

Strategic optimization of harvest collection points in oil palm plantations[☆]

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Abstract – Oil palm harvesting operations, particularly the collection and transportation of fresh fruit bunches (FFB), represent a significant portion of production costs and rely heavily on manual labor. The spatial configuration of fruit collection points (FCPs) directly impacts operational efficiency, yet their placement is often determined through empirical criteria rather than systematic optimization. This study presents a methodology for optimizing FCP locations in oil palm plantations, taking into account spatial yield variability and labor productivity constraints. Using data from a 148.1-ha plantation in Colombia's eastern region, we first characterized the relationship between plot productivity and harvesting efficiency, finding that the area serviced by harvest teams decreased from 4.0 to 1.7 ha day⁻¹ as yield increased from 10 to 30 t ha⁻¹. This relationship informed the subdivision of production plots into operational units, which served as input for a p-median optimization model to determine optimal FCP locations. The optimized configuration reduced the mean transport distance by 15.8% (from 239.7 m to 201.9 m) and the median distance by 10.6% (from 218.8 m to 195.7 m), while maintaining the current number of collection points. The methodology provides a data-driven approach to plantation infrastructure planning that could be particularly valuable for operations seeking to improve logistics efficiency without additional capital investment.

Keywords: facility location / logistics optimization / oil palm production / operations research / p-median problem

Résumé – Optimisation stratégique des points de collecte de récolte dans les plantations de palmiers à huile. Les opérations de récolte des palmiers à huile, en particulier la collecte et le transport des régimes de fruits frais (RFF), représentent une part importante des coûts de production et dépendent fortement de la main-d'œuvre manuelle. La configuration spatiale des points de collecte de fruits (PCF) impacte directement l'efficacité opérationnelle, mais leur placement est souvent déterminé par des critères empiriques plutôt que par une optimisation systématique. Cette étude présente une méthodologie pour optimiser les emplacements des PCF dans les plantations de palmiers à huile, en tenant compte de la variabilité spatiale du rendement et des contraintes de productivité du travail. En utilisant des données d'une plantation de 148,1 hectares en Colombie orientale, nous avons d'abord caractérisé la relation entre la productivité des parcelles et l'efficacité de la récolte, constatant que la superficie desservie par les équipes de récolte diminuait de 4,0 à 1,7 hectares par jour lorsque le rendement augmentait de 10 à 30 tonnes par hectare. Cette relation a permis la subdivision des parcelles de production en unités opérationnelles, qui ont servi d'entrée pour un modèle d'optimisation p-médian afin de déterminer les emplacements optimaux des PCF. La configuration optimisée a réduit la distance moyenne de transport de 15,8% (passant de 239,7 m à 201,9 m) et la distance médiane de 10,6% (passant de 218,8 m à 195,7 m), tout en maintenant le même nombre de points de collecte.

[☆] Contribution to the Topical Issue: "Palm and palm oil / Palmier et huile de palme".

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La méthodologie fournit une approche basée sur les données pour la planification des infrastructures de plantation, qui pourrait s'avérer particulièrement précieuse pour les opérations cherchant à améliorer l'efficacité logistique sans investissement supplémentaire en capital.

Mots-clés : localisation des installations / optimisation logistique / production de palmier à huile / recherche opérationnelle / problème du p-médian

Highlights

- Strategic optimization of fruit collection points in oil palm reduced transportation distances by 15.8%
- Yield variability directly impacts harvesting efficiency, with serviceable area decreasing from 4.0 to 1.7 ha d⁻¹ as yield increases
- P-median model effectively balanced spatial yield patterns and operational constraints to improve logistics

1 Introduction

Oil palm, *Elaeis guineensis*, is the predominant oil crop on a global scale, accounting for approximately 40% of the total vegetable oil traded worldwide. Presently, oil palm is extensively cultivated in plantations located within the humid tropical regions of Asia, Africa, and the Americas (Murphy *et al.*, 2021). The growing global demand for oil palm products is driving the expansion of oil palm plantations, fueled by both large-scale producers and smallholders (Lee *et al.*, 2014).

The competitiveness of the oil palm industry in countries such as Colombia is challenged by higher production costs, particularly in terms of labor, compared to the leading producers, Malaysia and Indonesia (Mosquera-Montoya *et al.*, 2019). Harvesting, the costliest practice, accounts for 18–20% of the total production costs in Colombian oil palm cultivation. The workforce involved in harvesting represents approximately 85% of the total labor costs, making it the most labor-intensive activity within the palm oil agribusiness (Mosquera-Montoya *et al.*, 2023).

On the other hand, spatio-temporal variability in oil palm yield is influenced by a complex interplay of environmental, management, and endogenous factors. For instance, high vapor pressure deficit (VPD) and water-use inefficiency are linked to reduced yields, particularly during critical growth periods such as bunch failure and anthesis (Monzon *et al.*, 2022). Management practices for both surface and subsurface soil nutrients, as well as leaf nutrients, have significantly affected the yield variability in oil palm plantations (Behera *et al.*, 2022; Rahim Anuar *et al.*, 2008). Given the long lifespan and large scale of most oil palm plantations, differences in agronomic factors, microclimate conditions, pests, and diseases incidence can accumulate over time, leading to uneven crop performance and substantial variations in FFB yield across the plantation. Such variations can be observed at plot level.

Over time, this FFB yield variability impacts harvesting practices and the associated logistics. In a typical operation, after harvesting the bunches, workers transport them to fruit collection points (FCPs), usually bins with a 7-8 t capacity

(Soesatrijo, 2023), where the produce from surrounding plots is gathered for subsequent transport to the mill. In the inner FFB transportation process from fields to FCPs, harvested bunches and loose fruits are sent to the FCPs using manual, animal-drawn, and mechanized systems such as tractor+ Grabber systems and tractor+ trailer systems (Zapata-Hernández *et al.*, 2024). Manual transport relies on human labor, using tools such as baskets, wooden frames, and wheelbarrows. Animal-drawn systems involve animals such as buffaloes, mules, donkeys, oxen, or horses to pull carts or carry baskets. Mechanized systems use machines such as All-Terrain Vehicles (ATVs), small or large tractors, and aerial cableway tractors to move meshes filled with bunches (Cortés Gómez *et al.*, 2017).

Once harvesting begins, the FCPs are located within the plantation based on criteria that are often not well-defined. In most instances, the selection of these sites relies heavily on the discretion of the individual responsible for the harvest. This decision-making process can be influenced by various factors, including personal experience, logistical considerations, and subjective assessments of the plantation layout, potentially leading to variability in the efficiency of fruit collection and transport. The location of the FCPs remains fixed throughout the lifespan of the plantation despite the spatio-temporal variability of yield. Therefore, after several years, as yield patterns shift, an initially optimal location for the FCPs may become suboptimal. It is worth noting that relocating FCPs is not a costly operation and does not require heavy financial resource investment, making such adjustments a feasible strategy to maintain efficient internal logistics and ensure continued optimization (Opananon and Lertsanti, 2013).

This type of optimization problem falls within the scope of operations research, which provides methodologies such as linear programming, integer programming, and spatial analysis to tackle challenges related to resource allocation, logistics, and facility location (Melo *et al.*, 2009). Location theory has been applied to agriculture since the early development of the field. Agricultural location problems are particularly challenging due to their large scale, the involvement of multiple commodities, the need to consider multiple periods, and the presence of conflicting objectives. Additionally, the inherent variability in agricultural production and the perishability of products further complicate these problems, offering a valuable context for enhancing the practical application of location theory (Lucas and Chhajer, 2004).

Most studies addressing location selection have primarily focused on identifying optimal sites for key infrastructure, such as processing facilities, storage centers, or distribution hubs, to enhance the efficiency of regional supply chains (Gu *et al.*, 2023; Li *et al.*, 2022; Liu and Luo, 2023). On the other hand, relatively little attention has been devoted to internal farm logistics, which play a crucial role in efficiently transporting produce. In the case of oil palm, it was only

recently that [Lim *et al.* \(2021\)](#) proposed the first mathematical model specifically designed to optimize the routing of fresh fruit bunches (FFB) harvesting and evacuation processes within a plantation. The developed model effectively optimized FFB harvesting and evacuation routes by considering plantation floor plan shapes, harvestable FFB densities, and transporter loading capacities. The findings revealed that the model enhances routing efficiency by accommodating unique site boundaries and fluctuations in FFB distribution, while also emphasizing the impact of transporter capacity on operational requirements ([Lim *et al.*, 2021](#)).

In the context of a global labor shortage in agriculture and the pressing need to enhance labor efficiency, this study proposes a methodology based on operations research techniques to optimize the placement of FCPs. This study focuses specifically on inner FFB transportation within plantations (from plots to FCPs), which should be distinguished from external FFB transportation that occurs between plantations and oil palm extraction mills. This approach considers the spatiotemporal variability of oil palm production, the layout of the plantation, and the available road infrastructure.

2 Methodology

2.1 Problem statement

The model for determining the optimal locations of FCPs to efficiently aggregate production from multiple plots within an oil palm plantation is formulated as a p -median problem. The uncapacitated p -median problem is a facility location model that seeks to optimally position a fixed number of facilities (p) among a set of candidate locations to serve a given set of demand points (m), with the objective to minimize the total weighted distance between demand points and their nearest facilities ([Zaferanieh *et al.*, 2022](#)). For the present study, p denotes the predetermined number of FCPs to be established, selected from n potential locations representing candidate sites. The parameter m represents the number of places from which FFBs are harvested. The optimization model is defined as follows:

$$\min \left\{ \sum_{i=1}^m \sum_{j=1}^n c_{ij} x_{ij} \right\}, \quad (1)$$

s, to

$$\sum_{j=1}^n x_{ij} = 1, \forall i = 1, \dots, m, \quad (2)$$

$$\sum_{j=1}^n y_j = p, \quad (3)$$

$$x_{ij} \leq y_j, \forall i = 1, \dots, m, \forall j = 1, \dots, n, \quad (4)$$

$$x_{ij} \in \{0, 1\}, \forall i = 1, \dots, m, \forall j = 1, \dots, n, \quad (5)$$

$$y_j \in \{0, 1\}, \forall j = 1, \dots, n, \quad (6)$$

where I, \dots, n is the set of candidate locations at which FCPs may be established, $1, \dots, m$ is the set of harvest locations, c_{ij} is the total cost of sending the FFB from location i to a FCP located in j , and p is the number of FCPs allowed in the solution. Two binary decision variables are employed: x_{ij} Eq. (5) indicates whether the FFB from location i is sent to a collection point j (1 if yes, 0 if no), and y_j Eq. (6) denotes whether candidate location j is selected for an FCP (1 if yes, 0 if no). The model includes the following restrictions:

- All FFB from each harvest location i is fully allocated to exactly one collection point j Eq. (2).
- The number of FCPs is limited to p locations Eq. (3).
- FFB from harvest locations can only be sent to locations where an FCP has been established Eq. (4).

2.2 Case study

This study was conducted at the Campo Experimental Palmar de las Corocoras (4.37°N, 73.17°W, 230 masl), a research station operated by the Colombian Oil Palm Research Center (Cenipalma). The experimental station is in Paratebueno municipality, Cundinamarca Department, representing typical conditions of the Colombian Eastern oil palm planting region.

The study area encompassed 148.1 hectares (ha) of oil palm plantation, subdivided into 18 production plots (C01a through C15), as shown in [Figure 1](#). The plantation layout follows a systematic arrangement with plots of varying sizes interconnected by a network of internal roads. The road infrastructure consists of primary and secondary roads that facilitate daily operations and fruit bunch transportation.

The selected area features oil palms planted between 2012 and 2016, introducing temporal variability in palm age and productive capacity across the plantation. The study site comprises a diverse mix of planting materials, including both interspecific hybrid varieties (*Elaeis oleifera* x *Elaeis guineensis*) and *E. guineensis*. Specifically, plots planted between 2012 and 2014 predominantly contain hybrid cultivars, while those established from 2014 onwards are mainly planted with *E. guineensis*, with some plots containing hybrid cultivars. This genetic diversity adds another layer of complexity to the spatial yield variability, as different materials exhibit distinct growth patterns, bunch characteristics, and productivity profiles. The heterogeneity in planting years and genetic materials creates a dynamic production landscape that directly impacts harvesting operations and, consequently, the optimal positioning of FCPs.

The plots are managed following standard recommended practices for oil palm cultivation in the Eastern region of Colombia, including integrated pest management, optimal fertilization regimes, and systematic harvesting protocols. Currently, seven FCPs are strategically positioned along the main roads ([Fig. 1](#)), with each FCP serving multiple adjacent plots. This existing configuration of FCPs provided the baseline scenario for evaluating the optimization model, considering the complex interplay between spatial layout, genetic diversity, and temporal variations in production patterns.

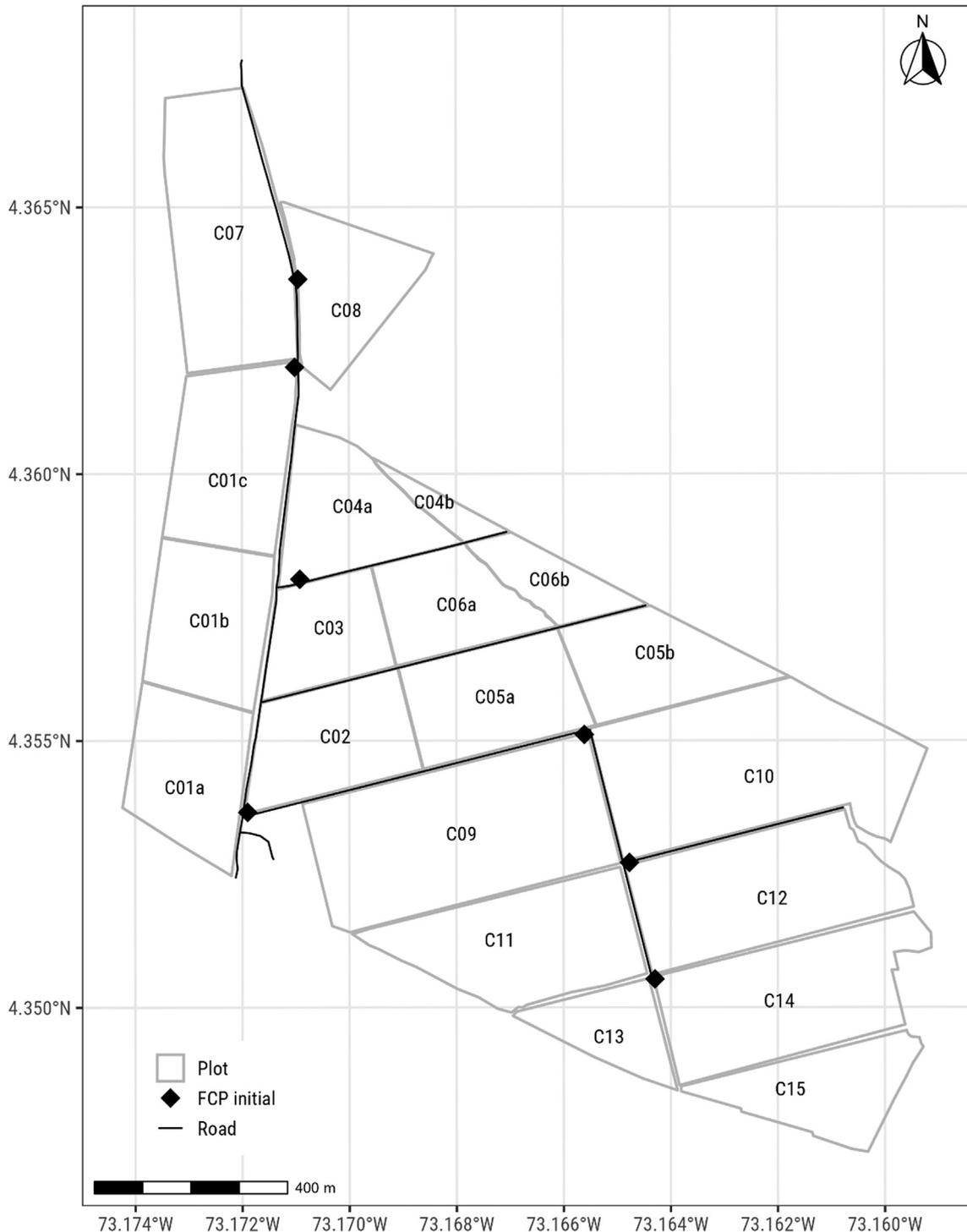


Fig. 1. Spatial layout of the oil palm plantation study area indicating plots, initial FCPs, and road network.

2.3 Spatial data processing

To accurately model the harvesting logistics, plots were subdivided into operational units based on harvesting capacity. Harvesting operations in the plantation are conducted by two-person teams: a cutter responsible for harvesting FFB from the palms, and a collector who gathers the cut bunches from the ground and loads them onto a buffalo-drawn cart for

transportation to the FCPs. This buffalo-assisted harvesting system represents the standard practice in Colombian oil palm plantations, particularly adapted to the local terrain and labor conditions (Camperos-Reyes *et al.*, 2024).

To characterize the relationship between plot productivity and harvesting efficiency, we analyzed operational data from a comparable oil palm plantation in the central region of Colombia (Camperos-Reyes *et al.*, 2024). The data included

daily records of the area covered by collectors and the corresponding plot FFB yield. A linear regression analysis was performed to model the relationship between plot productivity (t ha^{-1}) and the daily area (ha day^{-1}) that could be efficiently serviced by a collector.

Based on this yield-efficiency relationship, each production plot was subdivided into smaller operational units. The number of subdivisions required for each plot was determined by dividing the total plot area by the calculated serviceable area for its specific productivity level. The actual spatial subdivision of plots was implemented using a k-means clustering algorithm. For each plot requiring subdivision, the process involved: (1) generating 10,000 random points within the plot boundary, (2) applying k-means clustering to group these points into the required number of subdivisions, (3) creating Voronoi polygons based on the cluster centers, and (4) clipping the resulting polygons to the original plot boundary. This approach ensured the creation of operational subunits of approximately equal area while accounting for the variable entry and exit points that harvesting teams might use within each plot.

Potential locations for FCPs were generated along the plantation's road network. The road network was first converted into line segments, and points were then placed at regular 50 m intervals along these segments using a systematic sampling algorithm. This process generated a set of candidate FCP locations that served as input for the optimization model.

A cost-weighted distance matrix was constructed to represent the transportation costs between plot centroids and potential FCP locations. The Euclidean distances were calculated between the centroids of each subdivided plot and all candidate FCP points along the road network. These distances were then weighted by the differential payment rates applied in the plantation, where harvesters are compensated at higher rates per ton for low-yielding plots compared to high-yielding ones, reflecting the increased effort required to collect scattered fruit bunches in areas of lower productivity. The resulting matrix incorporated both spatial distances and plot-specific payment rates to represent the total economic cost of fruit transportation from each plot to potential collection points.

2.4 Optimization model implementation

Following the p-median problem formulation presented in equations (1)–(6), we implemented the optimization model using the PuLP library in Python. The model was designed to minimize the total weighted distance between harvesting points ($m = 47$) and FCPs, selecting from $n = 97$ potential FCP locations along the road network.

The implementation directly mapped the mathematical formulation to computational elements. The binary decision variables x_{ij} and y_j correspond to equations (5) and (6), respectively, where x_{ij} indicates whether harvesting point i is assigned to FCP j , and y_j represents whether a candidate location j is selected for FCP placement. The objective function Eq. (1) was implemented as the sum product of the cost-weighted distance matrix (c_{ij}) and the assignment

variables (x_{ij}), representing the total transportation cost to be minimized.

The model constraints were implemented to match equations (2)–(4) from the theoretical formulation. The first constraint Eq. (2) was enforced by requiring the sum of x_{ij} over all candidate locations j to equal 1 for each harvesting point i , ensuring complete assignment of all harvesting points. The second constraint Eq. (4) was implemented by requiring $x_{ij} \leq y_j$ for all ij pairs, guaranteeing that harvesting points could only be assigned to selected FCP locations. The third constraint Eq. (3) was satisfied by setting the sum of y_j equal to 7, maintaining the plantation's current operational capacity with the same number of existing FCPs. The optimization problem was solved using the CBC (COIN-OR Branch and Cut) solver with a relative gap tolerance of 0.0, a single thread configuration, and a time limit of 600 s.

2.5 Performance assessment

To evaluate the performance of the optimization model, we compared the spatial configuration and efficiency metrics between the initial and optimized FCP locations. The assessment was based on Euclidean distances between subplot centroids and their assigned FCPs. The comparison metrics included mean and median transport distances, and the distributions of distances in both configurations were visualized through comparative boxplots to examine changes in the spatial efficiency of FCP placement.

2.6 Sensitivity analysis

In addition to the base model using the current number of FCPs ($p = 7$), a sensitivity analysis was performed to evaluate the impact of varying the number of facilities. Two additional scenarios with $p = 6$ and $p = 8$ were implemented, representing practical variations that could be considered within the plantation's operational constraints. These alternative configurations were assessed using the same optimization framework, and results were compared based on mean and median distances from subplots to their assigned FCPs, allowing for evaluation of the trade-offs between infrastructure investment and transportation efficiency.

3 Results

3.1 Spatial variability in oil palm production

Evaluation of FFB production data from 2023 revealed substantial yield heterogeneity across the study area (Fig. 2). Annual yields varied significantly among plots, ranging from 10.39 to $32.6 \text{ t ha}^{-1} \text{ year}^{-1}$, with a mean yield of $21.7 \text{ t ha}^{-1} \text{ year}^{-1}$ and a coefficient of variation of 35%.

A distinct spatial pattern emerged in the yield distribution, with the highest-producing plots (C02, C01b, C01c, and C04b) consistently achieving yields above $29 \text{ t ha}^{-1} \text{ year}^{-1}$. In contrast, the lowest-producing plots (C11, C13, C09, and C15) yielded less than $12 \text{ t ha}^{-1} \text{ year}^{-1}$. This more than three-fold difference in productivity among plots reflects the complex interaction of factors, including planting year, genetic

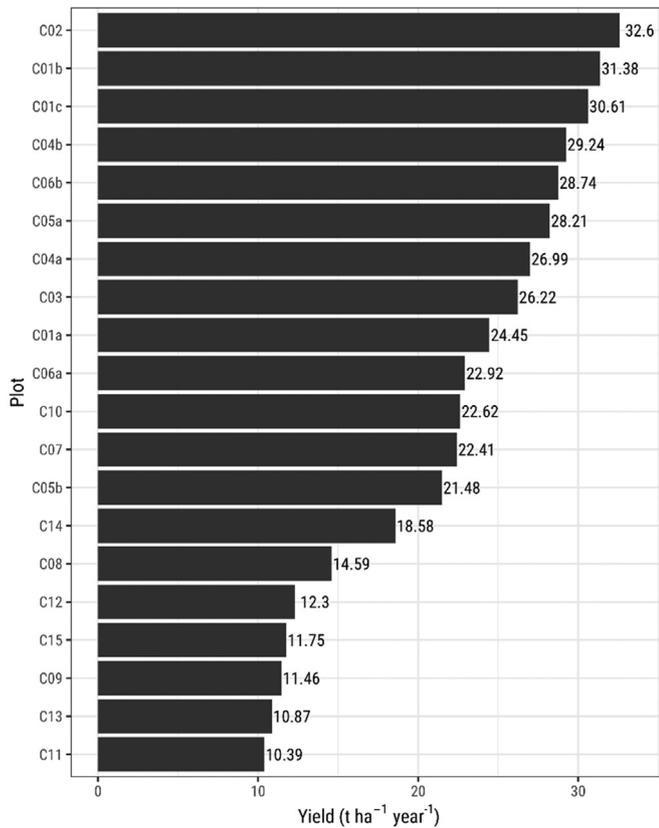


Fig. 2. Annual distribution of fresh fruit bunch yield across oil palm plots. Values represent average production for the 2023 year.

materials, phytosanitary issues, and micro-environmental conditions described in the study site.

The observed spatial heterogeneity in FFB production directly impacts the efficiency of harvest operations and fruit collection logistics. The current configuration of FCPs, established without consideration of these production patterns, may not optimally serve the actual distribution of FFB production across the plantation. This spatial mismatch between production intensity and collection infrastructure provides a strong empirical basis for applying our optimization model to determine more efficient FCP locations based on actual yield patterns.

3.2 Labor productivity analysis

Analysis of harvest operations revealed a significant linear relationship between plot productivity and the area that could be efficiently serviced by a collector (Fig. 3). The regression analysis yielded a strong negative correlation ($R^2=0.66$), indicating that the daily area covered by collectors systematically decreases as plot productivity increases. In plots yielding 10 t ha^{-1} , FFB collectors could service approximately 4.0 ha day^{-1} , while this capacity decreased to 1.7 ha day^{-1} in plots producing 30 t ha^{-1} .

This inverse relationship between yield and serviceable area directly reflects the operational dynamics of FFB collection and transportation. In high-yielding plots, FFB collectors must make more frequent trips to transport the larger

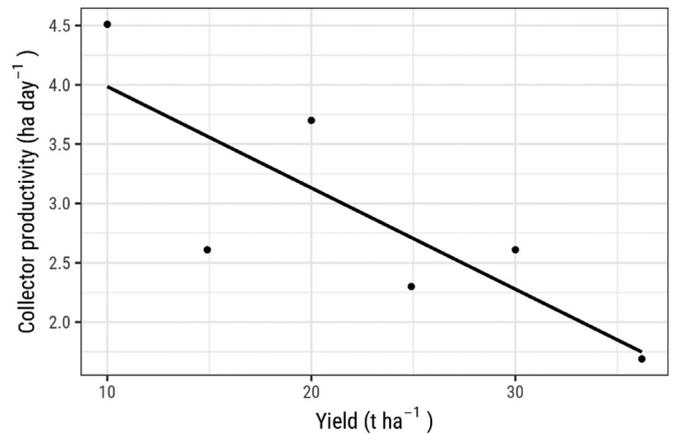


Fig. 3. Relationship between plot FFB yield and collector productivity. Points represent observed field data, and the solid line shows the fitted linear regression model.

volume of harvested fruit to FCPs, resulting in reduced daily coverage area. Conversely, in low-yielding plots, the reduced fruit density allows FFB collectors to cover larger areas as they spend less time on fruit collection and transportation at each location. However, in these low-yielding areas, FFB collectors spend more time searching for FFB to collect along the fields, which is not an optimal use of labor.

The demonstrated relationship between plot productivity and FFB collector efficiency highlights the importance of considering yield variability in harvest logistics planning. The more than two-fold difference in serviceable area between low and high-yielding plots suggests that the spatial optimization of FCPs should account not only for distances but also for the varying operational constraints imposed by yield differences across the plantation.

3.3 Optimization of FCP locations

The p-median optimization model successfully identified new locations for the seven fruit collection points along the plantation's road network (Fig. 4). The optimized configuration maintained coverage of all production areas while significantly reducing transport distances. The model's solutions favored locations that balanced service to multiple plots, particularly considering the varying production yield across the plantation.

A key finding from the optimization was the redistribution of FCP locations to better serve high-yielding areas. While the original configuration placed FCPs at regular intervals along the roads, the optimized locations show a more nuanced distribution that responds to the spatial patterns of production identified earlier. This adjustment is particularly evident in the central section of the plantation, where several high-yielding plots are concentrated. It should be emphasized that relocating FCPs from their original positions to these optimized locations does not require significant financial investment.

The optimization achieved a substantial improvement in transport efficiency, reducing the mean distance from subplot centroids to their assigned FCPs from 239.7 m to 201.9 m, representing a 15.8% decrease. Similarly, the median distance decreased from 218.8 m to 195.7 m, indicating a 10.6%

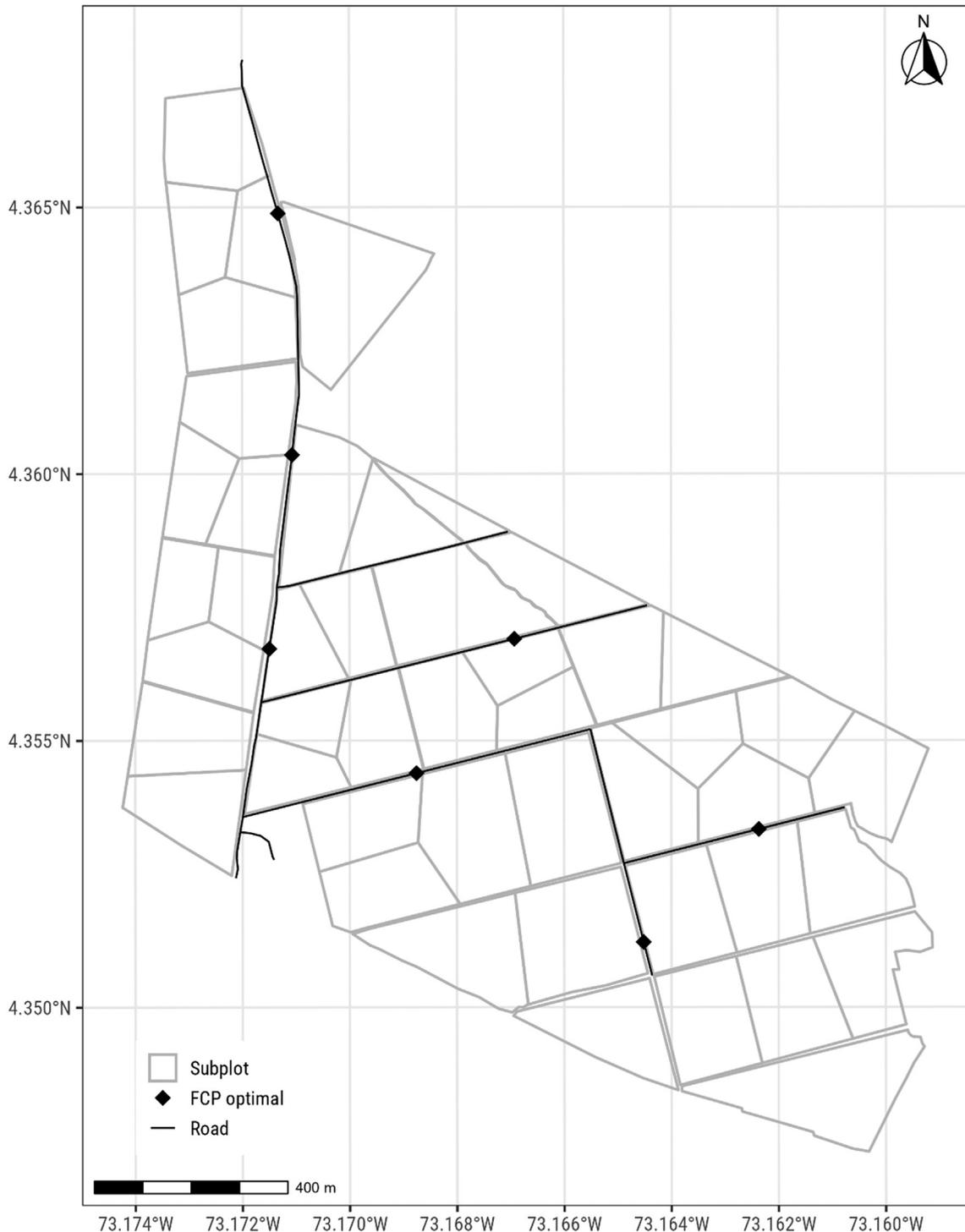


Fig. 4. Optimized configuration of FCPs, including the subdivided plot polygons, across the plantation.

improvement. This reduction in transport distances directly translates to increased operational efficiency for the collection and transportation of FFB.

The more compact distribution of distances in the optimized configuration, as evidenced by the comparative boxplots, suggests a more equitable service coverage across the plantation. This improved spatial efficiency could contribute to more consistent working conditions for harvest

teams and potentially more uniform fruit evacuation times, which is crucial for maintaining fruit quality.

While the optimization achieved overall improvement in transport distances, some outliers remain in the optimized configuration, particularly for subplots located in the southeastern extreme of the plantation (C14, C15). These outliers, visible in [Figure 5](#) as points beyond 400 m, represent areas where the absence of road infrastructure limits the

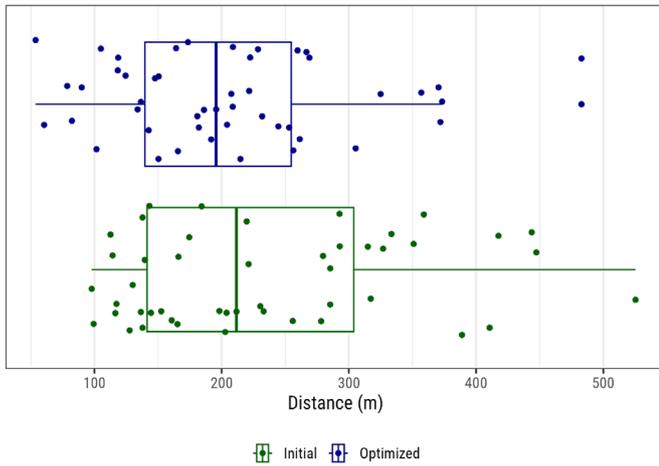


Fig. 5. Distribution of distances between subplot centroids and their assigned FCPs for both initial and optimized configurations. Box plots show the median, quartiles, and range of distances, while points represent individual subplot-to-FCP distances.

potential locations for FCPs. This highlights how the existing road network constrains the optimization possibilities, suggesting that future infrastructure development in this area could further improve harvest logistics efficiency.

3.4 Sensitivity analysis

The sensitivity analysis revealed a clear relationship between the number of FCPs and transportation efficiency across the plantation. As shown in [Table 1](#), increasing the number of FCPs from 6 to 8 resulted in progressive improvements in both mean and median distances from subplot centroids to their assigned collection points.

When comparing the optimized 6-FCPs scenario to the initial 7-FCPs configuration, the results are particularly interesting. Despite using one fewer collection point, the optimized 6-FCPs layout still outperformed the initial 7-FCPs arrangement, with a 6.8% reduction in mean transport distance. This finding suggests that strategic positioning of fewer FCPs could potentially achieve better operational efficiency than a larger number of suboptimally placed collection points, offering plantation managers flexibility in resource allocation while maintaining or improving transportation efficiency. While continuously increasing the number of FCPs would theoretically reduce transport distances further, such an approach would eventually become logistically unfeasible due to increased evacuation complexity, higher infrastructure maintenance, and diminishing returns on operational efficiency.

3.5 Practical implementation considerations

The proposed optimization of FCP locations presents several practical considerations for implementation. While the model demonstrates clear potential for improving transport efficiency, the relocation of FCPs must be carefully planned to minimize disruption to ongoing harvest operations. The transition could be implemented gradually, perhaps during low production periods, to allow harvest teams to adapt to the new collection points.

Table 1. Comparison of mean and median distances from subplots to their assigned FCPs for different field collection points (FCPs).

Number of FCPs	Mean distance (m)	Median distance (m)
6	223.5	211.7
7	201.9	195.7
8	191.5	174.4

The optimized locations all fall along existing roads, which is crucial for implementation feasibility as it requires no additional infrastructure development. The structural requirements for FCPs are relatively simple, primarily needing a stable, elevated platform for fruit collection and sufficient space for truck access during evacuation to the mill. However, specific site conditions at each proposed location should be evaluated to ensure adequate drainage and ground stability for heavy vehicle traffic, particularly during rainy seasons.

A key advantage of the proposed configuration is that it maintains the current number of FCPs, meaning no additional investment in collection infrastructure is required. This makes the optimization strategy particularly attractive from a cost-benefit perspective, as improvements in operational efficiency can be achieved through reorganization of existing resources rather than capital investment.

Recent literature has explored different approaches to optimizing logistics networks for agricultural products, with varying focuses on network design and uncertainty handling. While [Lim *et al.* \(2021\)](#) concentrated on optimizing harvesting and evacuation routes within plantations using a single mathematical model, and [Li *et al.* \(2022\)](#) developed robust hub location models for regional distribution networks, our study bridges a crucial gap by addressing the localized collection point optimization problem within oil palm plantations, considering both spatial yield variability and operational constraints.

A key methodological distinction lies in how uncertainty is addressed across these studies. [Li *et al.* \(2022\)](#) employed a robust optimization approach to handle demand uncertainty in their hub location problem, introducing uncertainty budgets and robust prices to control the conservatism of their solutions. In contrast, [Lim *et al.* \(2021\)](#) focused on deterministic optimization of route efficiency based on plantation floor plans and FFB density. Our study takes a different approach by incorporating both yield variability and operational efficiency through the p-median optimization model, which provides a more targeted solution for the specific context of oil palm harvesting operations.

There are notable similarities in how these studies consider operational constraints. Both [Lim *et al.* \(2021\)](#) and our study acknowledge the importance of field-level operational factors, such as harvesting patterns and transportation efficiency. However, while [Lim *et al.* \(2021\)](#) focused on route optimization for varying plantation shapes and FFB distributions, our study extends this by incorporating the relationship between yield levels and collection efficiency, demonstrated through the inverse relationship between plot productivity and serviceable area by harvest teams.

The conclusions across these studies demonstrate complementary insights for agricultural logistics optimization. [Li *et al.* \(2022\)](#) found that their capacitated model yielded better results than the uncapacitated version under uncertainty, like

our finding that optimized FCP locations can significantly improve operational efficiency. Lim *et al.* (2021) concluded that plantation layout significantly impacts transportation efficiency, with potential reductions in traveled distance of up to 21%, which aligns with our findings of 15.8% improvement in mean transport distances through optimized FCP placement. These parallel findings across different scales of agricultural logistics reinforce the importance of spatial optimization in improving operational efficiency.

4 Conclusions

The integration of plot productivity, harvesting efficiency, and optimized collection point placement offers a data-driven strategy to improve plantation logistics, particularly relevant given increasing labor costs. This spatial optimization approach is especially valuable during phases of plantation expansion or replanting, as it can inform the design of road networks and the initial placement of FCPs, reducing the likelihood of future relocations. Additionally, the observed relationship between yield variability and operational efficiency indicates that precision agriculture practices may enhance harvest logistics in addition to boosting productivity. Overall, this study highlights the importance of considering multiple operational factors such as yield patterns, labor performance, and infrastructure planning in plantation management, with potential applications in optimizing transport routes and aligning harvesting teams with specific plot characteristics.

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Conflicts of interest

The authors declare that there is no conflict of interest in relation to this article.

Author contribution statement

CRB: Conceptualization, Investigation, Methodology, Software, Writing – Original draft preparation; DAH: Investigation, Data curation, Validation, Writing – review & editing; AAT: Investigation, Resources, Writing – review & editing; JEC: Investigation, Validation, Writing – review & editing.

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