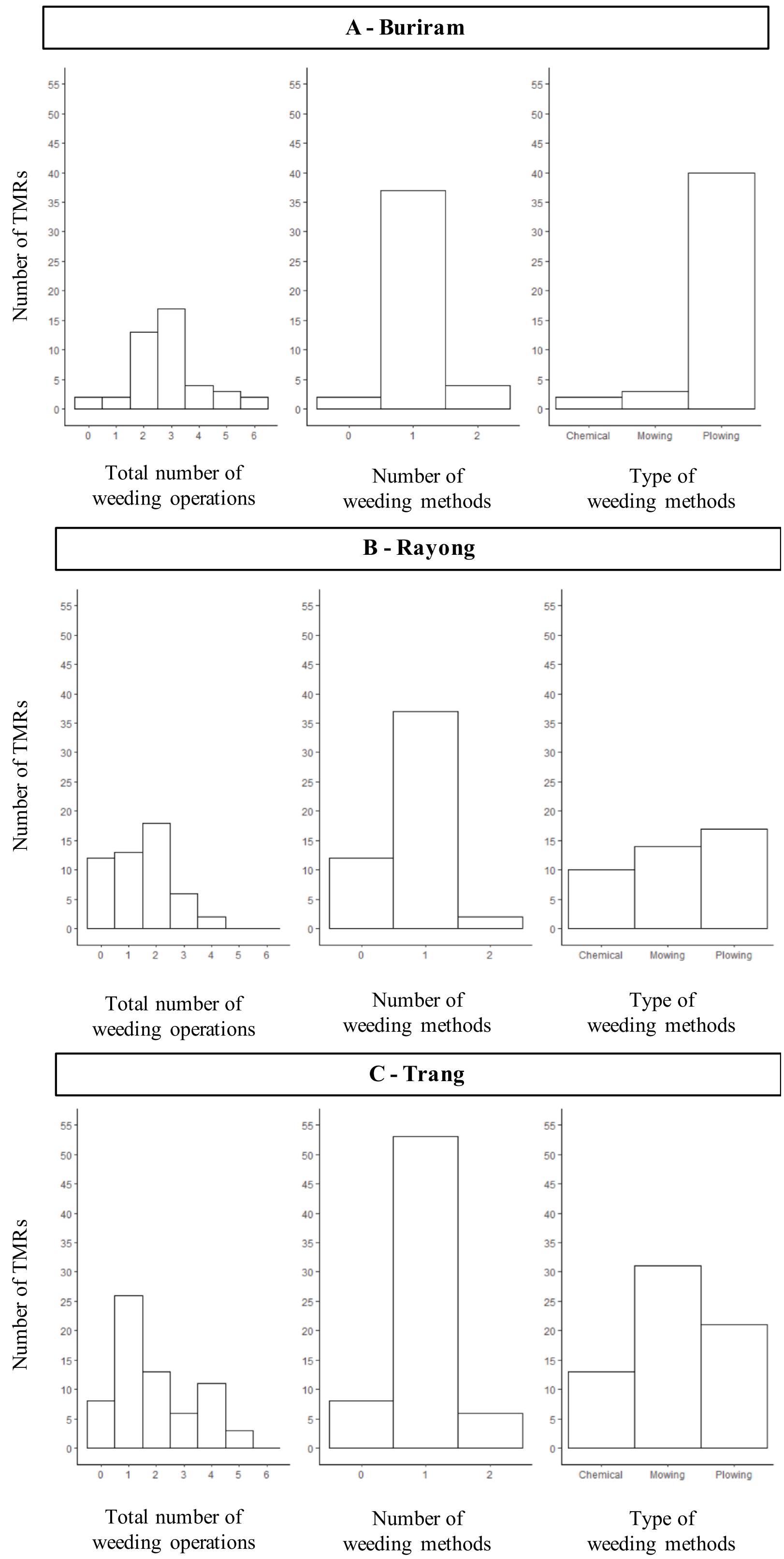

Fig. 7. Histograms showing the frequency of technical management routes (TMRs) in the inter-rows in mono-cropping systems in Buriram, Rayong and Trang, with for each province, the total number of weeding operations, the number of weeding methods used and the type of weeding methods per TMR.

compared to upland rice (1.01) and in the inter-rows of mono-cropping systems (1.09) (Fig. 9D). However, HI was similarly variable in the four systems studied, with standard errors (SE) ranging from 0.35 in pineapple systems to 0.66 in the inter-rows in mono-cropping systems.

Finally, the number of tillage operations was significantly higher in cassava, with around five tillage operations over 17 months, versus one in pineapple, two in the inter-rows of mono-cropping systems, and between three and four in upland rice (Fig. 9E). No significant difference

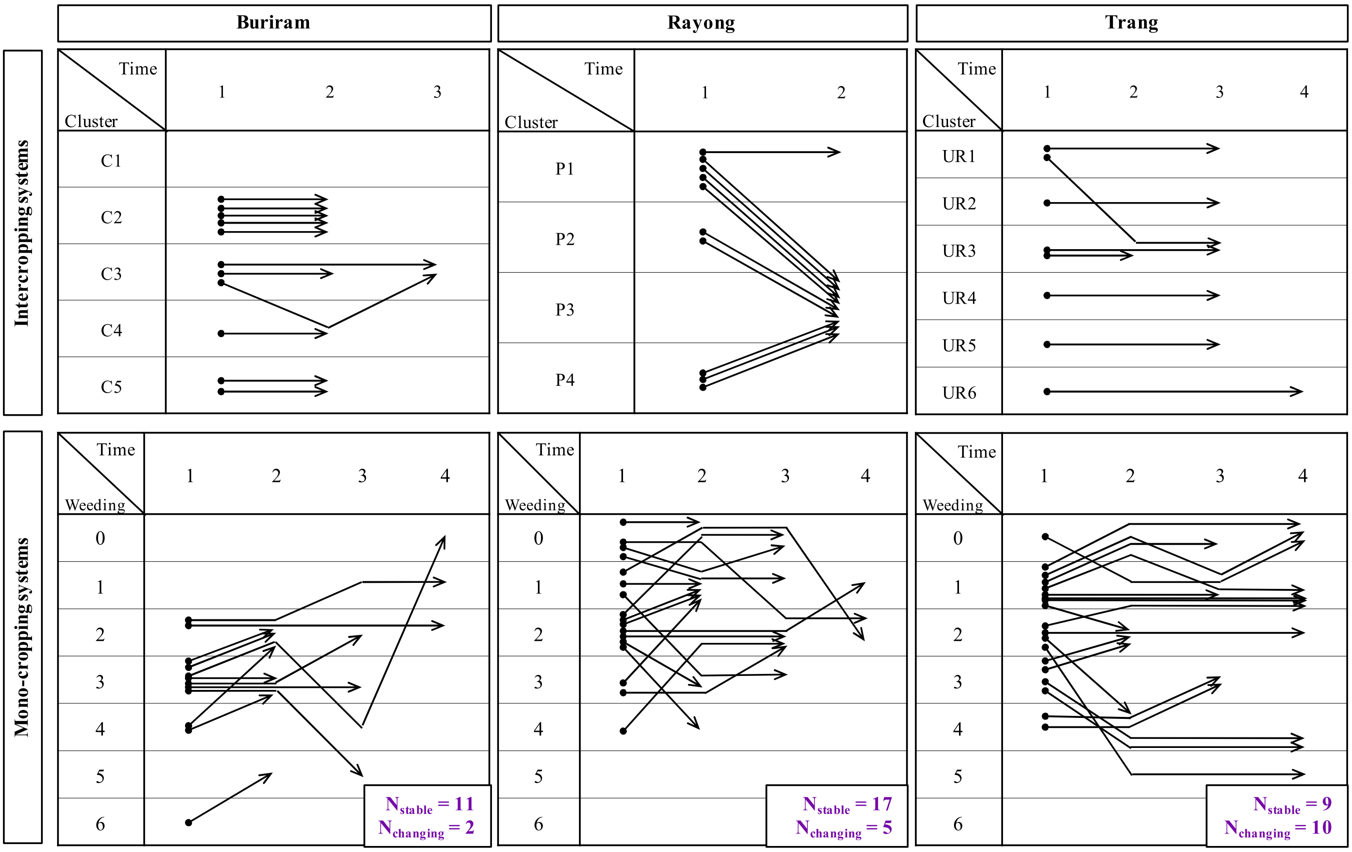

Fig. 8. Succession of technical management routes (TMRs) over time in the same plot for a given cropping system in inter-rows in intercropping and mono-cropping systems in Buriram, Rayong and Trang. Each arrow corresponds to a plot. For each time (in columns, from 1 to 4 maximum), we show the TMR from the cluster attributed for intercropping systems. The same approach was used for mono-cropping systems, with the total number of weeding operations regardless of the method ('Weeding') for mono-cropping systems (in lines, from 0 to 6 maximum). The purple inserts in the bottom right-hand corners are related to the weeding methods used over time, 'Nstable' indicates the number of plots where the weeding methods remained the same over time and 'Nchanging' indicates the number of plots where the methods changed from year-to-year. We only kept plots in which at least two TMRs were completed (Buriram: $N_{cassava} = 11$ and $N_{mono\text{-}cropping} = 13$; Rayong: $N_{pineapple} = 10$ and $N_{mono\text{-}cropping} = 17$; Trang: $N_{upland\ rice} = 8$ and $N_{mono\text{-}cropping} = 19$).

was observed between pineapple and the inter-rows in mono-cropping systems. The variability of the number of tillage operations was similar in the four systems studied, with SE varying from 0.22 for the inter-rows in mono-cropping systems to 0.40 in pineapple systems.

4. Discussion

4.1. A diversity of technical management routes was found in all four cropping systems studied

Our study highlighted a wide diversity of technical management routes (TMRs) for a given inter-row system, from originally 39 TMRs for cassava in Buriram, 35 TMRs for pineapple in Rayong, 44 TMRs for upland rice in Trang, and 161 TMRs for mono-cropping in the three provinces. While the diversity of inter-row management in perennial mono-cropping systems has already been demonstrated (e.g. Chen et al., 2022; Renaud-Gentié et al. 2014 in vineyard systems; Mettauer et al., 2021 in oil palm systems), to our knowledge, this study is the first to thoroughly characterize the diversity of management in diversified perennial systems. Our results differ from those of Koussihouèdé et al. (2020) who identified a single technical management system for a given crop choice in the inter-rows in intercropping immature oil palm systems in Benin.

In the three intercropping systems studied here, we were able to structure the diversity into four to six clusters depending on the intercrop. Each cluster was discriminated by four out of the five management steps described by Wezel et al. (2014), i.e. crop spatial distribution, tillage, fertilization and weed, disease and pest management, but also by specific technical operations linked to the harvest and removal of the intercrop. In our study, irrigation did not appear as an explanatory management step because the majority of farmers do not irrigate their intercrops. In pineapple systems, the clusters linked to the TMRs applied between the soil preparation and the first pineapple harvest (i.e. P1, P2 and P4) were closely linked to the two different marketing channels for pineapple mentioned in our interviews: industry with fruit processing (P1 and P2) versus fresh fruit market (P4). In P1 and P2, the production of pineapple for industrial processing means the fruit crown can be cut off after harvesting and used as planting material. In P4, since pineapple produced for the fresh fruit market must be sold with their crowns, only plant suckers can be used as planting material. Consequently, we observed lower pineapple planting density in P4 than in P1 and P2, due to the reduced availability of planting material. Likewise, according to the farmers we interviewed, the pineapple varieties used for fresh consumption require smaller quantities of Ethephon to induce flowering, resulting in a lower flowering index (FI) in P4. The clusters of cassava and upland rice systems were more difficult to interpret, as we could not identify an overall gradient of intensification in the TMRs but rather differences in specific technical operations. For example, the TMRs linked to C5 in cassava systems could be described as being more extensive in terms of soil preparation, planting density and chemical weeding compared to the other TMRs, but more intensive in terms of the frequency of application of chemical fertilizer. These results are in line with those of other studies that highlight a diversity of TMRs more complex to understand than a simple gradient of intensification in

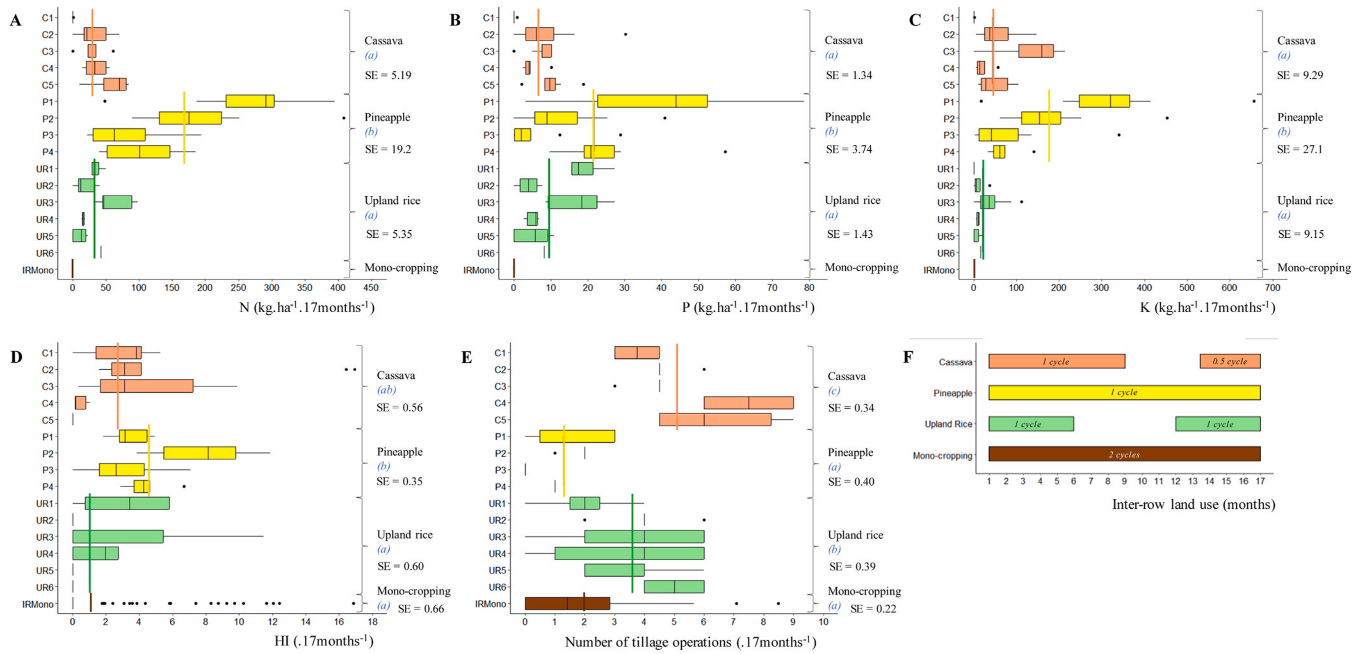

Fig. 9. Total quantities of Nitrogen (A), Phosphorus (B), Potassium (C), Herbicide Index (HI - D), Number of tillage operations (E) and Typical crop sequence (F) for each cropping system expressed over the reference duration of 17 months (i.e. the longest average cultivation cycle in the pineapple systems). Vertical colored lines represent the mean for each crop (including all the clusters), after adjustment with mixed linear models. Letter in blue indicate significant differences between crops in the inter-rows ($p \leq 0.05$). Standard error (SE) is indicated for each cropping system. Mono-cropping systems were not included in the mixed linear models on fertilization variables.

annual and perennial cropping systems (Le Bellec et al., 2011; Renaud-Gentié et al. 2014; Akakpo et al., 2021).

Despite the structuring of the diversity of TMRs into clusters, it is important to note that a certain degree of heterogeneity was nevertheless observed between TMRs in the same cluster in several clusters whatever the intercrop. Also, some clusters have to be interpreted with caution because of their small size, for example UR1 and UR6 for upland rice and C4 for cassava.

In mono-cropping systems, diverse inter-row management was observed within provinces in the frequency of weeding operations and in the methods used. This diversity was also observed between provinces. Weed control in Buriram was significantly more frequent than in Rayong ($p = 0.03$) and tended to be more frequent than in Trang (see Supplementary material 10). Regarding methods of weeding, plowing was almost the only method used in Buriram, whereas mowing and chemical methods were more used in Rayong and Trang. These differences could be linked to the differences in the topography of the three provinces. All the plots selected in Buriram were flat, hence facilitating the use of tractors for plowing while some of the plots in Rayong and Trang were on slopes. Moreover, most of the farmers in Buriram owned agricultural machinery (including tractors), to cultivate other crops such as cassava, paddy rice or sugarcane, which was not always the case in Rayong and Trang. Since the choice of crop in the intercropping systems differed from one province to another, we were unable to perform an analysis between provinces, despite some evidence of possible variability of management between the different regions (Chambon et al., 2014, 2018).

4.2. Depending on the cropping system, management was not always adjusted over the first four years

Some progressive adjustments of the TMRs over the first four years of the immature period might have been expected (Merot and Wery, 2017), with a global reduction in the intensity of the technical operations following the reduction in availability of natural resources in the inter-rows due to the growth of the rubber trees. This would be expected to lead to a reduction in planting density, in the quantity of fertilizers used, and to a reduction in the frequency of weeding in intercropping systems and mostly a reduced weeding frequency in mono-cropping systems. Surprisingly, we observed no such temporal changes in the management in either the cassava systems in Buriram or the upland rice systems in Trang. The stability of TMRs over time might be explained by the fact that resources are not particularly limiting in the inter-rows during these early years of rubber tree development, thus allowing farmers to repeat the same management operations several times. Nor did we observe any changes associated with variations in climate conditions (e.g. annual rainfall) or in economic conditions (e.g. the cost of inputs) between years. According to Jacobsen (1994), a farmer becomes experienced and may develop a certain routine in the management of annual crops, since the decisions made to manage these crops are cyclical and recurrent. In other words, once farmers have developed a TMR that meets their production objectives, they may use the same TMR until the end of inter-row cultivation.

However, we did observe some significant temporal changes in the management of pineapple in Rayong, where farmers generally reduced the number of interventions in their second TMR. The absence of soil preparation or planting operations after the first harvest was expected, since the same pineapple plant can be used for several harvests. Similarly, the reduction in the use of herbicides appears logical given the increase in shade linked to the development of both rubber trees and pineapple plants. However, it is noteworthy that the reduction in the amount of fertilizer applied during the second pineapple cycle meant the applications may do not satisfy all the plant's requirements, especially in K (Obiefuna et al., 1987; Leon and Kellon, 2012).

Concerning the mono-cropping systems, the results we observed differed with the province. In Buriram, the frequency of weeding in the inter-rows decreased significantly after three years, with no change in the weeding methods (i.e. plowing). In Rayong and Trang, the weeding frequency remained similar in the first four years, but some farmers alternated between plowing, mowing and applying chemical herbicides from year to year, especially in Trang. Among farmers who used different methods, the main reason given was the level of weed pressure in the plot, which varied from year to year depending on annual rainfall. Consequently, chemical herbicides were used when the weed pressure was considered high, while other methods were used when the weed pressure level was lower or during the dry season (Burgos and Ortuoste, 2020).

We were unable monitor for some plots the whole four-year period of the study. Indeed, we originally selected plots between one and four years old to ensure we could conduct enough interviews per province, but that would result in some incomplete timelines. For example, only two out of the 24 plots selected for cassava systems were four years old, eight plots were three years old, six were two years old and eight were only one year old. This methodological choice also limited possible analysis of the diversity of land use strategies over the whole four-year period. However, data collected during the interviews indicated that while some farmers maximized the use of available resources by cultivating intercrops continuously over the four-year period, other farmers either started to plant intercrops crops only one or two years after planting rubber to limit competition on very young trees, or stopped cultivating the inter-rows one to two years after planting rubber.

4.3. Pineapple systems were the most intense, but also the most variable

Comparing the four cropping systems showed that pineapple systems were the most intense in terms of chemical inputs used for fertilization and weed control. This difference in intensity could be primarily linked to crop requirements (see Supplementary material 11 - Rice Department, 2012; DOAE, 2017; Horticultural Research Institute, DOA, 2017; FCRI and DOA, 2020). In addition, pineapple cropping systems could be managed by another farmer under contract (the case of 12 out of the 24 plots in our study), in contrast to other intercropping systems that are managed by the owner or a member of the owner's household (Manarungsan and Suwanjindar, 1992). More intense management is thus hypothesized in pineapple systems managed under contract, since the objectives of the contracting farmers may focus on optimizing intercrop productivity rather than on the growth of immature rubber trees (Siju et al., 2012).

Concerning the other technical operations, the pineapple cultivation cycle (17 months) is longer than that of upland rice (six months) and cassava (nine months). This means less frequent tillage for pineapple than for the other two intercrops, leading to an overall lower rate of soil tillage. Moreover, in the pineapple system, the soil cover was almost permanently complete during the four-year study period, in contrast to the other intercropping systems. Consequently, while the operational costs of chemical inputs and the environmental impacts associated with their use are likely to be higher in pineapple systems, the risks of soil compaction and erosion may be lower.

Our results revealed high variability of technical operations for a given cropping system, particularly operations concerning fertilization in the pineapple intercrop system, where variability between pineapple clusters outweighed the differences in intensity between pineapple and the other intercrops. This variability may be useful for adaptations aimed at achieving more sustainable cropping systems, given the current dependence on external inputs.

Our study focused on technical operations used for the main crop grown in the inter-rows. Considering the whole crop sequence over the four-year period, including the technical operations used for weed control or to manage additional crops grown between two successive cycles of cassava or upland rice, would make it possible to judge the real intensity of inter-row management more accurately. For example, even if negligible compared to the other more conventional systems, very short rotations were sometimes observed in a few plots such as cassava-watermelon-cassava in Buriram, upland rice-vegetables-upland rice in Trang).

4.4. Advantages and limitations of the methodology used

Some general advantages and limitations of the methodology used were identified from data collection to the analyses. The first limitation concerned the time required for the interviews (from one to three hours per interview), meaning we were only able to conduct a (1) a limited number of interviews and, (2) the risk of having less accurate data during the interview was higher. The time spent on the interviews may also limit their future replicability. Secondly, data collection concerned the technical operations applied ever since rubber was planted. The quality of the information consequently depended on the reliability of the farmers' memories and the age of the plot selected, in some cases, some technical operations had been undertaken four years before the interview. The use of a timeline together with an initial list of possible technical operations helped jog the farmers' memory of the chronological order of the technical operations. Thirdly, we used the Typ-iti method to characterize the TMRs in intercropping systems. This method, which has already been used for annual (Akakpo et al., 2021) and perennial cropping systems (Renaud-Gentié et al. 2014), proved relevant to characterize the diversity of TMRs in a given cropping system due to the complementarity of the statistical tools. Nevertheless, it has limitations similar to other typology methods. According to Alvarez et al. (2018), the decisions made in typology for data collection, variable selection, data reduction and clustering techniques can have a significant impact on the results. For example, we rejected technical operations that were rarely used for a given intercrop, i.e. when less than 20 % of the TMRs used the operation concerned (e.g. irrigation, crop associations such as upland rice and banana) leading to underestimation of the diversity of TMRs in real field conditions. Moreover, the numbers of variables and modalities chosen within each variable for a given crop may bias the level of homogeneity within clusters. While upland rice clusters appeared to be more homogeneous than pineapple clusters in terms of the total number of rules and the maximum length of the rules (Supplementary materials 7E and 9E), it is difficult to conclude greater diversity in pineapple TMRs due to the difference in the number of variables (17 for pineapple versus 14 for upland rice) and in the number of modalities per variable (11 variables with at least three modalities for pineapple versus only six for upland rice).

4.5. Perspectives of the study

We identified four main promising perspectives of the present study that partially address the knowledge gaps in the characterization of systems based on immature rubber trees (Simon et al., 2024). Firstly, our study focused on the most widely adopted immature rubber-based systems in smallholder contexts in Thailand (i.e. mono-cropping systems and intercropping systems, with annual or medium-term crops (Langenberger et al., 2017)). These dominant systems have so far been poorly studied, creating a need for knowledge production in order to better understand their management. In parallel, it would be of interest to explore management practices or rubber-based cropping systems that are considered innovative (e.g. upland rice – cover crop rotation observed in Trang). To this end, an on-farm innovation tracking approach might be implemented, with (1) the identification of smallholder farmers developing alternative technical operations or systems and (2) their description (Salembier et al., 2015; Blanchard et al., 2017). On-farm innovation tracking could be complementary to our study, shifting the focus from global considerations and representativeness to particularities and uniqueness (Périnelle et al., 2021).

Secondly, we highlighted diversity of TMRs for the same inter-row crop in the same province, faced with similar production, climatic and economic conditions (Yvoz et al., 2020; Akakpo et al., 2021). This diversity could be linked to the variety of economic, environmental and sociocultural objectives of the different farmers (Kallas et al., 2010; Aouadi et al., 2015). All the farmers who adopted intercropping in immature rubber plantations chose to grow an intercrop to increase their income, but while some chose to maximize the yield to be obtained from the intercrop, others preferred to reduce their operating costs and the labor time required. This management diversity could also be linked to the external and internal context of the farm, including economic factors (e.g. household income, investment capacity), biophysical factors (e.g. soil type, topography) and social factors (e.g. age of the farmer, previous experience) (Blazy et al., 2009; Aouadi et al., 2015; Fanchone et al., 2020). Studying the plot, farm and household level determinants of the intensity of management of the three intercrops in different provinces would be an interesting way to identify general versus crop choice-dependent drivers and constraints.

Thirdly, we studied the possible temporal changes in inter-row management during the first stage of the immature period, disregarding the management operations applied after the first four years. Even though the drastic reduction in light intensity, nutrients, and water resources limits opportunities for diversification and the growth of weeds, rubber trees are still unproductive during the second stage of the immature period and maintenance operations are still required to secure the long-term viability of the plantation. Nor did we explore possible spatial changes at the plot scale by including technical operations applied in the rows of rubber trees themselves. Considering the spatialization of technical operations and the relationships between the management of the inter-rows and that of the rows of rubber trees would lead to a better understanding of the farmer's overall strategy at the plot level and enable the assessment of the real performances of the plantations (Simon et al., 2024). Three different management relationships might exist: (1) similar management (e.g. intensive applications of fertilizer to both rows and inter-rows); (2) adaptive management (e.g. the amount of fertilizer applied to the rows of rubber depends on the amounts already applied to the inter-rows) or; (3) independent management (e.g. the quantity of fertilizer applied to the rows is independent of the quantity already applied to the inter-rows). Such spatial analysis does not exist yet for immature rubber systems. In immature oil palm intercropping systems, Koussihouèdé et al. (2020) highlighted adaptation of the intercrop planting density in Benin, while Nchanji et al. (2016) concluded that management strategies of intercrops in Cameroon did not take into consideration the interactions with oil palms.

Fourthly, our results concerning the intensity and variability of technical operations in the different cropping systems highlighted the importance of considering the crop choice together with the TMR in the characterization of immature rubber plantations. Our results also call for the inclusion of crop choice and technical operations in the assessment of current immature rubber systems, since a diversity of technical management routes may lead to variability in performances (Mouron et al., 2006; Yvoz et al., 2020). In this perspective, characterization by clustering is an appropriate way to select interesting cases for assessment (Renaud-Gentié et al. 2014). The assessment should cover multiple performances linked to all the dimensions of sustainability in order to better identify the trade-offs between a given management strategy at plot scale and the associated performances (Rapidel et al., 2015; Simon et al., 2024).

5. Conclusion

In this study, we characterized the inter-row management of 137 immature rubber plantations and showed that technical management routes varied greatly in all four cropping systems. In the three intercropping systems studied, this diversity was structured into clusters, which are more complex to describe than a single management step (e.g. fertilization or weed control) or a general intensification gradient. Concerning mono-cropping systems, the diversity of inter-row management was based on the technical operations linked to weed control, with differences observed both within and between provinces. Depending on the cropping system, the management strategy was not always adjusted over the first years of the immature period despite changing biophysical conditions in the plot due to the growth of the rubber trees. In the systems in which the management strategy did change over time, this took the form of either a reduction in the intensity of the technical operations (i.e. pineapple in Rayong and mono-cropping in Buriram) or alternating these operations from one year to another (i.e. mono-cropping in Trang). Pineapple systems appeared to be the most intensive in terms of chemical inputs used for fertilization and weed control, while cassava systems were the most intensive in terms of tillage, but with high variability of technical operations for a given crop. The different levels of both management intensity between cropping systems and management variability for a given cropping system in immature rubber plantations highlight the importance of considering both crop choices and technical operations applied on each. From a broader perspective, this approach appears to be important for all diversified cropping systems, as it better encompasses the link between system diversity and related performances.

CRediT authorship contribution statement

Aurélie Metay: Writing – review & editing, Conceptualization, Supervision, Writing – original draft, Methodology. **Charlotte Simon:** Visualization, Formal analysis, Writing – review & editing, Methodology, Conceptualization, Software, Data curation, Writing – original draft, Investigation. **Alexis Thoumazeau:** Writing – original draft, Funding acquisition, Project administration, Supervision, Conceptualization, Writing – review & editing, Methodology. **Bénédicte Chambon:** Supervision, Writing – review & editing, Conceptualization, Methodology, Writing – original draft. **Patjima Kongplub:** Methodology, Data curation, Project administration. **Kannika Sajjaphan:** Supervision, Writing – review & editing.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127774.

Data availability

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References

Ahrends, A., Hollingsworth, P.M., Ziegler, A.D., et al., 2015. Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. Glob. Environ. Change 34, 48–58. https://doi.org/10.1016/j.gloenvcha.2015.06.002.

Akakpo, K., Bouarfa, S., Benoît, M., Leauthaud, C., 2021. Challenging agroecology through the characterization of farming practices' diversity in Mediterranean irrigated areas. Eur. J. Agron. 128, 126284. https://doi.org/10.1016/j.eja.2021.126284.

Alvarez, S., Timler, C.J., Michalscheck, M., et al., 2018. Capturing farm diversity with hypothesis-based typologies: an innovative methodological framework for farming system typology development. PLOS ONE 13, e0194757. https://doi.org/10.1371/journal.pone.0194757.

Aouadi, N., Aubertot, J.N., Caneill, J., Munier-Jolain, N., 2015. Analyzing the impact of the farming context and environmental factors on cropping systems: a regional case study in Burgundy. Eur. J. Agron. 66, 21–29. https://doi.org/10.1016/j.eja.2015.02.006.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Soft 67. https://doi.org/10.18637/jss.v067.i01.

Bessou, C., Basset-Mens, C., Tran, T., Benoist, A., 2013. LCA applied to perennial cropping systems: a review focused on the farm stage. Int J. Life Cycle Assess. 18, 340–361. https://doi.org/10.1007/s11367-012-0502-z.

Blanchard, M., Vall, É., Loumbana, B.T., Meynard, J.-M., 2017. Identification, caractérisation et évaluation des pratiques atypiques de gestion des fumures organiques au Burkina Faso: sources d'innovation. Autrepart 115–134. https://doi.org/10.3917/autr.081.0115.

Blazy, J.-M., Ozier-Lafontaine, H., Doré, T., et al., 2009. A methodological framework that accounts for farm diversity in the prototyping of crop management systems. Application to banana-based systems in Guadeloupe. Agric. Syst. 101, 30–41. https://doi.org/10.1016/j.agsy.2009.02.004.

Burgos, N., Ortuoste, J., 2020. Weed management in natural rubber. Weed Control: Sustainability, Hazards, and Risks in Cropping Systems Worldwide. CRC Press, Cleveland, pp. 485–504.

Chambon, B., Angthong, S., Kongmanee, C., et al., 2014. A comparative analysis of smallholders tapping practices in four rubber producing regions of Thailand. Adv. Mater. Res. 844, 34–37. https://doi.org/10.4028/www.scientific.net/AMR.844.34.

Chambon, B., Dao, X.L., Tongkaemkaew, U., Gay, F., 2018. What determine smallholders' fertilization practices during the mature period of rubber plantations in Thailand? Exp. Agric. 54, 824–841. https://doi.org/10.1017/S0014479717000400.

Chavent M. (2015) Analyse Des Correspondances Multiples (ACM).

Chen, Y., Herrera, R.A., Benitez, E., et al., 2022. Winegrowers' decision-making: A pan-European perspective on pesticide use and inter-row management. J. Rural Stud. 94, 37–53. https://doi.org/10.1016/j.jrurstud.2022.05.021.

Cheyns, E., Rafflegeau, S., 2005. Family agriculture and the sustainable development issue: possible approaches from the African oil palm sector. The example of Ivory Coast and Cameroon. OCL 12, 111–120. https://doi.org/10.1051/ocl.2005.0111.

Cittadini, E.D., Lubbers, M.T.M.H., de Ridder, N., et al., 2008. Exploring options for farm-level strategic and tactical decision-making in fruit production systems of South Patagonia, Argentina. Agric. Syst. 98, 189–198. https://doi.org/10.1016/j.agsy.2008.07.001.

DOAE (2017) Important Techniques in production - Pineapple (เทคนิคสำคัญในการผลิต - สับปะรด). Department of Agricultural Extension, Ministry of Agriculture and Cooperatives, Thailand.

Fanchone, A., Alexandre, G., Chia, E., et al., 2020. A typology to understand the diversity of strategies of implementation of agroecological practices in the French West Indies. Eur. J. Agron. 117, 126058. https://doi.org/10.1016/j.eja.2020.126058.

FCRI, D.O.A. (2020) Technology of cassava production (เทคโนโลยีการผลิตมันสำปะหลัง). Ministry of Agriculture and Cooperatives, Thailand.

Fox, J., Castella, J.-C., 2013a. Expansion of rubber (Hevea brasiliensis) in Mainland Southeast Asia: what are the prospects for smallholders? J. Peasant Stud. 40, 155–170.

Fox, J., Castella, J.-C., 2013b. Expansion of rubber (Hevea brasiliensis) in Mainland Southeast Asia: what are the prospects for smallholders? J. Peasant Stud. 40, 155–170.

Gohet E., Thaler P., Rivano F., et al (2015) A tentative composite climatic index to predict and quantify the effect of climate on natural rubber yield potential.

Gravesen, L., 2003. The Treatment Frequency Index: an indicator for pesticide use and dependency 572 as well as overall load on the environment. Proceedings of the PAN Europe Policy Conference, pp. 28–30.

Hahsler M., Buchta C., Gruen B., Hornik K. (2023) arules: Mining Association Rules and Frequent Itemsets. R package version 1.7-7.

Häuser, I., Martin, K., Germer, J., et al., 2015. Environmental and socio-economic impacts of rubber cultivation in the Mekong region: challenges for sustainable land use. CAB Reviews Perspectives Agriculture Veterinary Science Nutrition Natural Resources. https://doi.org/10.1079/PAVSNNR201510027.

Horticultural Research Institute, DOA (2017) Quality Management in the Suppply Chain of Pineapple (เอกสารวิชาการ: การจัดการการผลิตสับปะร□ คุณภาพ). Department of Agriculture, Ministry of Agriculture and Cooperatives, Thailand.

Husson F., Le S., Pagès J. (2017) Exploratory Multivariate Analysis by Example Using R, 0 edn. Chapman and Hall/CRC.

Jacobsen, B.H., 1994. Farmers' decision making behaviour: empirical findings from Denmark. Farmers' decision making: a descriptive approach: Proceedings from the 38th EAAE seminar. SJFI, Copenhagen, Denmark, pp. 77–89.

Kallas, Z., Serra, T., Gil, J.M., 2010. Farmers' objectives as determinants of organic farming adoption: the case of Catalonian vineyard production. Agric. Econ. 41, 409–423. https://doi.org/10.1111/j.1574-0862.2010.00454.x.

Koussihouèdé, H., Clermont-Dauphin, C., Aholoukpè, H., et al., 2020. Diversity and socio-economic aspects of oil palm agroforestry systems on the Allada plateau, southern Benin. Agroforest Syst. 94, 41–56. https://doi.org/10.1007/s10457-019-00360-0.

Langenberger, G., Cadisch, G., Martin, K., et al., 2017. Rubber intercropping: a viable concept for the 21st century? Agroforest Syst. 91, 577–596. https://doi.org/10.1007/s10457-016-9961-8.

LDD (2019) Data summarizing land use types in Thailand by province 2016-2018. (ข้อมูลที่สรุปประเภทการใช้ที่ดินของประเทศไทยรายจังหวัด 2559-2561). Land Development Department, Bangkok, Thailand.

Lê, S., Josse, J., Husson, F., 2008. FactoMineR: An *R* Package for Multivariate Analysis. J. Stat. Soft 25. https://doi.org/10.18637/jss.v025.i01.

Le Bellec, F., Cattan, P., Bonin, M., Rajaud, A., 2011. Building a typology of cropping practices from comparison with a technical reference: first step for a relevant cropping system redesigning process – results for tropical citrus production. Fruits 66, 143–159. https://doi.org/10.1051/fruits/2011026.

Lechenet, M., Dessaint, F., Py, G., et al., 2017. Reducing pesticide use while preserving crop productivity and profitability on arable farms. Nat. Plants 3, 1–6. https://doi.org/10.1038/nplants.2017.8.

Lehoux H., Peroches A., Poline L., et al (2019) Rubber growing throughout the World. Overview of production dynamics, market and value-chain sustainability challenges. CIFOR, Montpellier.

Lenth R. (2024) emmeans: Estimated marginal means, aka least-squares means. R package version 1.7. 2.

Leon, R.G., Kellon, D., 2012. Characterization of 'MD-2' pineapple planting density and fertilization using a grower survey. HortTechnology 22, 644–650. https://doi.org/10.21273/HORTTECH.22.5.644.

Manarungsan, S., Suwanjindar, S., 1992. Contract farming and outgrower schemes in Thailand. Contract Farming in Southeast Asia - Three Country Studies. Kuala Lumpur, pp. 10–70.

Merot, A., Wery, J., 2017. Converting to organic viticulture increases cropping system structure and management complexity. Agron. Sustain Dev. 37, 19. https://doi.org/10.1007/s13593-017-0427-9.

Mettauer, Baron, R., Turinah, V., et al., 2021. Investigating the links between management practices and economic performances of smallholders' oil palm plots. a case study in Jambi province, Indonesia. Agric. Syst. 194, 103274. https://doi.org/10.1016/j.agsy.2021.103274.

Meynard, J.-M., Doré, T., Habib, R., 2001. L'évaluation et la conception de systèmes de culture pour une agriculture durable. Comptes Rendus De. l'Acad. émie D. 'Agric. De. Fr. 87, 223.

Mouron, P., Nemecek, T., Scholz, R.W., Weber, O., 2006. Management influence on environmental impacts in an apple production system on Swiss fruit farms: combining life cycle assessment with statistical risk assessment. Agric. Ecosyst. Environ. 114, 311–322. https://doi.org/10.1016/j.agee.2005.11.020.

Nchanji, Y.K., Nkongho, R.N., Mala, W.A., Levang, P., 2016. Efficacy of oil palm intercropping by smallholders. case study in South-West Cameroon. Agroforest Syst. 90, 509–519. https://doi.org/10.1007/s10457-015-9873-z.

OAE (2014) Rubber: Perennial Area that can be tapped, yield and yield per rai including countries, regions and provinces in 2013 (ยางพารา: เนื้อที่ยืนต้น เนื้อที่กรีดได้ ผลผลิต และผลผลิตต่อไร่ รวมทั้งประเทศ รายภาค และรายจังหวัด ปี 2556). Office of Agricultural Economics of Thailand, Thailand.

OAE (2023) Rubber: Perennial Area that can be tapped, yield and yield per rai including countries, regions and provinces in 2022 (ยางพารา: เนื้อที่ยืนต้น เนื้อที่กรีดได้ ผลผลิต และผลผลิตต่อไร่ รวมทั้งประเทศ รายภาค และรายจังหวัด ปี 2565). Office of Agricultural Economics of Thailand, Thailand.

Obiefuna, J.C., Majumder, P.K., Ucheagwu, A.C., 1987. Fertilizer rates for increased pineapple production in the tropical ferrallitic soils of South Western Nigeria. Fertil. Res. 12, 99–105. https://doi.org/10.1007/BF01048911.

Pagès, L., Le Roux, Y., Thaler, P., 1995. Modélisation de l'architecture racinaire. Plant. Rech. D. éveloppement 2, 19–34.

Panklang, P., Thoumazeau, A., Chiarawipa, R., et al., 2022. Rubber, rubber and rubber: How 75 years of successive rubber plantation rotations affect topsoil quality? Land Degrad. Dev. 33, 1159–1169. https://doi.org/10.1002/ldr.4171.

Périnelle, A., Meynard, J.-M., Scopel, E., 2021. Combining on-farm innovation tracking and participatory prototyping trials to develop legume-based cropping systems in West Africa. Agric. Syst. 187, 102978. https://doi.org/10.1016/j.agsy.2020.102978.

Perrin, A., Yannou-Le Bris, G., Angevin, F., Pénicaud, C., 2023. Sustainability assessment in innovation design processes: place, role, and conditions of use in agrifood systems. A review. Agron. Sustain Dev. 43, 10. https://doi.org/10.1007/s13593-022-00860-x.

Pinheiro, J., Bates, D., Team, R.Core, 2023. NLME: linear and nonlinear mixed effects models. R. Package Version 3, 1–164.
Rapidel, B., Ripoche, A., Allinne, C., et al., 2015. Analysis of ecosystem services trade-offs to design agroecosystems with perennial crops. Agron. Sustain. Dev. 35, 1373–1390. https://doi.org/10.1007/s13593-015-0317-y.
Renaud-Gentié, C., Burgos, S., Benoît, M., 2014. Choosing the most representative technical management routes within diverse management practices: application to vineyards in the Loire Valley for environmental and quality assessment. Eur. J. Agron. 56, 19–36. https://doi.org/10.1016/j.eja.2014.03.002.
Rice Department (2012) Sustainable Technology on Upland Rice Cultivation (เทคโนโลยีการผลิตข้าวไร่อย่างยั่งยืน). Agricultural Cooperatives Association of Thailand, Bangkok, Thailand.
Sahuri, S., 2017. Increasing of Land Productivity and Smallholders Income through rubber based food crops intercropping system. J. Suboptimal Lands 6, 33–42. https://doi.org/10.33230/JLSO.6.1.2017.278.
Sail, R.M., Muhamad, M., 1994. Factors associated with Non-adoption of technology by rubber smallholders. Pertanika J. Soc. Sci. Hum. 2, 29–41.
Salembier, C., Elverdin, J.H., Meynard, J.-M., 2015. Tracking on-farm innovations to unearth alternatives to the dominant soybean-based system in the Argentinean Pampa. Agron. Sustain Dev. 36 (1). https://doi.org/10.1007/s13593-015-0343-9.
Schroth, G., Ruf, F., 2014. Farmer strategies for tree crop diversification in the humid tropics. A review. Agron. Sustain Dev. 34, 139–154. https://doi.org/10.1007/s13593-013-0175-4.
Sébillotte M. (1974) Agronomie et agriculture: essai d'analyse des tâches de l'agronome.
Siju, T., George, K.T., Lakshmanan, R., 2012. Changing dimensions of intercropping in the immature phase of natural rubber cultivation: A case study of pineapple intercropping in Central Kerala. Rubber Sci. 25, 164–172.
Simon, S., Lesueur-Jannoyer, M., Plénet, D., et al., 2017. Methodology to design agroecological orchards: Learnings from on-station and on-farm experiences. Eur. J. Agron. 82, 320–330. https://doi.org/10.1016/j.eja.2016.09.004.
Simon, C., Thoumazeau, A., Chambon, B., et al., 2024. Diversity, adoption and performances of inter-row management practices in immature rubber plantations. A review. Agron. Sustain Dev. 44, 12. https://doi.org/10.1007/s13593-024-00944-w.
Therond, O., Duru, M., Roger-Estrade, J., Richard, G., 2017. A new analytical framework of farming system and agriculture model diversities. A review. Agron. Sustain Dev. 37, 21. https://doi.org/10.1007/s13593-017-0429-7.
TMD (2023) Thai Meterological Department - Home. In: กรมอุตุนิยมวิทยา. https://www.tmd.go.th/en/. Accessed 6 Dec 2023.
Tongkaemkaew, U., Chambon, B., 2018. Rubber plantation labor and labor movements as rubber prices decrease in southern Thailand. FS 2, 18. https://doi.org/10.24259/fs.v2i1.3641.
Vrignon-Brenas, S., Gay, F., Ricard, S., et al., 2019. Nutrient management of immature rubber plantations. A review. Agron. Sustain Dev. 39, 11. https://doi.org/10.1007/s13593-019-0554-6.
Wang, Y., Hu, Y., Niu, X., et al., 2022. Land use/cover change and its driving mechanism in Thailand from 2000 to 2020. Land 11, 2253. https://doi.org/10.3390/land11122253.
Wezel, A., Casagrande, M., Celette, F., et al., 2014. Agroecological practices for sustainable agriculture. A review. Agron. Sustain Dev. 34, 1–20. https://doi.org/10.1007/s13593-013-0180-7.
Yvoz, S., Petit, S., Biju-Duval, L., Cordeau, S., 2020. A framework to type crop management strategies within a production situation to improve the comprehension of weed communities. Eur. J. Agron. 115, 126009. https://doi.org/10.1016/j.eja.2020.126009.