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Trade-offs between fuel chip quality and harvesting efficiency in energy plantations

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ABSTRACT

Single-pass cut-and-chipping with modified foragers currently represents the most efficient technique for harvesting fuel chips from short rotation forestry (SRF). Modified foragers are designed to produce small chips, in the 25–30-mm length range. However, chip length settings can be adjusted for obtaining different commercial products. In that regard, it is important to determine the trade-offs of chip length manipulation, which may affect machine performance. This study tested the same modified forager designed for producing 30-mm chips, under variable chip length settings. In particular, chip length setting was adjusted both downwards to a minimum length of 5 mm (microchips), and upwards to a maximum length of 90 mm (billets). As expected, any setting adjustments that deviated from optimum values resulted in performance decline. Downward alterations of chip length setting resulted in a steady performance decline, which peaked at the shortest length setting (5 mm). Under that setting, productivity was 56% lower and diesel fuel consumption was 183% higher than under the optimum 30-mm setting. In contrast, upward alterations of chip length setting resulted in an immediate and moderate decay of machine performance at the very first increment, followed by the absence of further significant decline as additional increments were introduced. Reducing target chip length below 30 mm doubled or even quadrupled the proportion of fine particles (<3 mm) in the total chip mass, which detracted from chip quality.

1. Introduction

Large amounts of biomass fuel can be sourced from dedicated crops, which could account for three quarters of the total supply of biomass in the near future [1]. Compared with other biomass fuel sources, dedicated crops offer the benefits of intensive management, and may secure the highest yields within the shortest delays [2]. Compared to conventional agricultural crops, fuel crops accrue significant environmental and social benefits, and for this reason they are often supported with public subsidies [3]. Among fuel crops, short rotation coppice (SRC) requires the lowest external inputs [4] and seems particularly suited to farmers, who are used to short waiting times and show little interest towards conventional tree plantations [5]. However, the biomass fuel obtained from SRC plantations is less valuable than conventional farm products, which requires a proportional reduction of management cost in order to maintain financial viability. High efficiency must be achieved in all steps of the production process, and especially during harvesting, which often accounts for over 50% of total production cost [6]. At the same time, the selected harvesting technique may have a strong impact on product quality, and thus on the capacity of maximizing revenues [7].

Previous studies have shown that harvesting cost is lowest when using modified foragers for single-pass cut-and-chip harvesting [8]. However, cut-and-chip harvesting has the limit of producing fresh chips, characterized by a low energy content [9] and prone to rapid decay [10,11]. Furthermore, cut-and-chip operations imply that chip size must be managed at harvest time through the forager, and not at later time through a dedicated chipper. While moisture content issues can be solved by targeting users that tolerate high moisture or by blending [12], the solution to any chip size issues stays with the forager, where the chips originate. The increasing diversification of the biomass fuel market poses additional challenges for what concerns chip size distribution [13], and favours flexible solutions that may adapt to changing user requirements [14]. Different customers may issue different chip size specifications, and the ideal machine should rapidly adapt to customer requirements in order to target the highest-paying fuel markets.

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Fortunately, modern energy wood harvesters offer the possibility of adjusting target chip length, in order to match varying particle size specifications. One of the most recent models can produce particles with a target length between 5 mm and 90 mm [15]. While this machine is designed for optimum operation at a chip length target of 30 mm, chip length can be reduced directly from the cab through the simultaneous increase of feeding speed and chopper rotary speed, and by adjusting the spacing between the blades and the anvil. This way, chip length is decreased from 30 to 5 mm in 1-mm steps. The lower chip length the smaller the boiler that can use it, which implies targeting small-scale residential plants [16]. In fact, the smallest size class configures as micro-chip, which can be supplied to the pellet manufacturing sector. On the other hand, chip length can be increased from the optimum 30-mm length by removing part of the knives from the chopper, although that is a bit more laborious than just adjusting feeding and chopper speed. In that case, the machine can produce so-called "billets", up to a maximum length of 90 mm. Billets are only suitable for large plants, but they offer the distinctive advantage of higher pile permeability, with all its benefits in terms of drying [17], cooling [18] and ignition-risk prevention [19].

Of course, manipulation of target chip length has an impact on other parameters than target particle size, such as productivity, diesel fuel consumption and bulk density. Better knowledge of the trade-offs between chip quality and machine performance is required for making informed choices. Therefore, the goal of this study was to determine the relationship between target chip length, productivity, fuel consumption, bulk density and particle size distribution for a modified forager used in SRC plantations. In particular, the study explored the effect of deviations from optimum chip length, both downwards and upwards.

2. Materials and methods

The machine used for the test was the 441 kW New Holland FR9060 model, fitted with the new 130FB header, which is specifically designed for harvesting large-size SRC (Fig. 1). The header is equipped with a pair of large diameter circular saws placed at the bottom of the vertical crop collector rollers. The saws cut the stems and the crop collectors move them towards the horizontal feed rollers, which convey cut stems to the chopper unit, butt first. The chopper itself is part of the original forager unit and is located inside the carrier. It consists of the same drum device used for chopping maize, which is normally equipped with 16 knives divided in two sections. Once detached from the stem, wood chips are engaged by the blower, and launched through the outlet pipe. While the manufacturer recommends production of 30-mm chips, chip length can be set to any values between 5 and 30 mm, directly from the operator's seat by changing the speed of the feed rollers and the chopper, and by adjusting the distance between the blades and the anvil. Chip length can be further increased from the 30-mm recommended setting, by removing part of the knives from the chopper, in order to reduce the number of cuts produced during each revolution. The maximum chip length achieved with this method is 90 mm.

Fig. 1. A view of the energy plantation, the modified forager and the chips.

The tests were conducted in Brazil, on two of the new energy wood plantations, established with selected eucalypt clones. The two plantations belonged to different owners, who required different product types. Therefore, the settings from 5 to 30 mm (treatments) were tested at site A, and the settings from 45 to 90 mm were tested at site B. Within each site, the sequence of chip length settings was changed randomly, in order to spread the effect of knife wear equally on all treatments.

The two sites exemplified two main cases. Case 1 consisted in decreasing target chip length from the optimum 30-mm setting, with the purpose of producing small chips and micro-chips. In that instance, the machine was tested with the standard 16-knives configuration for the following length settings: 30, 25, 20, 15, 10 and 5. In contrast, case 2 gauged the effects of increasing target chip length above the optimum 30-mm value, with the purpose of producing billets. In such instance, the machine was tested after removing 10 knives from the chopper, for the following length settings: 45, 60, 70, 80 and 90 mm. In this case, the optimum 30-mm configuration could not be tested because the smallest length one could produce with a 6-knives configuration was 45 mm. Therefore, the results for the 30-mm setting were acquired from the previous test and included into the second dataset, in order to provide a theoretical term of comparison. That allowed gauging the general effect of deviation from the optimum. Of course, the chip length figures reported above represented target lengths, i.e. the expected lengths of the largest chips (or billets) produced by the machine for each setting. They did not represent cut length proper, although cut length and chip length were closely related.

The plantations sampled at the two sites differed for spacing and age, but they were similar for what concerned field stocking and moisture content (Table 1). Even if the machine used for the test was the same and there was no significant difference between the two sites in terms of tree species, moisture content and field stocking, the data from the two different sites were kept separate because age and planting density were different, which could have

Table 1
Characteristics of the test sites.

Site		A	B
Case		1	2
Thesis	From chips...	...to microchips	...to billets
Longitude		20°58′S	15°46′S
Latitude		48°25′W	42°07′W
Location		Botucatu	Taiboeiras
State		SP	MG
Elevation	m als	840	750
Climate		Meso-thermal	Semi-arid
Annual rainfall	mm	1600	855
Mean temperature	C°	20	21
Species		EG × EU	EG × EU
Age	years	2.5	3
Rows		Single	Single
Spacing	m	3 × 1.5	4 × 0.5
Plant density	trees ha^{-1}	2222	5000
Stocking	t ha^{-1}	130.8	136.1
Moisture content	%	53.4	54.5
Yield (dry matter)	t^{-1} ha^{-1} yr^{-1}	24.4	20.6

Notes: SP = Sao Paulo; MG = Minas Gerais; EG = Eucalyptus grandis. EU = Eucalyptus urophylla.

confounded the results. Even if the error introduced by these factors was likely small compared with the differences caused by the mechanical changes in the machine settings, tests were kept separate as an additional safeguard. Therefore, the study configures as two separate experiments, exploring deviations from optimum target length in the opposite directions. The datasets from each experiment were treated separately, except in the case of bulk density, where it was reasonable to assume that planting density and stem age had little effect. Only in this case, the two datasets were consolidated and treated as a single pool.

During all tests, the machine was operated by the same driver, who was well acquainted with the base unit, but had been driving the harvester on the eucalypt energy plantations for few weeks before commencing the test proper.

Each treatment was replicated three times, where the experimental replicate consisted of a full trailer with a capacity of 9 m^3. For each replicate, the following data was acquired: volume and mass outputs, time and fuel inputs, harvested surface and moisture content. Particle size distribution was determined for all chip length settings up to 30 mm, but not for the longer settings, due to limitations of the laboratory equipment.

Volume and mass outputs were determined by measuring the internal volume of the container receiving the chips, and by taking all loads to a certified weighbridge. Time and fuel inputs were obtained from the on-board computer. The forager was equipped with the new "Intelliview" automatic data collection system, designed for storing work data, including: fuel use ($l\,h^{-1}$), harvest time (h) and harvest distance (m). Time readings were checked against those provided by a conventional stopwatch and proved extremely accurate.

The surface area covered for completing each load was determined by multiplying inter-row space by total travel length, the latter determined through readings of the on-board computer. That allowed calculating field stocking in fresh tonnes per hectare, delivered to the weigh bridge (i.e. net of harvesting losses).

Moisture content was determined with the portable "M75 Mugmobil" moisture content gauge, developed by Marrari Automation Ltd. and based on electric conductance. Readings were conducted on 35 L samples, each obtained by consolidating multiple subsamples extracted randomly from the same 9 m^3 load. Moisture content was determined on five samples per field. A preliminary calibration test conducted in the laboratory with 30-mm chips showed that the portable device incurred a ±2% error in absolute value.

Particle size distribution was determined only for the chip length classes between 5 and 30 mm. To this purpose, one kg sample was collected from each load, bagged, tagged and dispatched to the laboratory. Once there, samples were dried to equilibrium, which was reached at the approximate moisture content of 13%. Then, samples were placed in a vibrating screen for sorting in the following three particle-size classes: 45–16 mm, 16–3 mm and <3 mm. Each component was then weighed on a precision scale, in order to determine mass distribution.

The dataset was analyzed with the Minitab 16 advanced statistics software using a general linear model (GLM). Compliance with normality assumptions was checked through the analysis of residuals; accordingly, particle-size distribution data were transformed as the square root of arcsine. Field stocking was introduced to the GLM as a covariate. Multiple comparisons were conducted with the Tukey-Kramer test. Only the consolidated dataset for bulk density was tested with linear regression analysis, treating chip length classes as a numerical variable. This strategy allowed gaining a much better perspective on the general effect of target chip length on bulk density, and it was deemed worth doing. For all tests, the elected significance level was $\alpha < 0.05$.

3. Results

Decreasing target chip length from the optimum 30-mm setting resulted in a loss of productivity (Table 2). Such loss became large (17%) and significant if the target chip length was halved to 15 mm. An additional 17% loss was incurred when the setting was changed from 15 to 10 mm. However, the largest loss (36%) occurred when the setting was changed again from 10 to 5 mm, to produce micro-chips. The loss incurred for the 5-mm setting were statistically significant when compared against all other settings, and represented 56% of the original productivity obtained for the optimum 30-mm setting. Hourly fuel consumption was inversely proportional to target chip length, but changes were smaller than recorded for productivity. However, the 5 mm setting was associated with a 25% increase in fuel consumption from the 30-mm baseline. Fuel consumption per product unit followed about the same trend, but differences were sharper due to the combined effects of length setting on hourly fuel consumption and productivity. In this case, the smallest length setting stood apart, because it represented the highest fuel consumption increment: 61% more compared with the 10-mm setting just above it, and 183% more compared with the optimum 30-mm setting. The analysis of variance suggested that productivity and fuel consumption were strongly affected by chip length setting (Table 3). Field stocking also had an effect, but this effect was seldom significant and did not account for more than 5% of the variability in the data, demonstrating that the experimental design was effective in containing background noise.

When target chip length was increased from the optimum 30-mm setting, the effect on productivity was small and devoid of statistical significance (Table 4). In contrast, increasing chip length from 30 to 45 mm resulted in a 20% increase of hourly fuel consumption and a 40% increase of fuel consumption per product unit. These differences were statistically significant. However, additional length increments had no significant effect on fuel consumption. In essence, all effects were found when departing from the optimum 30-mm setting: after that productivity and fuel consumption proved indifferent to any additional chip length increments. Again, the analysis of variance showed the strong effect of chip length setting on productivity and fuel consumption (Table 5). Field stocking had a stronger effect on productivity and hourly fuel consumption than in the previous experiment (chips to micro-chips), but its effect did not explain more than 16% of the overall variability in the data. Error was also higher in this experiment, possibly as the result of a less consistent process.

As expected, bulk density was inversely proportional to chip length, and the relationship was highly significant (Fig. 2). None of the other independent variables recorded in the study had any significant effect on bulk density. Production of 5-mm micro-chips resulted in a 10% increase in bulk density, compared with the 30-mm baseline case. In contrast, production of 90-mm billets resulted in a 13% decrease of bulk density, compared with same baseline case.

For case 1 (5–30-mm configurations) the proportion of particles falling within the largest size class (45–16 mm) decreased with target chip length (Fig. 3), and the change from one setting to the next was always significant, at least for the transformed data. The largest changes were recorded when shifting from 30 to 25 mm, and from 10 to 5 mm. At both shifts, the proportion of particles in the 45–16-mm class was reduced to less than half. The opposite trend was visible for the smallest size class (<3 mm). Its incidence quadrupled when the chip length setting was changed from 30 to 25 mm, and doubled when it was changed from 10 to 5 mm. The proportion of particles <3 mm was only 2% when the machine was set to produce 30-mm chips, and shot up to 48%

Table 2
From chips to micro-chips: main results of the study.

Chip length	Bulk density		Productivity		Fuel consumption				Field stocking	
	kg m^{-3}		t h^{-1}		l h^{-1}		l t^{-1}		t ha^{-1}	
mm	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
30	365.2	5.5	56.6[a]	3.8	66.2[a]	8.4	1.17[a]	0.14	137.5	27.5
25	389.8	15.8	50.3[ab]	3.5	73.3[ab]	2.0	1.46[ab]	0.11	122.9	10.8
20	396.1	15.6	53.9[ab]	2.9	76.7[ab]	4.2	1.42[ab]	0.06	150.2	11.7
15	398.1	1.2	47.0[bc]	3.3	81.6[b]	5.6	1.74[bc]	0.16	142.6	9.9
10	400.6	0.6	38.9[c]	3.3	79.7[b]	4.4	2.06[c]	0.20	116.4	23.2
5	411.1	3.6	24.8[d]	1.5	82.1[b]	4.4	3.31[d]	0.03	115.2	22.4

Notes: t = fresh tonnes; h = productive hour, harvesting only (no maneuvers and delays); SD = standard.
Deviation; means that do not share a letter are significantly different for $\alpha < 0.05$.

Table 3
From chips to micro-chips: Anova tables.

Effect	DF	SS	η^2	F	p
t h^{-1}	S = 2.289, Adjusted R^2 = 0.959				
Size	5	1352.23	0.92	51.6	<0.001
Field stocking	1	62.55	0.04	11.94	0.005
Error	11	57.65	0.04		
Total	17	1472.43			
l h^{-1}	S = 5.037, Adjusted R^2 = 0.510				
Size	5	599.82	0.65	4.73	0.015
Field stocking	1	47.32	0.05	1.87	0.199
Error	11	279.10	0.30		
Total	17	926.24			
l t^{-1}	S = 0.129, Adjusted R^2 = 0.969				
Size	5	7.01	0.97	83.54	<0.001
Field stocking	1	0.02	0.00	1.39	0.264
Error	11	0.18	0.03		
Total	17	7.21			

Notes: DF = Degrees of freedom; SS = Sum of squares.
η^2 = ratio of SS for the specific factor and the total SS.

when the chip length setting was reduced to 5 mm. Changes in the intermediate particle size class (16–3 mm) were smaller but significant (for the transformed data), and they were inversely proportional to the chip length settings. Within the range of length settings gauged in this study, the machine never produced any particles longer than 45 mm.

4. Discussion

Every machine is designed for working best at some optimal setting, and therefore any adjustments that deviate from optimum values are likely to negatively affect performance. This study provides a clear example of this kind of generalization. However, it also shows that patterns of decline can vary depending on the purpose and types of adjustments.

If the adjustment is aimed at decreasing target chip length, and involves manipulating feed and chopper speed only, then performance trends follow the classic pattern shown by standard chipping machines undergoing similar changes for the same purpose [20–22]. In fact, this specific machine had been previously tested for production under two chip length settings, which showed that a 17% production loss could be expected when decreasing target chip length from 30 mm to 20 mm, under the same field stocking levels explored in the present study. That value corroborates the results obtained in this more detailed experiment, which explored a much wider range of length settings. Another previous study had explored the possibility to produce micro-chips by altering the settings of a conventional forestry chippers [23]. This study showed that if cut length was decreased from 20 to 7 mm, then productivity dropped 30% and fuel consumption per unit product grew 50%, which also corroborates the results of the present study.

No previous studies available in the literature have explored the effect of increasing chip length settings with the purpose of producing billets, rather than chips. On these machines, larger sizes require mechanical alterations, and in particular removing knives from the chopper. This study suggests that losses are initially incurred from these modifications, but performance seems to stabilize and no additional decay is recorded when increasing target chip length from 60 to 90 mm. In fact, the worst performance is recorded for the 45-mm setting, which is obtained when setting infeed speed to its minimum value. That is also when performance is worst under the micro-chip treatment, with the only difference that in the billet treatment the drum is equipped with 6 knives and in the micro-chip treatment with 16 knives. Therefore, the experiment may simply indicate that the minimum infeed speed setting is so far from the optimum work regime that the machine may work least efficiently, under any of the two knife configurations (e.g. 6 or 16 knives).

The inverse relationship between chip length and bulk density is well known, and it depends on the better packing quality of smaller chips. Furthermore, larger particles are characterized by

Table 4
From chips to billets: main results of the study.

Chip length	Bulk density		Productivity		Fuel consumption				Field stocking	
mm	kg m^{-3}		t h^{-1}		l h^{-1}		l t^{-1}		t ha^{-1}	
Target	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
30	365.2	5.5	56.6[a]	3.8	66.2[a]	8.4	1.17[a]	0.14	137.5	27.5
45	361.2	1.1	48.2[b]	1.2	79.7[b]	0.4	1.65[b]	0.05	135.8	1.4
60	347.5	0.5	57.3[ab]	1.7	82.2[b]	1.1	1.44[ab]	0.02	146.3	1.2
70	331.3	0.7	52.7[ab]	2.3	78.9[b]	1.0	1.50[b]	0.06	130.4	1.8
80	330.4	8.9	50.1[ab]	2.2	76.5[b]	0.4	1.53[b]	0.06	135.5	2.2
90	327.3	5.0	50.1[ab]	5.8	78.5[b]	0.8	1.56[b]	0.16	132.4	9.7

Notes: t = fresh tonnes; h = productive hour, harvesting only (no maneuvers and delays); SD = standard.
Deviation; means that do not share a letter are significantly different for $\alpha < 0.05$.

Table 5
From chips to billets: Anova tables.

Effect	DF	SS	η^2	F	p
$t\ h^{-1}$	S = 2.737, Adjusted R^2 = 0.612				
Size	5	148.67	0.54	3.97	0.026
Field stocking	1	43.36	0.16	5.79	0.035
Error	11	82.38	0.30		
Total	17	274.41			
$l\ h^{-1}$	S = 2.848, Adjusted R^2 = 0.777				
Size	5	463.56	0.76	11.43	<0.001
Field stocking	1	56.41	0.09	6.95	0.023
Error	11	89.22	0.15		
Total	17	609.19			
$l\ t^{-1}$	S = 0.102, Adjusted R^2 = 0.664				
Size	5	0.40	0.76	7.72	0.002
Field stocking	1	0.01	0.02	0.05	0.822
Error	11	0.11	0.22		
Total	17	0.53			

Notes: DF = Degrees of freedom; SS = Sum of squares.
η^2 = ratio of SS for the specific factor and the total SS.

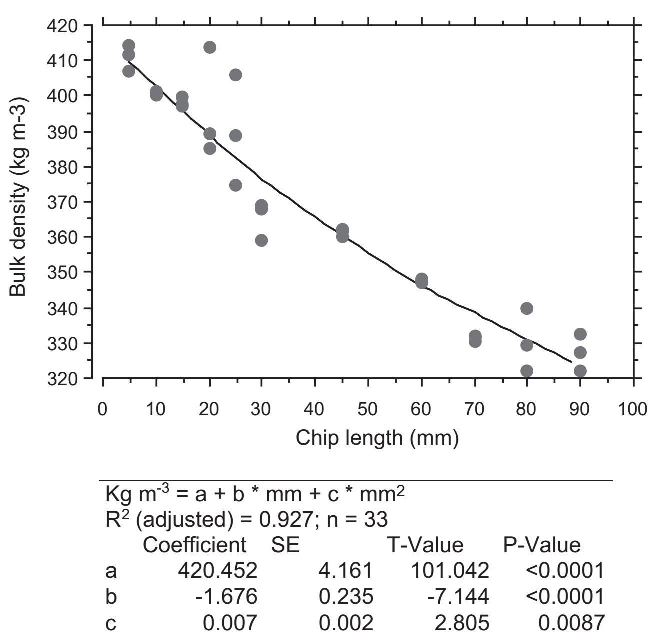

Fig. 2. Relationship between bulk density (kg m^{-3}) and target chip length (mm).

one dimension (length) being much larger than the other two, which favours accidental structuring [24]. Billets are especially prone to structuring, which explains the low bulk density of billet loads. Smaller chips have a much more regular shape, which severely reduces the chances for structuring and explains the higher bulk density of small chip loads. In any case, the results of this study are corroborated by earlier research conducted on another modified forager used for SRC harvesting [25]. In that case, a new chopper was installed for producing longer chips. Such intervention allowed increasing the proportion of chips in the 45–16 mm class from 63% to 73% (standard chopper), and resulted in an 8% decrease of bulk density.

Managing particle size distribution is the very purpose of target chip length manipulation, which provides ample justification to the close relationship between chip length setting and particle size distribution. This study shows that target chip length adjustments on the harvester do achieve the targeted 30-mm to 5-mm size range. However, decreasing target length increases the incidence of fines (<3 mm), which is a common phenomenon observed in many other cases [20,21,23,26]. It is extremely difficult to produce small size chips while limiting fines, and if that is a stringent requirement, then post-production screening might be the only solution [16,27].

It is also important to notice that the machine on test did not produce any significant proportion of oversize particles (>45 mm) when working with its standard 16-knives configuration. That is a very favourable characteristic, which has already been reported for the specific machine on test [12], as well as for other modified forager models used in SRC harvesting [25]. Oversize particles and fines detract from chip quality, complicate handling and limit use potential [28,29], which explains the keen interest in minimizing their contribution to total product mass.

Finally, a few "caveats" should be issued about the characteristics and the limits of this study. First of all, it is important to remind readers that the productivity levels in this study refer to net chipping productivity and are calculated for actual harvesting (cut-and-chipping) time only, excluding all maneuvering time, accessory work time and delays. That was done in order to focus on the machine function that is directly affected by changes in target chip length, so as to maximize study resolution. However, harvesting time represents slightly more than 60% of total worksite time [30]. Under real operational conditions, the effect of maneuvering, accessory work time and delays will not only decrease machine productivity and fuel consumption below the levels presented in this study, but it may also blur the eventual differences between treatments.

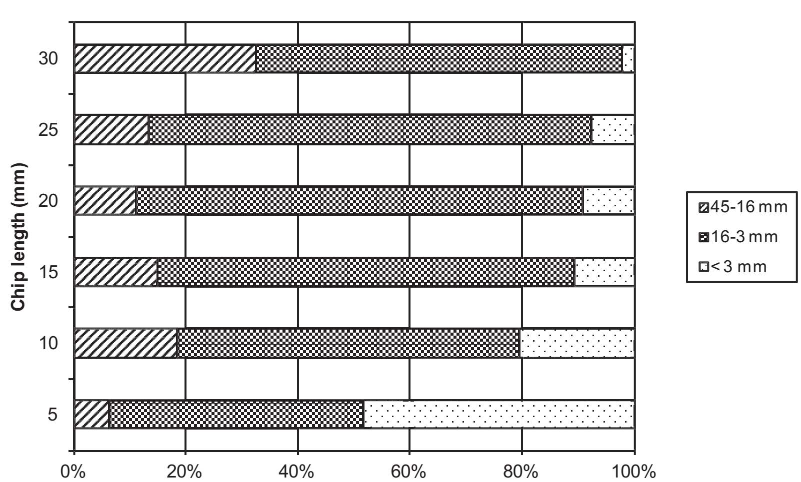

Fig. 3. Particle size distribution for the chip length settings between 5 and 30 mm.

Secondly, the study lacks particle size distribution figures for billets, and therefore it cannot gauge the extent to which target chip length adjustments above 30 mm are effective in steering particle size distribution towards a higher representation of longer particles. Therefore, while the study finds that adjustments in this length range have no significant effect on productivity and fuel consumption, it cannot prove that there is a significant effect on particle size distribution. However, bulk density results imply such an effect is present. Further experiments should be conducted when better screening equipment will be available to resolve the effect of chip length settings in the 45-mm to 90-mm range on actual particle size distribution.

Third, the experiment was split in two parts, due to the conflicting requirements of plantation owners. For this reason, the two target chip length ranges (5–30 mm and 45–90 mm) were tested in two different fields, located in different states. Although the main driver of particle size is certainly the mechanical setting of the machine and the field conditions were quite similar in terms of species, moisture content and stocking, the residual differences in plantation density and age made it preferable that the two experiments be kept separate, because merging the two datasets could have resulted in increased error. For this reason, consolidation was reserved to the bulk density data only, on the assumption that once the stems had been processed into chips their attributes were less likely to be affected by minor differences in stand characteristics.

5. Conclusions

Any time machine settings are changed from optimum values, performance is likely to degrade. For this reason, the goal of setting manipulation must be worth the inevitable performance losses. This study determines the effects on productivity and fuel consumption that derive from manipulating the target chip length settings of a modified forager used for harvesting Brazilian energy wood plantations. In particular, production of micro-chips (5-mm target length) incurs the highest productivity losses and fuel consumption increases, but yields very small particles, with a large proportion of fines (<3 mm). In contrast, production of billets (<45 mm) seems to have a weaker effect on machine productivity and fuel consumption, although performance degrade is still recorded. In both cases, the study provides reliable figures that can be used by managers for estimating the trade-offs of chip length manipulation, so that informed decisions can be taken.

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