OPERACINAL PERFORMANCE OF MECHANICALLY HARVESTED COFFEE AND SELECTIVITY IN ACCORDANCE TO FORCE DETACHMENT OF FRUIT

Flávio Castro da Silva, Fábio Moreira da Silva, Antônio Carlos da Silva, Murilo Machado de Barros, Marcos Antônio Zambillo Palma

(Recebido: 04 de abril de 2011; aceito 12 de setembro de 2011)

ABSTRACT: In mechanized harvesting, one of the difficulties encountered by farmers is to determine the appropriate time to start harvesting, as well as vibration and determine the most appropriate operating speed for each cultivar during the harvest period. In general, the regulation of vibration and operating speed of the harvester has been made by producers in an empirical way, by trial, seeking greater operational performance. This study aimed to evaluate the efficiency of mechanical harvesting of eight progenies according to the traction force required for detachment of the fruit. The tests were conducted with three replications using a completely randomized design (CRD) within the same plot in random plots containing five plants. We tried to raise the strength of detachment from coffee fruits on the plant, according to the ripening of fruits, and graded to determine the strength, the green fruits and cherries. We also evaluated the efficiency of the harvest in the progenies analyzed over two years of harvest. It was concluded that there are significant differences between progenies in both the force of detachment as to the efficiency of picking and that picking efficiency is directly related to the force of detachment of mature fruits on the plant.

Index terms: Progenies, maturation, mechanized harvest.

DESEMPENHO OPERACIONAL DA COLHEITA MECANIZADA E SELETIVA DO CAFÉ EM FUNÇÃO DA FORÇA DE DESPRENDIMENTO DOS FRUTOS

RESUMO: *Na colheita mecanizada, uma das dificuldades encontradas pelos cafeicultores é determinar o momento adequado de iniciar-se a colheita, bem como determinar a vibração e a velocidade operacional mais adequada para cada cultivar ao longo do período de colheita. De modo geral, a regulagem da vibração e da velocidade operacional das colhedoras tem sido feita pelos produtores de modo empírico, por tentativas, buscando o maior desempenho operacional. Objetivou-se, neste trabalho, avaliar a eficiência de colheita mecanizada em oito progênies de acordo com a força de tração necessária para o desprendimento dos frutos. Os ensaios foram realizados com três repetições, utilizando-se o delineamento inteiramente casualizado (DIC) dentro de uma mesma gleba, em parcelas aleatórias ,contendo cinco plantas. Buscou-se levantar a força de desprendimento dos frutos de café na planta, de acordo com a maturação dos frutos, sendo classificados, para a determinação da força, os frutos verdes e cerejas. Também foi avaliada a eficiência de colheita nas progênies analisadas em dois anos de safra. Concluiu-se que há diferença significativa entre as progênies avaliadas tanto na força de desprendimento como na eficiência de colheita e que a eficiência de colheita está relacionada diretamente com a força de desprendimento dos frutos maduros na planta.*

Termos para indexação: *Progênies, maturação, colheita mecanizada.*

1 INTRODUCTION

Mechanical harvesting of coffee is made by means of rods located in the cylinders oscillating harvester which work vertically, laterally surrounding the trees, plummeting the fruits by the effect of vibration. Parchomchuk and Cooke (1971) state that the detachment of the fruits of coffee takes place when the inertial forces due to the movement in the fruit become larger than the tensile force required to cause the detachment. Silva et al. (2002) say that to produce the highest number of fruits cherries, it is necessary to adjust the vibration of rods of the harvester, leaving most of the greens at the plant, which is done by varying the vibration from 650 to 950 cycles minute^{-1}. Souza et al. (2005) describe the number of cycles required to detachment of the fruits is proportional to the release time, and significant influence of maturation on this parameter indicates the time of application of vibration is a parameter that should be considered in the process of picking the fruits of coffee aiming selective harvest. A possible parameter for determining vibration and operating speed could be appropriate force required by coffee fruits for their detachment from the plant.

However, the force required for detachment of the fruits to occur is different in each stage of maturation. Crisosto and Nagao (1991) state that this difference is significant, particularly in

[1,2,3,4,5] Universidade Federal de Lavras/UFLA - Departamento de Engenharia Agrícola/DEG - Cx. P. 3037 - 37200-000 - Lavras/MG - flavioengufla@gmail.com, famsilva@deg.ufla.br, engcarlinhos@hotmail.com, egmurilo@yahoo.com.br, markospalma@gmail.com

the detachment force of green fruits and cherries and the difference is also significant in different cultivars of coffee. In addition, they observed that the strength to detachment of green fruit was similar in five cultivars, but this force was approximately twice that required for removal of fruit at the cherry phase. Tongumpai (1993) also concluded that the force for detachment of unripe fruits is generally greater than the force to detach cherry fruit. Furthermore, According to the authors, the largest vibration amplitudes tend to have similar numbers of cycles values, regardless of the stage of ripeness of fruits. Silva et al. (2010) claim that the difference of the detachment force of green fruits and cherries differs among cultivars and during the ripening period. Still according to the authors, this difference in strength between the maturity stages green and cherry can be a parameter for the management of mechanized harvesting.

2 MATERIALS AND METHODS

The sutides took place in the Campos Altos Farm, in the municipality of Campos Altos, Minas Gerais state, whose geographic coordinates are 19°41' S and 46°10' W, with average altitude of 930 m during the harvests of 2007, 2008 and 2009. The progenies used in the evaluations are the result of interbreeding between 'Catuaí Vermelho IAC 141' with Híbrido de Timor, as well as 'Catuaí Amarelo IAC 86' with Híbrido de Timor, transplanted using 4,0 x 1,0 m spacing with an average population of 2,5 thousand plants per hectare; spacing commonly used in commercial areas aiming mechanized harvesting.

The studies were conducted with three replicates, using the Totally Random Lining (Delineamento Inteiramente Casualizado-DIC) within a plot, in random plots containing five plants. We sought to assess the strength of the coffee fruit detachment in the plant according to maturity and was categorized to determine the strength green fruits and cherries before detachment. The detachment force and selective harvest data were collected during the harvests of 2007, 2008 e 2009, as for the harvest of 2007 was not performed due to low crop load status present in plants and the unavailability of the harvester in the field. The determination of the force of detachment was performed using a portable dynamometer constructed specifically for this purpose. Its construction took place in Prototypes engineering Department of the Federal Lavras University (Laboratório de Protótipos do Departamento de Engenharia da Universidade Federal de Lavras - UFLA), allowing measurements from 0,30 to 15,00 N.

The dynamometer calibration was performed by means of elastic deformation of the spring requested by bodies with known masses, measured on a precision balance. From this procedure, we determined the value of the elastic constant of the spring, obtaining the value of 0,008375 $N.m^{-1}$. The determination of this detachment force was based on the Hooke's law that correlates the deformation of bodies within the elastic range, with the force exerted on the body, since the force is proportional to the displacement from its equilibrium.

The determination of the detachment force of the fruit on each marked plant was made in three positions inferior, middle and upper thirds. At each position was determined the detachment force of 24 coffee fruits inripening stage, using the dynamometer. The values collected in the field were transferred to spreadsheets to determine the average force of detachment from all replicates in each progeny, as well as within each maturity stage of fruits.

For the 2008 harvest was used the K-3 automotive model ahrvester, built by "Jacto Máquinas Agrícolas S.A.", operating at operacional speed of 1300 meters . h^{-1} and in the vibrations of 800, 900 and 1000 cicles . $minute^{-1}$ (13,34; 15,00 and 16,67 Hz). For the 2009 harvest, the same harvester was used, however, a selective harvest was performed with two passings of the harvest at operacional speed of 1300 meters . h^{-1} and vibration of 950 cicles $minute^{-1}$.

It was considered detachment efficiency, both for the first and for the second pass, the volume of harvested coffee plus the volume of coffee lying on the ground, once fallen to the ground coffee was also plummeted by interaction effect between speed and vibration harvester with plant. As for harvest efficiency was considered the amount of load status and harvested coffee plants. For the 2008 harvest, harvesting was done with only one pass of the harvester, held on August 12 in which we analyzed the efficiency of crop. For the 2009 harvest, the harvest was carried out with two of the harvester aiming for selective harvest, the first passed in July 06 and the second 29 days later, on August 4 in which we analyzed the detachment efficiency and harvest. Obtaining the detachment efficiency and crop was obtained from the equations (1) and (2) below.

$$\text{Harvest Ef.} = \frac{\text{Pending load}}{\text{harvested vol.+groud vol.}} \times 100 \quad \text{equation (1)}$$

$$\text{Harvest Ef.} = \frac{\text{Coffee harvested}}{\text{Pending load}} \times 100 \quad \text{equation (2)}$$

To obtain the average pending load, a manual harvesting was performed, detaching the fruits of five plants at random over cloth and measures the volumes in litres for each asessed progeny, using a graded recipient.

The volume of coffee harvested in each plot was measured in L . plant^{-1}, being directly collected at the sprout of the harvester, using a graded measurement of 60 L to which was dislocated all the volume of picked fruits. To determine the harvesting losses, the ground under the crown of five plants from each parcel was lined with cloth and the harvester operated over them. The amount of coffee fallen on the ground was measures in volume (L.plant^{-1}) being considered as harvesting loss. To prevent waste of progeny evaluated previously to influenciate the subsequent progeny, the harvester operated in a break of 25 meters in line of the following progeny, before the data collection.

The obtained data were analyzed using Microsoft Office Excel® and for statistic assesment was used the software Sisvar®. The significative variables at the variance analysis ($p<0,05$) were subjected to the Scott-Knott test ($p = 0,05$).

3 RESULTS AND DISCUSION

Analysing Figure 1, it is observed that the progeny (H2) presented lower values of detachment force in the 2007 and 2009 harvests, of respectively 4.68 and 4.06 N.

Only in the year of 2008 , such progeny did not show lower values, remaining an intermediate value between the assessed progenies. As for the progeny (H4) it showed higher detachment force values throughout the entire assessment period, showing average detachment force levels of 8,43 N, 10,15 N and 7,20 N in the years of 2007, 2008 e 2009, respectively. It was noticed that the detachment force is a behavior of each progeny and that, throughout the years, did not suffer great variation. The progenies that showed higher detachment force values in the beginning of the evaluation period remained with such behavior during the assessments.

It is verifyable in Figure 1 that the average detachment force (N) of fruits in cherry stage of the progenies assessed in 2007, 2008 and 2009 differs significantly among the assessed progenies. Note that the progeny (H4) had higher detachment force in all the years of assessment and also presented a lower harvest efficiency in the 2008 harvest. So the average force of detachment and harvest efficiency are directly related as for the referred progeny. For the 2008 crop, the progenies which showed the lowest values of fruit detachment force were (H3), (H6) and (H7), requiring 4.83, 6.50 and 5.23 N, respectively.

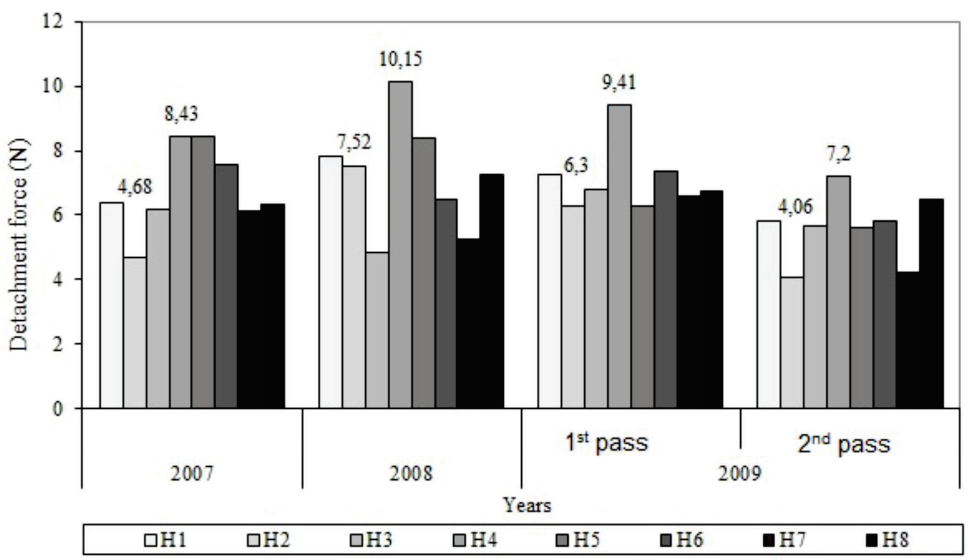

FIGURE 1- Average detachment force (N) of the progenies during the evaluation years.

These three genotypes do not differ significantly, but differed from the others. The progeny whichshowed higher detachment force was (H4), needing 10,15 N, which differed from the other progenies. The difference between the progeny (H4), with greater detachment force and progeny (H3), with lower detachment force of the cherry was 5.32 N, (110,1%). Analyzing the detachment force for the cherry progenies (H3), (H6) and (H7), respectively 4.83, 6.50 and 5.23 N, could indicate the onset of mechanical and selective harvesting for the progeny (H3), followed by (H7) and (H6).

From the methodology and based on these results one can observe a significant difference of the detachment force of the coffee cherry fruit among the progenies, and the progeny (H3) had lower detachment force.

As for the average harvest efficiency, variations were observed between 34,13% and 66,87%, among the assessed progenies. The lower harvest efficiency occurred with the progeny (H4) having efficiency 34.13%, and showed the highest average detachment force of the cherry, 10,15 N, highlighting that the detachment force of the green fruits was 12,0 N.

The progenies that showed detachment force of cherry fruit lower than 7.00 N, (H6), (H7) and (H3), had higher percentages of cherry fruit harvested with averages of 73.00, 62.24 and 76, 67% respectively (Table 1). This behavior is explained by the fact that the detachment force of the cherry is relatively low, which facilitates the detachment. However, it was observed that for the progeny (H7) the average harvesting efficiency was 49,34%, in which the detachment force of green fruits was 8,8 N, with a difference between the detachment force for the cherry fruit of 3,57N. Thus, in the slightest vibration, few green fruits were picked increasing the proportion of cherries. This behavior was not verified in the progenies (H3) and (H6) which could be explained by the low detachment force difference between cherry and green, only 1,3 and 1,7N, respectively.

Table 2 shows that for the 2008 crop, the highest average efficiency of harvest and a higher percentage of cherry fruit harvested were obtained in the progeny (H2), with values of 66.87 and 64.97% respectively, which earned value detachment force intermediary between other progenies however, especially as related to the harvest efficiency and percentage of fruit harvested cherries.

Based on Table 3, where is found the efficiency of harvesting in different vibrations for the progenies evaluated in the 2008 harvest, it is observed that the efficiency of harvest did not differ significantly between the vibrations of 800 and 900 cycles . min-1 for all the assessed progenies. This occurred only for the progenies (H3), (H4), (H6) and (H8) in which the vibration increase favored the significative increase in harvesting efficiency. Analyzing the harvesting efficiency within the same vibration, it is observed that there is significative difference within the asesed progenies, in which (H2) highlighted from the others.

In Table 4, there is the statistic analysis in which is evident that the harvesting efficiency significantly differs between the progenies assessed and the vibrations used in the 2008 harvest.

TABLE 1- average detachment force (N) of cherry fruits in progenies, in the harvest years 2007, 2008 and 2009.

Progeny	2007*	2008*	2009*	
			1st pass	2nd pass
H1	6,39 a	7,83 b	7,27 a	5,83 b
H2	4,68 a	7,52 b	6,30 a	4,06 a
H3	6,20 a	4,83 a	6,81 a	5,66 b
H4	8,43 b	10,15 c	9,41 b	7,20 b
H5	8,44 b	8,39 b	6,27 a	5,63 b
H6	7,54 b	6,50 a	7,37 a	5,80 b
H7	6,13 a	5,23 a	6,58 a	4,20 a
H8	6,35 a	7,24 b	6,74 a	6,50 b

Averages followed by the same letter do not significantly differ by the Scott-Knott test.

*Significative at 5% average.

TABLE 2 - Average pending load values, cherry fruit detachment force, percentage of cherry fruits picked and average coffee bean harvesting efficiency in the progenies, in August 12th 2008.

Progenies	Pending load (L/plant.)*	Cherry fruit detachment force (N)*	Picked cherry (%)*	Average harvesting efficiency (%)*
H1	2,6 d	7,83 b	64,97 a	39,38 b
H2	1,8 c	7,52 b	71,34 b	66,87 d
H3	1,4 a	4,83 a	73,00 b	51,34 c
H4	3,2 g	10,15 c	75,00 b	34,13 a
H5	2,8 e	8,39 b	52,67 a	35,82 a
H6	1,7 b	6,50 a	62,24 a	46,57 b
H7	4,6 h	5,23 a	76,67 b	49,34 c
H8	3,1 f	7,24 b	73,34 b	53,73 c

Averages followed by the same letter do not significantly differ by the Scott-Knott test.

*Significative at 5% average.

TABLE 3 - Harvesting efficiency in different vibrations for the progenies asessed in August 12th 2008.

	Harvesting efficiency (%)*		
	Vibration (ciclos . min^{-1})		
Progenies	800	900	1000
H1	32,94 aA	38,60 aA	46,59 aA
H2	64,60 cA	65,21 cA	70,80 bA
H3	46,00 bA	46,67 aA	61,36 bB
H4	31,00 aA	33,30 aA	38,09 aB
H5	32,72 aA	34,53 aA	40,20 aA
H6	33,28 aA	42,60 aA	63,83 bB
H7	40,10 bA	50,98 bA	53,92 aA
H8	44,78 bA	53,73 bA	62,69 bB

Averages followed by the same letter do not significantly differ by the Scott-Knott test.
*Significative at 5% average.

TABLE 4 - Statistic analysis table for the efficiency of harvesting of the progenies assessed in the vibrations used for the 2008 harvest.

FV	GL	SQ	QM	FC	Pr > Fc
Progeny	7	5932,85	847,55	2484,35	0,00
Vibration	2	2664,22	1332,11	3904,71	0,00
Progeny x Vibration	14	778,53	55,60	163,00	0,00
error	48	16,37	0,34		
CV (%)	1,21				

By Table 5, shows the results gathered in experimental trials of selective harvest of the progenies, with two passings of the harvest in the 2009 harvest performed in July 7th and August 5th, with operating speed of 1300 meters . hour-1 and vibration of 950 cycles . minute-¹.

In the first pass, the average efficiency of detachment varied between progenies from 47.0 to 72.0%, to vibration and velocity employed. The largest detachment efficiency occurred in progeny (H2) with 72.0% and the lowest efficiency in progeny (H3), (H5) and (H6) with 47.0%.

Considering the two passes (first and second), the largest detachment efficiency total was 93.0% and occurred in the progeny (H2), which also showed higher detachment efficiency in the first pass. This detachment efficiency in selective harvesting with two runs can be considered high, being very close to the results obtained by Oliveira (2006), which reached 97.64%, on a crop of the Acaiá cultivar. Santinato, Correia and Zaranza Júnior (1998) and Silva et al. (2000) found similar results, where the full detachment efficiency reached 97.00%, but by using lower operating speeds.

The lowest total detachment efficiency occurred in progeny (H6) with 80,0%, being this one the same which showed the lowest efficiency during the first pass. It is also noticeable that in the first pass the lower detachment efficiencies occurred in the progenies (H3), (H5) and (H6), with 47,00%, observing that these progenies showed different pending loads varying from 4,03 to 5,17 litres . plant-¹, demonstrating that the harvesting efficiency was influenced by the pending loads on plants (Table 6). This behavior shows higher and lower facilitations that the many progenies show as for harvesting, highlighting the progenies (H1), (H2) and (H7), as the most indicated to mechanized harvesting.

TABLE 5 - Average pending load levels, coffee picked, harvesting efficiency, coffee fallen to the ground, detachment efficiency and total detachment efficiency in the progenies assesses in July 6th (first run) and August 4th (second run) in the harvest of 2009.

Progenies	Pending load (L/plant)*	Coffee picked (L/plant)	Harvesting efficiency (%)*	Coffee fallen on the ground (L/plant)	Detachment efficiency (%)	Total detachment efficiency (%)
			First run			
H1	4,02 a	1,81	45,0 g	0,43	56,0	-
H2	3,33 a	1,99	60,0 h	0,41	72,0	-
H3	4,03 a	1,15	28,0 a	0,77	47,0	-
H4	3,94 a	1,68	43,0 f	0,96	67,0	-
H5	4,78 b	1,50	31,0 b	0,76	47,0	-
H6	5,17 b	1,68	32,0 c	0,77	47,0	-
H7	5,30 b	2,10	40,0 e	1,06	60,0	-
H8	5,02 b	1,86	37,0 d	0,66	50,0	-
			Second run			
H1	1,09 a	0,53	48,0 c	0,18	-	89,0
H2	0,66 a	0,35	53,0 f	0,09	-	93,0
H3	2,06 b	1,05	51,0 e	0,27	-	81,0
H4	1,63 b	0,76	46,0 b	0,29	-	86,0
H5	2,52 c	1,26	50,0 d	0,52	-	85,0
H6	1,80 b	0,71	39,0 a	0,26	-	80,0
H7	1,92 b	1,03	54,0 g	0,34	-	89,0
H8	1,99 b	0,91	46,0 b	0,34	-	84,0

Averages followed by the same letter do not significantly differ by the Scott-Knott test.
*Significative at 5% average.

TABLE 6 -Statistic analysis table for the efficiency of selective harvesting of the progenies assessed in the 2009 harvest.

FV	GL	SQ	QM	Fc	Pr>Fc
Progeny	7	15,65	2,23	14,50	0,00
Run	1	88,72	88,72	575,40	0,00
Progeny x Run	7	3,25	0,46	3,01	0,01
Error	32	4,93	0,15		
CV (%)	12,71				

In Table 6 there is the statistic analysis in which is evident that the harvesting efficiency differs significantly between the assessed progenies and between the two harvester runs, therefore aiming selective harvesting.

4 CONCLUSIONS

The progeny (H2) was the one who obtained the lowest detachment force value for the cherry fruits as well as the highest harvest efficiency, both as using one run as for perfoming selective harvesting, showing itself more indicated for mechanized harvesting.

When using one run of the harvester, the efficiency of the harvest is increased as there is increasing in the vibrations of the rods.

The fruits' detachment force was observed as an objective parameter to indicate the beginning of the mechanized harvest as well as selective, and also a parameter for the management of mechanized harvest.

5 THANKS

To the National Scientific and Technological Development Council (Conselho Nacional de Desenvolvimento Científico e Tecnológico-CNPQ), for the support to this study.

6 BIBLIOGRAPHIC REFERENCES

CRISOSTO, C. H.; NAGAO, M. A. Evaluation of fruit removal force of coffee cultivars. **HortiScience**, Alexandria, v. 26, n. 2, p. 210-230, 1991.

OLIVEIRA, E. **Colheita mecanizada do café em maiores velocidades operacionais**. 2006. 92 p. Dissertação (Mestrado em Engenharia Agrícola) - Universidade Federal de Lavras, Lavras, 2006.

PARCHOMCHUK, P.; COOKE, J. R. Vibratory fruit harvesting: an experimental analysis of fruit-stem dynamics. **Transactions of the ASAE**, Saint Joseph, v. 15, n. 4, p. 598-603, 1971.

SANTINATO, R.; CORREIA, J. P.; ZARANZA JÚNIOR, L. Número e modo de passada da colhedora K3-Jacto e seu efeito na produção do cafeeiro. In: CONGRESSO BRASILEIRO DE PESQUISAS CAFEEIRAS, 24., 1998, Poços de Caldas. **Anais...** Poços de Caldas: MAPA/PROCAFÉ, 1998. p. 60-61.

SILVA, C. F.; SILVA, F. M.; ALVES, M. C.; BARROS, M. M.; SALES, R. S. Comportamento da força de desprendimento dos frutos de cafeeiros ao longo do período de colheita. **Ciência e Agrotecnologia**, Lavras, v. 34, n. 2, p. 468-474, mar./abr. 2010.

SILVA, F. M.; OLIVEIRA, E.; SALVADOR, N.; TOURINO, E. S. Avaliação da colheita mecanizada e seletiva do café. In: CONGRESSO BRASILEIRO DE PESQUISAS CAFEEIRAS, 28., 2002, Caxambú. **Anais...** Rio de Janeiro: MAPA/PROCAFÉ, 2002. p. 150-152.

SILVA, F. M.; RODRIGUES, R. F.; SALVADOR, N.; TOURINO, E. S.; SILVA, S. S. S. Custo da colheita mecanizada de café com colhedoras automotrizes no Sul de Minas. **Engenharia na Agricultura**, Viçosa, v. 8, n.1, p. 54-60, jan./mar. 2000.

SOUZA, C. M. A.; QUEIROZ, D. M.; PINTO, F. A. C.; RAFULL, L. Z. L. Desenvolvimento de uma máquina vibradora para estudo do desprendimento de frutos do cafeeiro. **Engenharia Agrícola**, Viçosa, v. 13, n. 1, p. 7-18, jan./mar. 2005.

TONGUMPAI, P. **Strategies for machine harvesting of mature coffe (*Coffee arabica L.)* fruits**. 1993. 167 f. Thesis (Ph.D. in Crop Science) - Oregon State University, Saint Joseph, 1993.