OCL 2023, 30, 15
© M. Mosquera-Montoya *et al.*, Published by EDP Sciences, 2023
https://doi.org/10.1051/ocl/2023014

OCL Oilseeds & fats Crops and Lipids

Available online at:
www.ocl-journal.org

RESEARCH ARTICLE — OPEN ACCESS

Labor productivity assessment of three different mechanized harvest systems in Colombian oil palm crops[☆]

Mauricio Mosquera-Montoya[1,*], Daniel Eduardo Munévar Martínez[2], Elizabeth Ruíz Álvarez[3], Carlos Andrés Fontanilla-Díaz[4], Óscar Hernán Salamanca[5] and José María Obregón Esguerra[5]

[1] Research Results Validation Unit, Colombian Oil Palm Research Center (Cenipalma), Bogotá D.C., Colombia
[2] Research Results Validation Unit, Colombian Oil Palm Research Center (Cenipalma), Barrancabermeja, Santander, Colombia
[3] Research Results Validation Unit, Colombian Oil Palm Research Center (Cenipalma), Villavicencio, Meta, Colombia
[4] University of Tennessee, Knoxville, United States
[5] Investments and Plots of Meta (INPARME), Cabuyaro, Meta, Colombia

Received 11 August 2022 – Accepted 4 July 2023

Abstract – Labor shortages are increasingly problematic in rural areas worldwide and, in particular, in the oil palm sector in Colombia. Therefore, alternative methods and systems that increase labor productivity, such as using machines for collecting and lifting fresh fruit bunches (FFB), are needed. In oil palm cultivation, the most labor-intensive process is harvesting. We aimed to assess the labor productivity (in t · FFB/person/day) of three harvesting systems using mechanized lifting systems (harvest A: manual cutting, manual harvesting using meshes, carts, and livestock and lifting using a hydraulic arm; harvest B: manual cutting, manual harvest using a tractor, and lifting using a side-turning container; and harvest C: manual cutting, mechanized harvest using a tractor-grabber, and lifting using a side-turning container). Two bunch density scenarios were considered. Data were collected from adult palm crops in three oil palm plantations in the Eastern Plains of Colombia, and similar crop yields were obtained. Labor productivity was 1.20–2.53 t · FFB/person/day depending on the FFB density and the harvest system. Finally, the cost per ton harvested was $ 8.9–$ 16.6 per ton, being lower in the systems that demanded fewer personnel. The highest labor productivity and the lowest cost per ton harvested were obtained for harvest C.

Keywords: yield / mechanization / *E. guineensis* / labor yield

Résumé – Évaluation de la productivité de la main-d'œuvre de trois systèmes de récolte dans la culture du palmier à huile en Colombie. La pénurie de main-d'œuvre est de plus en plus problématique dans les zones rurales du monde entier et, en particulier, dans le secteur du palmier à huile en Colombie. Par conséquent, les méthodes et systèmes alternatifs qui augmentent la productivité de la main-d'œuvre, comme l'utilisation de machines pour la collecte et le levage des régimes de fruits frais (FFB), sont nécessaires. Dans la culture du palmier à huile, le processus le plus demandeur en main-d'œuvre est la récolte. Nous avons cherché à évaluer la productivité de la main-d'œuvre (en t · FFB/personne/jour) de trois systèmes de récolte utilisant des systèmes de levage mécanisés (récolte A : coupe manuelle, récolte manuelle à l'aide de filets, de chariots et de bétail et levage à l'aide d'un bras hydraulique ; récolte B : coupe manuelle, récolte manuelle à l'aide d'un tracteur et levage à l'aide d'un conteneur à retournement latéral et récolte C : coupe manuelle, récolte mécanisée à l'aide d'un tracteur à pince et levage à l'aide d'un conteneur à rotation latérale). Deux scénarios de densité de FFB ont été envisagés. Les données ont été collectées pour des palmiers adultes dans trois plantations des plaines orientales de Colombie, et des rendements similaires ont été obtenus. La productivité du travail était de 1,20–2,53 t · FFB/personne/jour en fonction de la densité de FFB et du système de récolte. Enfin, le coût par tonne récoltée était de 8,9 à 16,6 dollars par tonne, étant plus bas dans les systèmes qui nécessitaient moins de personnel. La productivité du travail la plus élevée et le coût le plus bas par tonne récoltée ont été obtenus pour la récolte C.

Mots clés : rendement / mécanisation / *E. guineensis* / rendement du travail

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

*Correspondence: mmosquera@cenipalma.org

Highlight

Labor shortages are increasingly problematic in rural areas worldwide and the Colombian oil palm sector is not an exception. This study presents results from a comparison among three mechanized harvesting systems implemented in Colombian oil palm crops and, it provides useful insights on harvest labor productivity.

1 Introduction

Oil palm harvest is a very difficult task, requiring specialized labor (Yusuff *et al.*, 2007; Azman *et al.*, 2015; Ruíz Álvarez *et al.*, 2020). The harvest in oil palm crops comprises a set of sub-processes whose objective is to cut fresh fruit bunches (FFB) and deposits them in containers or trucks, which will transport them to the palm oil mill. Overall, these sub-processes are defined as FFB cutting, FFB collection (until the FFB are delivered to the stockpile areas), and the lifting of the FFB to the containers or trucks in these stockpile areas.

FFB cutting is a critical process because it determines the oil content and acidity of the raw material (FFB) from which palm oil is extracted (Caicedo *et al.*, 2017; Hernández *et al.*, 2020; Sinambela *et al.*, 2020). Likewise, both FFB lifting and the transportation to the palm oil mill must be carried out as soon as possible. This is because once the FFB are cut, the acidification process of the oil contained in the fruit begins, thus affecting the quality of the final product (*i.e.*, palm oil). The acidification of the oil contained in the fruits only stops when the FFB are treated in autoclaves (Corley and Tinker, 2016).

The harvest cost constitutes 18%–20% of the production costs in Colombian oil palm crops. The workforce responsible for the harvest represents about 85% of the total labor cost and this is the cultivation activity in the palm oil agribusiness that requires the most workers (Mosquera-Montoya *et al.*, 2021, 2022; Ruíz Álvarez *et al.*, 2022). Indeed, in Colombia, of the 28 average person days required for the cultivation of one hectare of oil palms per year, 17 are needed for the harvest (Ruíz Álvarez *et al.*, 2022). It must be noted that the price of labor in Colombia is quite high with a daily payment of $ 17 to field workers, which threatens Colombian oil palm competitivenes (Ruíz Álvarez *et al.*, 2022).

This scenario is worsened by the gradual decrease in the labor supply in rural areas. In fact, the rural population has been aging and decreasing due to the migration of young adults out of these areas (Urdinola, 2014; Otero-Cortés, 2019; Coronel, 2020). This explains the search for mechanized harvest systems by the managers of oil palm cultivation companies in Colombia.

Notably, most mechanized technologies adopted in Colombia have been developed in Malaysia, where the shortage of workers also afflicts oil palm cultivation. The Malaysian Palm Oil Board has developed technologies such as mechanized knifes for FFB cutting and mini-tractors, hydraulic arms (grabber), and mechanized loose fruit pickers for FFB lifting (Hitam *et al.*, 1994; Shuib *et al.*, 2004; Jelani *et al.*, 2008; Aramide *et al.*, 2015; Jelani, 2018; Ruíz Álvarez *et al.*, 2020). Although mechanization leverages the agricultural labor, its implementation depends on the characteristics of the soil, the availability of financial resources, the area to be served, the crop yield, among other factors (Ortiz-Martínez *et al.*, 2016; Mosquera-Montoya, 2022).

Regarding the harvest of FFB in the Eastern Plains of Colombia, some companies that are leaders in the adoption of good management practices and have some of the highest yields in the market have implemented the use of machines to complement manual labor.

Here, we show the results of the time and motion studies performed to compare the costs and labor productivity of the harvest systems previously mentioned. The effect of seasonality on the labor productivity and harvest costs was also considered. This work is relevant because our results will help the managers of oil palm companies making decisions about the adoption of mechanized technologies to increase the labor productivity of FFB harvest.

2 Materials and methods

2.1 Harvest systems assessed

The harvest process was documented through field observations of the different sub-processes comprising the harvest. For every system, the time was recorded over the whole working day. For the analysis, the harvest was defined as being comprised of FFB cutting, FFB collecting, and FFB lifting. In all cases, the assessed operators were chosen together with the plantation managers, considering the historical records of payments received as a starting point because the amount of FFB harvested are considered for payroll. We aimed to characterize the selected operators by obtaining a labor yield as close as possible to the average labor yield value of the plantation. We addressed three different harvest systems, whose main operations are described below. It is important to highlight that this study was undertaken at plantations with timely harvest cycles, so loose fruit picking was not a task to be performed by an extra-worker.

2.1.1 Harvest with manual cutting, manual FFB collection using meshes, carts, and buffaloes, and lifting using a hydraulic arm (harvest A)

In this system, the harvest begins by cutting the mature FFB using an oil palm harvesting sickle. Then, one must prepare the bunches (peduncle cutting) and picking loose fruit in sacks. Afterwards, FFB are collected from the ground, and placed on a mesh located inside a cart. This cart is pulled by a buffalo. Once the mesh is filled with the FFB, the cart is taken from inside the lot to the stockpile area. There, the lifting process is performed using a hydraulic arm that collects the FFB-filled meshes from the ground and places them in the containers/trucks that will transport the FFB to the oil palm mill. A time study was performed during 15 working days in two contrasting crop yield scenarios: peak (8 days) and off-peak (7 days) harvest.

2.1.2 Harvest with manual cutting, manual FFB collection using a tractor, and lifting using a side-turning container (harvest B)

In this system, the harvest begins by cutting the mature FFB using a Malay knife. Then, one must prepare the bunches

Table 1. Characteristics of interest of the plantations studied.

Harvest system	Harvest A	Harvest B	Harvest C
Municipality (Meta Department)	Cumaral	Barranca de Upía	Cabuyaro
Study area (ha)	1324	224	402
Annual crop yield (t · FFB/ha)	27	26	28
Average bunch weight (kg)	19	27.5	24.8
FFB cutting	Manual labor using a Malay knife		
FFB collection	Manual labor using meshes in carts pulled by buffalos	Manual labor using a side-turning container pulled by a tractor	Mechanized (a grabber) using a side-turning container pulled by a tractor
FFB raising*	Hydraulic arm that loads the mesh	Side-turning container	Side-turning container

*Filling the containers/trucks in which the FFB will be transported to the extraction plant

and place them along the harvesting paths inside the lots, so it makes it easier for the FFB to be collected. Also, this operator picks loose fruits in sacks and once the sack is full it is placed next to the FFB to be picked. Afterwards, FFB are collected from the ground and are deposited in a side-turning container pulled by a tractor. The side turning container has a hydraulic scissor that allows the operator to lift the container vertically and once at the required height the containers turn to the side, so it dumps FFB to a truck container. Once the side-turning container is full, the tractor transports it to the stockpile area. There, the FFB lifting consists of transferring the bunches from the side-turning container into the containers/trucks that will transport the FFB to the oil palm mill. A time study was performed during 13 working days in two contrasting crop yield scenarios: peak (7 days) and off-peak (6 days) harvest.

2.1.3 Harvest with manual cutting, mechanized FFB collection using a tractor-grabber, and lifting using a side-turning container (harvest C)

In this system, the harvest begins by cutting the mature FFB using a Malay knife. Then, one must prepare the bunches and place them along the traffic rows inside the lots, so it makes it easier for the FFB to be collected. Additionally, this operator picks loose fruits in sacks and once the sack is full it is placed next to the FFB to be picked. Afterwards, with the help of the grabber, FFB are collected and deposited in the side-turning container. Once the side-turning container is full, the tractor transports it to the stockpile area. There, FFB lifting, which consists of depositing the bunches in the containers/trucks, is performed. A time study was performed during 24 working days in two contrasting crop yield scenarios: peak (16 days) and off-peak (8 days) harvest.

2.1.3.1 Location

The three plantations included in the study are at the Eastern Plains (Meta Department) and have above average crop yield. Geographically, they share the same landscape and climate variables are alike. The study was performed in oil palm lots in the adult stage (with more than 7 years). Table 1 summarizes some characteristics of interest of the plantations included in the study and the corresponding predominant harvesting system, which can also be seen in Figure 1.

2.2 Estimation of the personnel required for each harvesting system

Each plantation has its own harvest system design based on the resources available; therefore, the logistics, job design, labor requirements, and equipment used vary from plantation to plantation.

2.2.1 Harvest A

One operator is devoted to cutting the FFB (using a Malay knife) and another one to collecting the FFB (using a mesh, cart, and buffalos) and picking loose fruit in sacks. This second operator is responsible for taking the FFB to the stockpile area where the mesh is filled in (the buffalos pull the cart). Once the mesh is released, it returns to the lots to continue the collection of the FFB until the end of the working day. At the stockpile area, a third operator is responsible for weighing and recording the weight of each mesh; a fourth operator uses the hydraulic arm to collect each meshes with the FFB from the ground and deposit them in a container. Another operator is responsible for handling each mesh to allow the emptying of its content into the container (Fig. 1).

2.2.2 Harvest B

An operator is devoted to cutting the FFB (using a Malay knife). Another operator prepares the FFB (the peduncle of each bunch is cut and the FFB are placed at the edge of the traffic system). Additionally, this operator picks loose fruits in sacks and once the sack is full it is placed next to the FFB to be picked. A third operator loads the FFB manually and deposits them in the side-turning container. A fourth operator drives the tractor that pulls the side-turning container. Once the side-turning container is full, the FFB are transferred to the stockpile area. Once the FFB are deposited in the vehicle that will take them to the extraction plant, the tractor-side-turning container returns to the lots to continue the collection of the FFB until the end of the working day.

2.2.3 Harvest C

An operator is devoted to cutting the FFB (using a Malay knife). Another operator prepares the FFB (cutting the

Fig. 1. Bunch harvesting and lifting systems studied.

peduncle of each bunch and placing it on the edge of the traffic system). Additionally, this operator picks loose fruits in sacks and once the sack is full it is placed next to the FFB to be picked. Another operator drives the tractor and operates the grabber to fill the side-turning container. Once the side-turning container is full, the FFB are transported to the stockpile area. Once the FFB are deposited in the vehicle that will take them to the extraction plant, the tractor-grabber-side-turning container returns to the lots to continue the collection of the bunches, until the end of the working day.

The quantification of the labor requirements was carried out considering the performance of every operator involved in each of the harvesting systems assessed. The results are reported as tons of FFB harvested per man per day, divided by subprocess. In other words, the number of people required for FFB cutting, collection, and lifting was determined.

2.3 Estimation of the labor productivity by harvesting system

The yield of the harvest was estimated from the time and movement studies. Following the methodology for the time and movement studies performed in oil palm crops by Hernández *et al.* (2022), a process diagram was first elaborated and then we recorded the times for each of the processes comprising the diagram (Tab. 2)

To estimate the standard yield of all the harvesting systems, an overtime factor of 9% was considered to compensate for the basic fatigue and the time needed for the personal needs of the workers (Hernández *et al.*, 2022). A variable value, depending on the nature of each system, was also estimated to compensate for the effect of environmental factors, such as temperature, the use of body strength, and noise on the resulting yield (Hernández *et al.*, 2022).

To determine the impact of fruit availability on the yield, two bunch density scenarios (30% and 60%) were considered. These refer to the relationship between the number of bunches harvested and the number of palms planted in the harvested area during a working day (number FFB/number of sown palms). A 100% density indicates that the number of bunches harvested was equal to the number of palms planted, *i.e.*, that an average of one bunch was obtained per palm.

Labor yield was estimated as tons of bunches harvested per day (understood as one working day) and hectares harvested per day. Data analysis was performed using descriptive statistics. Finally, to corroborate the performance of the harvesting equipment, the payment reports of each plantation were considered. The results involving the harvest system, considering the area covered in one day and the tons harvested in one day, are also shown.

2.4 Cost analysis

For the cost estimate, we considered that the investment in capital goods (CAPEX) and the operating expenses of the harvest work (OPEX) were constant during 2022. The CAPEX was estimated considering the price of the machine, the tools required, and the financing cost (assuming that the machine is 100% financed). The annual value necessary for the replacement of the machinery was determined by considering that the useful life of the tractors, hydraulic arms, side-turning containers, carts, livestock, and tools is 15, 10, 10, 10, and

Table 2. Harvest steps and their corresponding functions.

	Harvest A	Harvest B	Harvest C
FFB cutting	Cut the bunches at the optimum harvest point and cut the leaves needed to access the bunch		
FFB preparation	NA	Cut the peduncle, place the leaves cut during harvest in the no-traffic system, and arrange the bunch for harvesting	
FFB collection	Cut the FFB peduncle, place the leaves cut during harvest in the no-traffic system, and place the bunch in the cart containing a mesh. Take the whole cart to the collection point	Transfer the FFB from the soil to the container	NA
Driving the tractor	NA	Drive the tractor through the harvest streets and, when the FFB container is full, direct it to the stockpile area	Drive the tractor through the harvest streets and collect the bunches using the grabber. When the FFB container is full, direct it to the stockpile area
Truck and hydraulic arm operation	Drive the truck to the stockpile area and transfer the mesh to the truck using the hydraulic arm	NA	NA
Recording the mesh weight	Record the mesh weight	NA	NA
Handling the meshes	Release the knots from the meshes so that the FFB are deposited on the truck	NA	NA

Table 3. Personnel required in the harvesting teams according to the harvesting system.

Harvest system	Harvest A		Harvest B		Harvest C	
Harvest density ((FFB/ha)/(palms/ha)) (%)	30	60	30	60	30	60
FFB cutters (# operators required)	37	42	4	4	7	7
FFB collectors (# operators required)	37	42	2	2	0	0
Operator preparing the bunches (# operators required)	–	–	2	2	3	4
Driver of the tractor pulling the container box (# operators required)	–	–	1	1	1	1
Driver of the truck with a hydraulic arm (# operators required)	1	1	–	–	–	–
Operator recording the mesh weight (# operators required)	1	1	–	–	–	–
Operator responsible for mesh handling (# operators required)	1	1	–		–	–
Total (# operators required)	**77**	**87**	**9**	**9**	**11**	**12**

10 years and 1 year, respectively (Srivastava *et al.*, 2013). For machines, tools and buffaloes the depreciation was calculated in a straight-line manner. Regarding, salvage value at the end of useful life, we considered a 10% value with respect to the buying price and, the price data come from plantation records. In Colombia, there is market for old machinery and even for old male buffaloes that reached the end of their working life. The former are bought by growers lacking financial resources to buy new equipment and the latter are bought at informal meat markets for human consumption in rural areas. It must be noted that in Colombia plantations tend to buy male buffaloes that are already trained to work at oil palm fields. Other entrepreneurs oversee raising and training buffaloes.

The financial cost was estimated using the interest rate offered by FINAGRO, the main source of subsidized funding for the agroindustry in Colombia, corresponding to the annual effective rate for fixed-term deposits plus 7% (DTF + 7%). The mean annual effective DTF for 2022 was 8.92%.

The OPEX was estimated considering the labor and implements required yearly for harvesting. The labor cost was calculated considering the number of workers required by the harvest teams and the daily wage corresponding to each process. The maintenance costs for operating the machinery and equipment paid by the companies were also considered, as were the fuel costs (fuel oil). The US gallon price of fuel oil was defined as the average 2022 value in the area ($ 2.21/gallon).

Table 4. Work performance and harvest system indicators.

Harvest system	Harvest A		Harvest B		Harvest C	
Harvest density (%)	30	60	30	60	30	60
Work performance per operator (t · FFB/day)						
Cutter	2.47	2.68	3.87	5.28	3.00	4.30
Collector	2.47	2.68	7.65	13.20	–	–
Bunch preparer	–	–	7.74	13.20	6.00	8.40
Tractor driver	–	–	15.30	20.00	20.30	30.10
Daily yield indicators of the harvest system						
FFB tons harvested (t · FFB)	92.40	111.60	15.3	20	20.3	30.1
Hectares harvested per day (ha/day)	340.42	195.3	12.96	8.47	22.28	12.82
Tons of FFB harvested per day (t · FFB/wage)	1.20	1.28	1.53	2.00	1.69	2.32
Hectares harvested per person (ha/person*day)	4.42	2.24	1.44	0.94	2.02	1.06

Table 5. Daily harvest system cost and cost per ton.

Harvest system	Harvest A		Harvest B		Harvest C	
Bunch density (%)	30	60	30	60	30	60
Daily cost per harvesting system ($)						
Cost of capital (CAPEX)	87.5	87.5	9.2	9.2	18.5	18.5
Tools	46.5	46.5	3.5	3.5	7.6	7.6
Labor	1263.6	1427.3	149.6	146.9	179.2	199.4
Maintenance	60.7	62.2	38.8	38.8	11.9	10.5
Inputs and fuel	38.1	38.5	9.9	9.9	10.3	9.6
Financial cost	12.2	12.2	6.5	6.5	10.4	10.4
Administration and monitoring	70.7	70.7	25.1	25.1	19.3	19.3
Total daily costs ($)	**1532.7**	**1698.3**	**239.2**	**236.4**	**249.7**	**267.8**
Cost per ton harvested ($/t · FFB)						
Unit cost	**16.6**	**15.2**	**15.6**	**11.8**	**12.3**	**8.9**

3 Results and discussion

3.1 Team conformation according to harvesting system

The data in Table 3 reflects the team required to operate the whole harvesting system, so one may require more than one team to harvest the entire plantation. The conformation of the harvest and lifting teams depended on the capacity of the lifting equipment. Table 3 shows the number of operators required for each of the sub-processes that comprise the harvest process for each harvest system. Note that the harvest A system has the capacity to harvest between 92.4 t · FFB/day, in times of low bunch density, and 111.6 t · FFB/day, in times of high bunch density (Tab. 4). This implies that the harvest work force that must be available in the field in a working day is composed of 77 and 87 operators during low and high bunch density seasons, respectively (Tab. 3).

The harvest B system has the capacity to harvest between 15.3 t · FFB/day, in low bunch density times, and 20 t · FFB/day, in high bunch density times (Tab. 4). This implies a requirement of nine workers, both in low and high bunch density times (Tab. 3).

Finally, the harvest C system has the capacity to harvest between 20.3 t · FFB/day, in low bunch density times, and 30 t · FFB/day, in high bunch density times (Tab. 4). This implies that the harvest team consists of 11 and 12 workers in low and high bunch density times, respectively.

3.2 Labor yield

Depending on the harvest system used, the labor yield may depend on the bunch density. Table 4 summarizes the yields reported for each type of operator that belongs to the harvest team in each of the assessed systems. During the high bunch density season, each worker can obviously harvest more bunches (up to 43% more) than during the low season (Tab. 4). However, the difference in yield between the productivity scenarios was greater in the harvest B and C systems (36% and 46%) than in the harvest C system because the work specialization required was greater, resulting in a higher labor productivity. This coincides with the results reported by Diamantidis and Chatzoglou (2019) (Tab. 3).

The results obtained are consistent with those reported in previous studies. For example, for manual cutting with bunch collection using carts, a value of 1.16 t · FFB/person/day was reported and for manual cutting with collection using buffalos, a maximum of 2.5 t · FFB/person/day (Shuib *et al.*, 2010; Corley and Tinker, 2016) (Tab. 4) was reported. Finally, the yield per person obtained using the grabber lifting harvesting system was similar to that reported in previous studies (Shuib *et al.*, 2010; Sierra and Alfonso, 2010; Pebrian and Yahya, 2013; Ho and Subramaniam, 2018; Shuib *et al.*, 2020).

Note that the yield per operator ranges from 1.2 to 2.32 t · FFB/person/day, *i.e.*, the harvest systems studied show a labor productivity that was within the range reported in studies on adult oil palm crops (Tab. 4).

Finally, in low bunch density times, more hectares can be harvested than that in high bunch density times, *i.e.*, the coverage area was greater (Tab. 4); however, the harvest teams took longer to move around the lots during the harvest rather than using that time for the actual harvest. Therefore, the harvest objectives should not be set in terms of the area covered but instead in terms of the tons to be harvested per day. The indicator of the hectares harvested per person per day (Tab. 4) sheds light on this, *i.e.*, the lower the crop yield, the greater the area that an operator can cover.

3.3 Cost of harvest

Among all systems, the harvest A system showed the highest cost per day in both bunch density scenarios: $ 1.533 and $ 1.698 in low and high bunch density scenarios, respectively (Tab. 5). This was due to the large number of cutters and collectors who ensured the loading of the meshes with FFB throughout the working day, so that the use of the hydraulic arm was feasible. Consequently, labor stood out as the costliest category (82.4% and 84% of the total cost). Likewise, the harvest A system showed the highest daily capital cost ($ 69 and $ 78 per day), which was derived from the investment in the meshes, trucks, hydraulic arm, carts, and livestock. Consequently, the financing, maintenance, and fuel costs were also the highest for the harvest system.

The harvest B system showed the lowest daily cost among the three assessed systems, being $ 239 and $ 236 in the low and high bunch density seasons, respectively. In the harvest B system, labor was the costliest item (62% of the total cost) in both productivity scenarios. The investment in machinery and equipment was concentrated on the tractor, side-turning container, and FFB cutting tools. The behavior of the cost of the harvest B system indicated that the estimated daily cost in the low bunch density season was higher than that in the high bunch density season. This is a consequence of the fact that the harvesting operations are more efficient when more FFB are available and that the number of operators comprising the team is constant.

Conversely, the harvest C system showed a daily cost of $ 250 in the low bunch density season and $ 268 in the high bunch density season. Notably, the cost was higher than that of the harvest B system due to the capital cost associated with purchasing the grabber and because two more people are required in the harvest team. The harvest C system reports a labor force share ranging from 72%, in low bunch density times, to 74%, in high bunch density times.

Finally, to make a fair comparison the three assessed harvest systems in terms of cost, the cost per ton harvested should be investigated (Tab. 5). During times of high availability of bunches, the harvest B and harvest C systems showed the lowest unit costs: $ 11.8 and $ 8.9, respectively (Tab. 5). Specifically, the cost of the harvest C system was 21.3% lower than that of the harvest B system and 41.5% lower than that of the harvest A system.

4 Conclusions

The labor productivity of harvesting systems depends on the crop yield, which is reflected in the density of bunches that the harvesting teams encounter when performing their job. Thus, the low yield of the crop translates into a higher harvest cost, especially in the lower bunch density season. Therefore, increasing the productivity in terms of the mean bunch weight and the number of bunches per hectare by ensuring proper agronomic management, is important.

Under high productivity conditions, which are associated with a higher bunch density, the harvest B and C systems were found to be economically feasible and resulted in yields greater than 2 t · FFB/person/day and in costs per ton of less than $ 12/t · FFB, even when labor availability was limited.

The performance of the harvesting system depended on guaranteeing the logistics and infrastructure requirements, the existence of passable roads, and work teams designs that ensured the lack of downtime in the harvest process, which is especially important in systems requiring high work specialization.

This study did not consider the effect of the traffic conditions inside the lots (well-drained soils, good management of covers, and plates) and bunch visibility (proper pruning) on the work performance. All these aspects should be addressed in our future research work. Finally, this study was performed in well-managed plantations with timely harvest cycles that do not incur in significant extra costs associated with collecting loose fruit. In plantations with longer harvest cycles, studying the process of collecting loose fruit may be necessary.

Acknowledgements. The authors express their gratitude to the Fondo de Fomento Palmero (FFP) for providing the financial resources required to conduct this study.

Conflicts of interest

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

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Cite this article as: Mosquera-Montoya M, Munévar Martínez DE, Ruíz Álvarez E, Fontanilla-Díaz CA, Salamanca ÓH, Obregón Esguerra JM. 2023. Labor productivity assessment of three different mechanized harvest systems in Colombian oil palm crops. *OCL* 30: 15.