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Mechanized harvesting of bamboo plantations for energy production: Preliminary tests with a cut-and-shred harvester

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ABSTRACT

Bamboo plantations can help expanding biomass production to marginal lands, while requiring limited chemical and labour inputs. However, the development of a modern industrial bamboo energy chain requires an adequate level of mechanization. The study presents the preliminary test of a new single-pass cut-and-shred harvester, designed for application to a powerful farm tractor. The machine is especially suited to negotiating disorganized crops, which offer challenging conditions for the more efficient forager-based harvesters. The results show that productivity may exceed 6 fresh t h^{-1}, which is close to the assumed theoretical limit for this machine type. Fuel use is over 3 l fresh t^{-1}, while harvesting cost varies around 33 € t^{-1}. Fuel use and harvesting cost are still relatively high, but they are likely to decrease as operators gain experience with the new system, and as the system itself is further improved. In any case, cost reduction is only one of the benefits accrued by mechanization, which also plays a major role in improving worker safety and overall supply chain efficiency.

Introduction

Bamboos are woody-stemmed perennial grasses that occur naturally in most tropical regions of the world. There are over 1200 species of bamboos, capable of occupying a large number of different habitats. Bamboos are frugal, adaptable and fast-growing, which makes them ideal for biomass production on marginal land (Liese, 1987). In fact, bamboos have remarkable technological qualities, and are already used for a range of different purposes, including construction, paper-making, food and medicinal preparation (Adhikari et al., 2015). Adaptability, effective reproduction strategy and human interest have resulted in a remarkable expansion of bamboo plantations, which currently cover more than 14 million ha, primarily located in Asia, Africa and South America (Maoy and Banik, 1996). The economic role of bamboos is especially important in South Asia, but it is increasing worldwide, to the point that the popular press is already talking about an alleged "bamboo boom" (Nijhuis, 2009). Whether or not the increased global interest for bamboo can be defined a boom, it is certain that the potential of bamboo is enormous. Already ten years ago, Brazilian scientists indicated bamboo as the second largest potential source of energy biomass in Brazil, right after sugar cane and way ahead of municipal solid waste, which was also a very large quarry of energy biomass (Filho and Badr, 2004). In fact, industrial bamboo plantations already cover 30,000 ha in Northeastern Brazil (Lobovikov et al., 2005), and they achieve high growth rates, due to the favourable soil and climate conditions, and to the availability of over 200 native species to select from (Shanmughavel and Francis, 1997; Viana et al., 2013). These plantations are exclusively grown for fibre production, but their surface and their role are likely to expand dramatically in the next decades (Li and Kobayashi, 2004). The increasing demand for renewable feedstock has raised interest in growing bamboo for the production of fuel chips (Guarnetti, 2014) pellets (Liu et al., 2016), liquid fuel (Dwivedi et al., 2009) and a variety of new bio-based products (Lee and Wang, 2006). At the same time, solutions must be found for reducing production cost, because industrial energy feedstock is a low-priced commodity, and competitive supply requires that all operations be conducted with the utmost efficiency (Spinelli et al., 2009). At present, bamboo harvesting is performed manually with bush knives (El Bassam, 2013; Obiri and Oteng-Amoako, 2007). That also accounts for Brazil, where mechanization is well established in most production systems (Bonilla et al., 2010). Bamboo harvesting techniques resemble the traditional manual methods used for harvesting sugar cane. However, sugar cane harvesting is becoming increasingly mechanized, through the introduction of single-pass cut-and-chop harvesters. Transfer of mechanized sugar cane technology to bamboo stands is made difficult by the very different characteristics of the two crops: bamboo stems are much larger than sugar cane stems and cannot be handled with conventional sugar cane technology, even if the harvesting technique could be the same

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cut-and-chop single-pass type. One possibility is offered by the modified foragers used for harvesting short-rotation coppice (SRC), but such machines perform best when the crop is laid down in regular rows, which is not the case with bamboo plantations (Spinelli et al., 2011). Furthermore, foragers are expensive specialised machines and farmers may prefer versatile equipment, based on the ubiquitous farm tractor. A few manufacturers do offer farm tractor attachments designed for the single-pass cut-and-shred harvesting of small trees and brushwood, and these machines may fit the bill. Among available models, those produced by Prinoth (Prinoth, 2016) have attracted considerable attention in Europe and North America, where they have been the object of several tests (Hannum, 2009; Lazdiņs, 2011). However, no one has yet considered using these machines for harvesting bamboo plantations, which seem to offer ideal conditions for the new equipment.

Therefore, the goal of this study was to determine the performance of a tractor-based single-pass cut-and-shred harvester applied to industrial bamboo plantations. In particular, the study aimed at determining productivity, fuel consumption and harvesting cost, in order to assess the technical possibility and the financial benefit of replacing manual harvesting with mechanized harvesting.

Materials and methods

The test was conducted with a 276 kW Valtra S353 four-wheel drive tractor, equipped with the new AHWI H600 Bioharvester attachment, designed and built in Europe. The latter consisted of a powerful hammer shredder, coupled with a blower and designed to cut shrubs and small trees, comminute them and discharge the comminuted particles into containers through a curved spout. The AHWI H 600 was a very versatile machine, capable of handling a wide range of work conditions. For this reason, it could be deployed on other potential energy biomass sources beside bamboo plantations, including short-rotation coppice, native shrubs and logging residues. During the test, the tractor was supported by a dump truck with a capacity of 15 m^3, which drove along the harvester and received the comminuted bamboo particles (Fig. 1).

The harvester was tested on a second rotation bamboo plantation regenerated from rootstocks after a fire. The plantation was located near Tatuì, in São Paulo State, at an altitude of 610 m asl. The plantation had been established with punting pole bamboo (*Bambusa tuldoides* Munro) on a typical Nitisoil (Table 1). Mean annual precipitation and temperature were 1260 mm and 20.2 °C, respectively. At the time of harvesting the bamboo stems were 3.5 years old.

Plantation characteristics were sampled by conducting a typical forest survey on three 25 m^2 plots, randomly located within the plantation. In each plot, researchers determined the diameter at breast height (DBH) and the height of all stems, which numbered at least 120 units. Furthermore, ten stems were selected within each plot and 5 discs were cut from each stem at the following positions along the stem: 0%, 25%, 50%, 75% and 100% of total plant height. The dry density of discs was determined in the laboratory as the ratio between dry mass and saturated volume, in order to estimate dry matter yield.

Fig 1. The tractor-powered swathe harvester and the dump truck at work.

Table 1
Characteristics of the test plantation.

		Mean	SD
Age	years	3.5	–
DBH	cm	2.3	0.9
Height	m	7.1	2.1
Stem density	stems ha^{-1}	48,266	4636
Dry density	kg m^{-3}	320.5	52.9
Moisture content	%	47.8	2.5

Note: DBH = diameter at breast height, SD = standard deviation.

Harvesting performance was determined through detailed time-and-motion studies conducted at the cycle level (Magagnotti et al., 2013). The filling of a full load of chips was assumed as a cycle, which began with the forward motion of the harvester discharging chips into an empty dump truck, and ended when the truck bin was full to capacity. For each cycle, researchers determined the following parameters: surface area, biomass output, time input and fuel input.

The surface area covered with each cycle was determined by multiplying swathe width by total travel length, the latter recorded automatically on the tractor on-board computer. Resulting figures were double-checked with those obtained from a Garmin CSX GPS device.

Biomass output was estimated by taking all loads to a certified weighbridge. Moisture content of comminuted bamboo biomass was determined with the gravimetric method, according to ASABE S358.2 Standard (2010), on five 500 g samples randomly collected from each truckload.

Fuel inputs were taken from the on-board computer, whereas time inputs were recorded manually, with a conventional stopwatch. Productive work time was separated from delay time, but all delays were included in the study, and not just the delays below a set duration threshold, because such practice may misrepresent the incidence of downtime (Spinelli and Visser, 2009). However, delays caused by the study itself were removed from the data set. The distance between the field and the landing (i.e. truck dump site) was 1.2 km, and therefore the truck had to travel 2.4 km every time it was full and had to dump its load.

Machine cost was estimated with the method developed by the European COST Action FP0902 (Ackerman et al., 2014). Cost input data were obtained from the Brazilian Prinoth dealer and from the forest company providing the tractor and its driver (Table 2).

Results and discussion

Unfortunately, the machine was available for a short time only, and it was tested on a relatively small field, measuring 0.24 ha. Therefore, valid data were recorded over a time of about 2.5 h. This figure excluded tune-up and a few test runs conducted with the purpose of getting the operator acquainted with the new job. For this reason, the results obtained from this study are preliminary, and must be considered as merely indicative. Nevertheless, this is the only test of mechanized bamboo harvesting available so far, and any indications are quite valuable.

Plantation yield

Bamboo stools re-sprouted vigorously after the fire: three and half years later, the average number of stems per stool was 29, which offered abundant evidence to the capacity of bamboo stools to regenerate after cut, and supported the idea of coppice management (Darabant et al., 2016). The density of live stools reached 1660 units ha^{-1}. Field yield averaged 48 fresh t ha^{-1}, or 25.1 dry t ha^{-1} (Table 3). That corresponded

Table 2
Cost calculations: assumptions, cost items and total cost.

Machine	make	Tractor	Attachment
Machine	model	Valtra S353	AHWI H600
Investment	€	160,000	250,000
Resale	€	32,000	50,000
Service life	y	8	5
Utilization	h y^{-1}	1500	1500
Interest rate	%	12	12
Depreciation	€ y^{-1}	16,000	40,000
Interests	€ y^{-1}	14,560	23,800
Insurance	€ y^{-1}	0	2500
Diesel	€ y^{-1}	34,650	0
Lube	€ y^{-1}	5198	0
Repairs	€ y^{-1}	16,000	20,000
Total	€ h^{-1}	58	58
Crew	n	1	0
Labour	€ h^{-1}	4	0
Overheads	€ h^{-1}	12	12
Total cost	€ h^{-1}	74	69

Note: y = year; overheads = 20% of total ownership and operating cost.
Fuel price 07 = € l^{-1}.

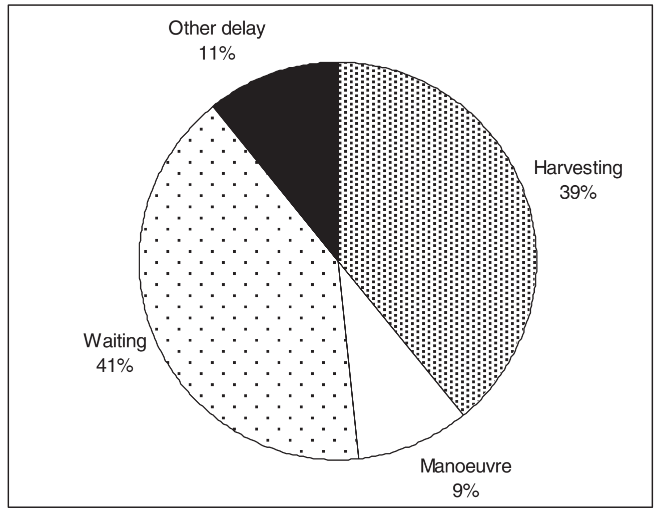

Fig 2. Breakdown of worksite time for the tractor-powered swathe harvester.

to an annual increment of 7.2 dry t ha^{-1}, which is half as much as obtained from high-density eucalyptus plantations established for biomass production (Guerra et al., 2016). However, bamboo is much more frugal than eucalypt and it adapts to sites with lower fertility, while requiring no fertilizer inputs. That represents a marked advantage when expanding biomass crops over marginal land, or when trying to maximize emission efficiency (Cheng et al., 2015; Demirbas, 2009).

Harvesting productivity

Harvesting productivity was 4.6 fresh tonnes per scheduled hour, including all delays. This figure is heavily weighed by the preliminary character of the study and by the use of a single support truck. Lacking a second support vehicle, the harvester was forced to wait idle as the full truck drove to the landing to unload (Fig. 2). A commercial operation would always be based on a fleet of two or more support units, so as to minimize waiting time (Spinelli et al., 2009). The use of a second truck would have reduced waiting time to 20% of the total (Spinelli et al., 2014), increasing productivity to 6.3 fresh t h^{-1}. That is much nearer to the estimated machine potential under the conditions of the test (i.e. 2.9 t/0.25 h = 11.7 t h^{-1}). Once operators gain experience with the new harvesting system, it is quite likely that actual field productivity will get increasingly near to machine potential, and that the 6.3 t h^{-1} figure estimated in this study will be exceeded.

Table 3
Machine performance: time and fuel consumption, productivity, cost.

		Mean	SD
Harvesting time	h $cycle^{-1}$	0.25	0.05
Manoeuvre time	h $cycle^{-1}$	0.06	0.04
Waiting time	h $cycle^{-1}$	0.26	0.02
Other delay time	h $cycle^{-1}$	0.07	0.01
Total work time	h $cycle^{-1}$	0.64	0.05
Surface	ha $cycle^{-1}$	0.06	0.01
Biomass	kg $cycle^{-1}$	2915	80
Bulk density	kg m^{-3}	193.6	6.2
Diesel	l $cycle^{-1}$	9.8	1.5
Yield	t ha^{-1}	48.3	10.3
Fuel use	l t^{-1}	3.4	0.6
Productivity	t h^{-1}	4.60	0.47
Cost	€ t^{-1}	38.7	4.3
If deploying a 2nd truck and halving waiting time			
Productivity	t h^{-1}	6.32	0.66
Cost	€ t^{-1}	33.7	3.7

Note: SD = standard deviation; cycle = the filling of one 15 m^3 load.
kg and t are fresh, including water mass fraction; Bulk density refers to the comminuted biomass loaded on the dump truck; cost includes the support fleet of 1 or 2 dump trucks with a 15 m^3 bin.

However, it is unlikely that experience alone will be able to push productivity much above these figures. Other studies of the same machine indicate productivity figures between 3 and 7 fresh t h^{-1}, respectively with short rotation willow (Lazdiņs, 2011) and forest undergrowth (Hannum, 2009). It is true that these studies concerned different crops than bamboo, but the study of another similar swathe harvester again indicated 7 fresh t h^{-1} as the reference productivity figure (Felker et al., 1999). All seems to suggest that 7 fresh t h^{-1} is a good ballpark figure for the productivity limits of a generic swathe harvester, based on the shredder principle and powered by a tractor in the 250 kW class.

This figure is about 25 times higher than for manual harvesting, which we calculated at 0.27 fresh t ha^{-1} using the only available time study about harvesting productivity in bamboo plantations (De La Cruz, 1989). On the other hand, the estimated productivity of the cut-and-shred harvester is much lower than achieved with forager-based harvesters, which work above the 20 t h^{-1} rate (Spinelli et al., 2011). These machines are generally more powerful (400 kW class) and they adopt a more efficient work principle, where stems are first cut and then fed to a chopper drum. However, their work principle is specifically designed for negotiating row plantations, and they may not perform as well when applied to disorganized crops. Under such conditions shredder-type swathe harvesters become a necessity, despite their lower productivity. Lower productivity depends on the somewhat crude working principle and on the smaller engine power, compared with modified foragers. It is reasonable to expect that the performance gap between the two machine types might be reduced if the new cut-and-shred harvesters were equipped with larger power units. Furthermore, readers should consider that current forager-based biomass harvesters benefit from a long evolution, which started in the late 1980s (Cordis, 2016). In contrast, cut-and-shred harvesters are a more recent development and appeared at the end of the 1990s, i.e. more than 10 years later. Therefore, it is likely that cut-and-shred technology still has a large margin for improvement, and that new models might be significantly more efficient than current ones.

Fuel consumption

Fuel consumption exceeded 3 l fresh t^{-1}, and was approximately 30% higher than recorded for the more efficient modified foragers (Guerra et al., 2016). It was also twice as high as recorded for modern industrial chippers (Magagnotti et al., 2016). However, one must recall that both foragers and chippers are used on different crops than bamboo. Compared with a conventional wood chipper the machine used for this test also performed cutting and collection, not just comminution. Finally, the comminution principle adopted on the machine on test was shredding, not chipping proper. Shredding is mechanically less efficient than chipping, which may partly explain the higher fuel consumption and the lower productivity of the machine on test (Spinelli et al., 2012). Once again, the disorganized character of bamboo plantations limits the use of more efficient machines, where the crop is first cut with circular saws and then fed to a proper chipper. Such machines work best with crops planted in regular rows, and they are challenged by disorganized crops.

Harvesting cost

Relatively low productivity and fuel efficiency impacted harvesting cost, which was in the range of 33 € fresh t^{-1}, after optimization. That was about 40% higher than estimated for manual harvesting, based on the figures reported by De La Cruz (1989). However, the figures available for manual harvesting did not include comminution, loading and extraction to the landing, which were part of the mechanized harvesting routine. If one included manual extraction on a 200 m distance, then the estimated cost of manual harvesting would be the same as for mechanized harvesting, and the biomass would still need to be comminuted and loaded. Of course, readers must be aware that we did not conduct a proper comparative experiment, but extrapolated data from two separate studies, conducted in different times and at different places. While not conclusive, this preliminary exercise hints at the better financial performance of the new cut-and-shred unit, compared with that of traditional manual harvesting techniques.

On the other hand, harvesting SRC plantations with modified foragers includes comminution and loading, and still incurs a cost that is 25% lower than found for the cut-and-shred unit on test (Spinelli et al., 2011). While it is risky to compare two different crops and technologies, this exercise indicates that harvesting cost should be further reduced before mechanized bamboo harvesting can become generally competitive.

This study singles out capital investment as the largest cost component, representing 45% of the total, partly as a result of high import taxes (Fig. 3). High capital cost is a main obstacle to the introduction of modern technology to developing countries (Dubey, 2008), but that may be solved by licencing local production. All efforts should be made to make mechanized harvesting more competitive, due to the high accident risk and operator discomfort associated with manual harvesting techniques (Rossi-Rocha et al., 2010, Darabant et al., 2016).

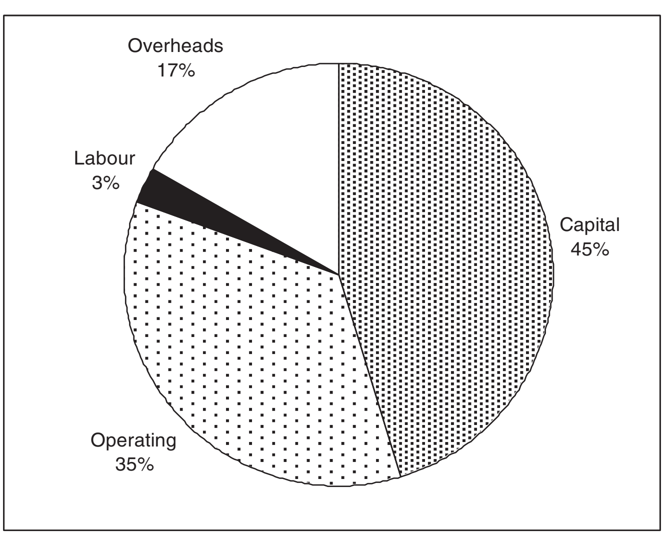

Fig 3. Breakdown of harvester cost (€ h^{-1}) by cost components.

Of course, this preliminary study cannot address all challenges - in fact, it cannot even detect all challenges in the first place. However, it may provide a general estimate for the potential of mechanized bamboo harvesting, and address future efforts. With all its limitations, our study is the only one that offers science-based data for the mechanized harvesting of bamboo plantations, while attempting a first comparison between manual and mechanical harvesting techniques.

Conclusions

Industrial bamboo plantations can be effectively harvested with single-pass cut-and-shred equipment, applied to powerful farm tractors. Productivity is capped by a relatively crude machine design, but the peculiar characteristics of bamboo plantations prevent use of more efficient devices. In any case, the preliminary trials described in this study yielded very promising results, and the new mechanized system could become competitive, if minor organizational improvements are introduced. Of course, this is just a preliminary study, which is limited by its short duration. However, no other studies are available for the mechanized harvesting of bamboo plantations. In fact, very few studies are available for manual harvesting, as well. Therefore, the general figures provided in this paper represent a valuable science-based reference for managers and planners. The study indicates that the new technology can handle bamboo plantations, offering a viable alternative to manual harvesting. Even where manual harvesting techniques are still competitive due to cheap labour, there is a general objective to introduce mechanization in order to improve worker safety (Bell, 2002) and streamline production, in anticipation of future labour shortages (Spinelli et al., 2001). Therefore, mechanization should be promoted for its social and logistical benefits, and not just for its potential to decrease production cost. Future research should assist with the further improvement of mechanized harvesting technology, in order to remove the remaining obstacles to its successful introduction.

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