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Economic Evaluation and Performance of a Tree Planting Machine Performing in Two Different Slope Classes and Conditions of Harvesting Slash

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Abstract

In recent years, fully mechanized planters have gained attention in Brazil on flat to steep terrain. A field study was conducted to analyze the potential of a planting machine composed of a hydraulic crawler excavator and a planter unit to perform soil preparation and planting in two slope classes and two conditions of slash presence. The experimental area was divided according to slope – undulating (8% to 20%) and strong undulating (20% to 45%) – and the presence of slash. Slope class did not significantly affect productivity, nor was there a significant interaction effect between the slope and slash factors. The presence of slash proved to be statistically different, with mean productivity of 236 seedlings hour-1 when reloading the carousel in an area without harvesting slash. Tree planting machine utilization was 75.13%, and the mechanical availability was 79.6%. The presence of slash significantly reduced the tree planting machine productivity, including the seedling reloading time, suggesting a newer research line for fasters reloading seedling systems.

Keywords: forestry operations, silviculture, mechanization

1. Introduction

In Scandinavia, mechanization in forest regeneration began in 1965, lagging behind the adoption of mechanization in harvesting operations (Bäckström 1978). The early 1980s were the height of research aimed at developing planting machines in North America and Nordic countries. At least 16 planting machines were developed during this period, either as prototypes or machines commercially available in Canada (Ersson 2010). At the end of the 1980s, a new planting machine was developed, which was successful in soil preparation and planting operations using the Öje-planter attached to the boom of a hydraulic excavator (von Hofsten 1993, Hallonborg et al. 1997). This equipment version continued to be developed and is currently known as the Bracke Planter (Hallonborg et al. 1997, Drake-Brockman 1998). These authors characterized the tree planting machine as being robust and adapted to various terrain conditions, able to plant several tree species, and having a carousel with over 85 seedlings. In Brazil, the lack of labour for manual silviculture operations is becoming critical, so developing mechanized solutions has occurred during the last decade.

When considering new planting equipment, its operational quality and performance must be similar to current systems (Harstela 2004) across the range of soil types, slopes, and slash conditions on planting sites. All of these factors can influence operational performance positively or negatively. As such, the harvesting system employed influences the amount and placement of slash following a timber harvest. The full tree harvesting system, in which each tree is felled and transported to a landing where additional processing occurs, retains the slash unless it is hauled back onto the harvest site. Under the cut-to-length harvesting system, trees were felled, delimbed, and cut to specific lengths at the stump, spreading the slash across the harvest site (Pulkki 2013, Machado et al. 2014). Thus, how the two harvest systems retain slash on a harvest site can impact subsequent operations on the site, such as planting (Saarinen 2006).

Several studies have analyzed the operating costs of mechanized equipment, splitting them into labour, investment, and operational costs (Ackerman et al. 2014). While there are many models and methodologies to determine operational costs, most were adapted from agricultural scenarios. European researchers developed the COST model (European Cooperation in Science and Technology) described by Ackerman et al. (2014) to standardize the results for analyzing operational costs. This model is a transparent and straightforward tool for calculating the costs of forest machines. In addition to these features, Action FP0902 allows international use of the COST model based on Microsoft Excel software (Ackerman et al. 2014).

The objective of this study was to evaluate the performance of a tree planting machine across a range of site and post-harvest conditions in Brazil. The tree planting machine was composed of a hydraulic crawler excavator (200 D LC model) and Bracke Planter P11.a, which performed soil preparation and planting in two slope classes and undern two different slash conditions.

2. Material and Methods

The experiment was conducted in southern Brazil in an area of 13.9 hectares with an average rainfall of 1814 mm a year and an average annual temperature of 17.8°C (Klabin 2016). The soil was classified as having a very clay texture and a high stoniness level with an undulating slope (5° up to 11° slope) and undulating hilly (11° up to 24° slope), according to EMBRAPA (2013). Before reforestation, the loblolly pine (*Pinus taeda L.*) forest was harvested using the full tree system, where all of the unmerchantable material (e.g., branches, broken logs, pine cones) was accumulated in a pile within a landing adjacent to the harvest site. After the harvesting, loblolly pine container seedlings grown in the company's nursery were planted 120 days after germination and rooting. Only seedlings with a well-developed, fibrous root system were selected to be planted because poorly formed root systems cause planting failures due to the loss of some substrate, which clogs the seedlings under the carousel. The hydraulic crawler excavator used and its specifications are presented in Table 1.

Table 1 Specifications for John Deere 200 D LC hydraulic excavator

The base machine was adapted for forestry operations; the equipment was installed at the tip of the excavator boom, and a 3500 litres water tank replaced the solid ballast. The water was needed for seedling irrigation during planting – one litre of water per planted seedling. Shelves were installed behind the water tank to carry the seedlings to the site, with a timed irrigation system to keep them moist during transportation. The equipment was a Bracke Planter P11.a with 72 cylinders – 60 mm in diameter each – in the seedling storage carousel.

The final version of the machine is shown in Fig. 1. The machine requires two workers: one inside to drive it and an assistant for checking and correcting any planting issues and failures and reloading seedlings into the carousel.

The original equipment version prepared the soil by mounding, using a blade to make a mound where the seedlings were planted (Guerra et al. 2019). However, for this study, a tool with three shanks was attached to the tree planting unit, with the side shanks 35 cm long and the middle 40 cm long (Figs. 2 and 3).

When some of the harvesting debris was still present at a planting spot for a seedling, the shanks cleaned the area, moving branches, small logs, and leaves

Fig. 1 Tree planter machine formed by a hydraulic excavator and mechanized planting equipment

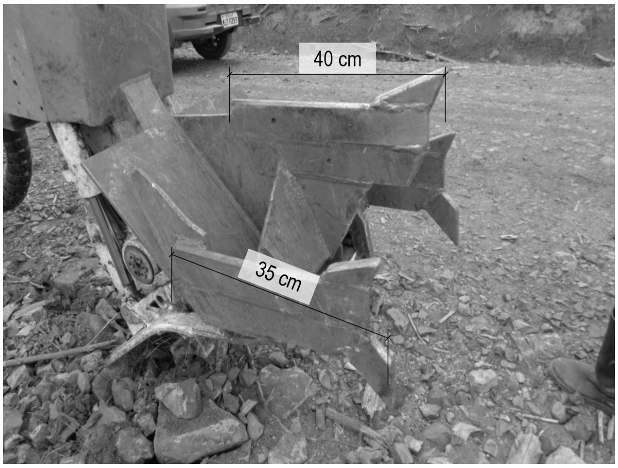

Fig. 2 Shanks adapted to the moving base of Bracke Planter P11.a

sideways to avoid planting on top of them. The combination of slope and presence or absence of slash treatments are shown in Table 2.

The tree planting machine was positioned above the stump row by utilizing the maximum boom length (9.45 m), and planting occurred sequentially in five rows, two rows on each side of the machine and one in the middle (Fig. 4). The targeting and spacing between seedlings were determined by remaining stumps, with the planting sites occurring between them based on the alignment of the stumps. Thus, the seedling spacing for this study was 2.5 m within rows by 3 m between rows.

Table 2 Classification of treatments according to slope class and presence or absence of harvesting slash

The data was collected using Barnes' time study methodology (Barnes 1977). It consists of using a stopwatch to collect every work element during a planting cycle and returning the stopwatch to zero after every step in the process. The planting cycle (Table 3) was divided into seven work elements beginning with the machine moving to reach a new planting position and ending when the soil was prepared by subsoiling using the riper ends (Table 3).

Machine use was defined as the percentage of time used for productive activities; in other words, the time used to conduct the planting activities and refill the carousel with seedlings. The mechanical availability corresponded to when the tree planting machine was

Fig. 3 Three soil preparation shanks in Bracke Planter P11.a

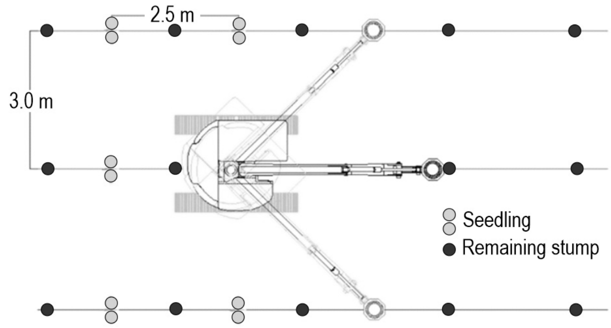

Fig. 4 Diagram of planting direction and spacing, where dots represent stumps retained and leaves are newly planted seedlings

in a condition to work, excluding the maintenance and repair times (Oliveira et al. 2009).

Each work shift was divided into the four work elements described below:

⇒ Refilling: time used for refilling consumables, such as diesel and water

⇒ Moving: the time required to move the machine from the field boundary to the planting area and vice-versa at the beginning and end of a workday, respectively

⇒ Mechanical stops: time lost due to maintenance and repairs, including travel time for the mechanic to get to the machine

⇒ Productive work: operational time spent planting and reloading the carousel with seedlings after completing one planting cycle.

Table 3 Work elements of a tree planting machine

Work element	Description
Driving	Move the base machine to reach the new planting positions
Between rows	Switch the excavator boom between the planting rows
Between seedlings	Move the planting unit from a planted seedling to the next planting spot
Failure	Return the planting unit to the previous spot to replant because no seedling was planted
Cleaning	Move the harvesting slash away from the planting spot
Planting	From the moment the planting unit is placed over the planting spot until the moment that the irrigation ends
Soil preparation	Subsoiling with the shank
Seedling reloading	Reload the carousel with new seedings

The choice of the techniques used for the productivity analyses is due to the non-randomization data. The model variance analysis technique was applied using two factors – slope and the presence of harvesting slash – complemented by the Tukey multiple comparison tests with a 5% significance level (Zar 1999). Planting performance was evaluated with and without the seedling reloading time to evaluate the effect of that action on planter performance. The productivity without seedling reloading (Eq. 1) consisted of the time spent carrying out the planting cycle. Planting cycles were considered to better evaluate the system during each shift to obtain a more realistic average estimate of productivity measured as seedlings planted per hour.

$$Yield_{\text{without}} = n° \ seedlings/T_{\text{p}} \quad (1)$$

Where:

$Yield_{\text{without}}$ yield without seedlings reloading into the carousel, seedlings hour^{-1}

$n°$ *seedlings* 72 seedlings per carousel

T_{p} planting time for one cycle, hour.

The yield with seedling reloading (Eq. 2) considered the time spent with the worker placing the new seedlings into the carousel and planting them.

$$Yield_{\text{with}} = n° \ seedlings/(T_{\text{p}} + T_{\text{r}}) \quad (2)$$

Where:

$Yield_{\text{with}}$ yield with seedling reloading into the carousel, seedlings hour^{-1}

$n°$ *seedlings* 72 seedlings per carousel

T_{p} planting time for one cycle, hour

T_{r} seedling reloading time, hour.

Costs were calculated using the model developed by COST Action FP 0902 (Ackerman et al. 2014). The results were expressed in € hour^{-1}, € hectare^{-1}, and € seedling^{-1}. Labour cost, including overheads, was 105% of the wage, including social charges (labour taxes, insurance, personal protective equipment, training, telephone, and transport costs). The forestry company provided the cost of seedlings (Table 4). The cost of salaries, equipment, consumables, fuel, and equipment tracks was first collected in Brazilian Reais (R$) and converted to Euros (€), using the average 2018 currency conversion rate of R$ 4.30 = € 1.00, according to the official website of the Central Bank of Brazil (www.bcb.com.br).

Table 4 Mechanized planting cost input data

Description	Units	Base machine	Planter unit
Estimated purchase price	€	144,186	36,233
Expected economic life	hours, h	13,500	7500
Productive machine hour	hour year^{-1}	1703	1703
Salvage value	percentage, %	10	10
Interest rate	percentage, %	14.5	14.5
Tax	percentage, %	1.0	1.0
Housing	percentage, %	0.75	0.75
Insurance	percentage, %	0.25	0.25
Fuel consumption	litre hour^{-1}	17.1	n.a
Fuel price	€ litre^{-1}	0.72	n.a
Additional tracks	n	4	n.a
Cost per track	€	2364	n.a
Driver's wage	€ hour^{-1}	3.84	
Assistant's wage	€ hour^{-1}	2.71	
Labour cost	percentage, %	105	

Table 5 Productivity according to the need to reload the carousel with seedlings, slope, and presence of harvesting slash

Slope*	Seedling reloading	Productivity**		
		Without slash seedlings hour^{-1}	With slash seedlings hour^{-1}	Mean seedlings hour^{-1}
Undulating	Without	295 ± 65.1a	268 ± 29.6a	282 ± 51.3
	With	236 ± 45.5A	216 ± 24.2A	226 ± 37.1
Undulating hilly	Without	293 ± 37.9a	247 ± 31.7a	270 ± 41.5
	With	237 ± 27.1A	200 ± 26.4A	219 ± 32.3
Mean	Without	294 ± 52.2a	258 ± 31.9b	276 ± 46.6
	With	236 ± 36.8A	208 ± 26.1B	222 ± 34.7

* Undulating (5° up to 11° slope – 8% up to 20%) and undulating hilly (11° up to 24° slope – 20% up to 45%)

**Like superscripts within a row denote no significant difference between slash treatments at $\alpha = 0.05$

3. Results

3.1 Time and Motion

The planting cycle was divided according to the time spent to perform each work element (Fig. 5), performed in areas with harvesting slash, requiring cleaning (using shanks), and in areas without harvesting slash. The machine utilization during the trial was 75.1%, and the mechanical availability was 79.6%. The primary factors which impacted machine availability were shank, planter equipment failure, and seedling jammed into the carrousel.

3.2 Planter Productivity

Tree planting machine productivity considering seedling reloading, slope, and the presence or absence of harvesting slash are shown in Table 5. The main effect of the slope was not statistically significant (*p*=0.425). There was not a significant interaction between slope and slash presence. Regardless of the slope, tree planting machine productivity was significantly higher when slash was absent (Table 5).

The interaction effect of slope *x* presence of harvesting slash (*p*=0.398) and the main effect of slope (*p*=0.332) was not statistically significant. However, there was a significant difference between areas with and without harvesting slash (*p*=0.003). Seedlings reloading productivity was not significantly affected by slope and the presence of harvesting slash (*p*=0.317). However, a significant difference was observed for the harvesting slash factor (*p*=0.002).

3.3 Operational Costs for Mechanized Planting

Operational costs for the mechanized tree planting machine were calculated. The total cost was calculated

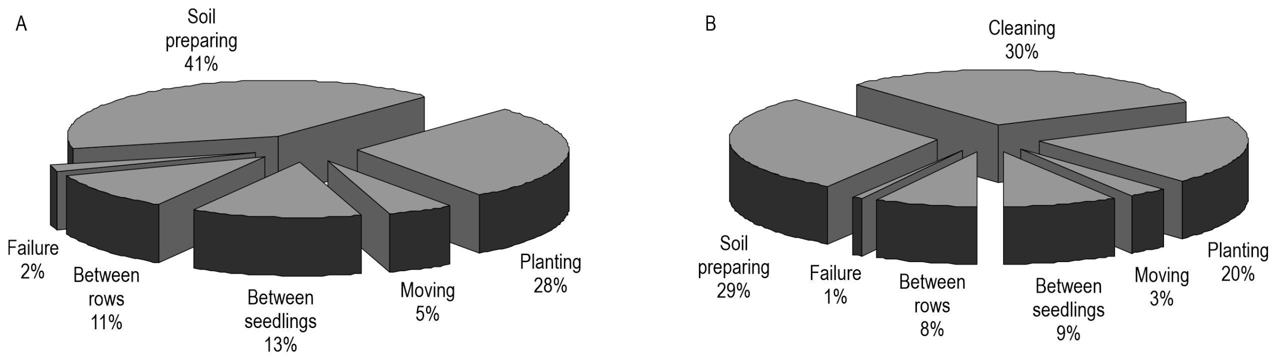

Fig. 5 Distribution of time spent during soil preparation and planting cycle for a seedling in areas without (A) and with (B) harvesting slash

Table 6 Cost output data for mechanized planting unit

Factor	€ pmh^{-1}	€ ha^{-1}	€ seedling^{-1}	%
Fixed costs				
Depreciation	13.96	83.76	0.06	17
Interest	9.46	56.76	0.04	12
TGI	1.05	6.30	0.00	1
Total fixed cost	24.47	146.82	0.10	31
Variable costs				
Fuel	13.00	78.00	0.06	16
Oil and lubricants	1.95	11.70	0.01	2
Maintenance and repairs	15.51	93.06	0.07	19
Additional tracks	1.58	9.48	0.01	2
Total variable cost	32.04	192.24	0.15	40
Operator and auxiliary costs				
Wages	6.55	39.30	0.03	8
Social charges*	6.88	41.28	0.03	10
Total operator and auxiliary costs	13.43	80.58	0.06	18
Seedlings	8.78	53.32	0.04	11
TOTAL COST	78.72	472.96	0.35	100

* Labour taxes, insurance, personal protective equipment, training, telephone, and transport costs

considering the average productivity when reloading the seedlings into the carousel at 222 seedlings per hour^{-1} (Table 5), the machine utilization rate (75.13%), and the mechanical availability rate (79.6%). The fixed, variable, and total costs are shown in Table 6.

4. Discussion

Soil preparation is an essential forest operation to improve productivity, regardless of whether or not slash is present. In the time and motion analysis, the share for soil preparation is 41% and 28% for planting, totalling 69% in areas without harvesting slash; and 30% for cleaning, 29% for soil preparation, and 20% for planting, totalling 79% of the planting cycle in areas with harvesting slash. Where harvesting residues were present, the time to clean the planting spot was the highest component of the planting cycle at 30%.

Rantala et al. (2009) reported that during 47% of the cycle time, the Bracke Planter P11.a equipment performed soil preparation, mounding, and planting operations, while 6% of the time was spent on cleaning the planting spot. A model M-planter performing the planting was evaluated, and it was observed to perform soil preparation and planting for 39% of the time during the operation (Liepins et al. 2011). Another study with the M-planter to evaluate nine experienced and four inexperienced drivers during two operation seasons in Finland showed an average machine utilization of 80.1% and mechanical availability of 89% (Rantala and Laine 2010). Rantala and Laine (2010) compared drivers who already had experience against those who had never worked with excavator base machines before, reporting differences in performance between the groups of drivers. When the drivers had no experience, machine utilization was reduced to 66.4%, and mechanical availability to 78.6%.

A few studies have previously evaluated planting equipment working in conditions similar to those of the present study. Comparisons had to be made to studies conducted in other countries under different conditions and with other equipment models, for example, M-planter and Risutec, in some northern European countries.

In this study, the machine utilization was 75.1%, lower than the average of other studies, and the mechanical availability was 79.6%. The driver for this study had previously worked using a hydraulic excavator with deep soil preparation equipment, with similar movements for subsoiling, but planting was a new experience for him. This new planting task may have influenced mechanical availability because it takes time to know the machine deeply and perform maintenance as fast as possible. Besides that, the driver's skill can also influence performance (Rantala and Laine 2010, Laine and Rantala 2013).

A study conducted in Finland in newly harvested areas, where stumps and slash had been removed (to plant using the Bracke Planter P11.a equipment coupled to a 14-ton hydraulic excavator), yielded an average of 244 seedlings per effective working hour (Laine and Saarinen 2014). In all treatments of this experiment in South Brazil, the average yield with reloading was 236 seedlings hour^{-1} in areas without harvesting slash. Thus, similar site conditions resulted in comparable productivity levels between these two studies. Removing harvesting slash from areas to be planted decreases the operation's productivity with the Bracke Planter and M-planter (Laine and Rantala 2013), the same as in this study, achieving a reduction of 12% in the number of seedlings planted per productive hour. In another study conducted in Ireland, different yields were obtained for areas of afforestation and reforestation, with 250 to 300 seedlings hour^{-1} and 180 to 200 seedlings hour^{-1}, respectively (Nieuwenhuis and Egan 2013). The main difference between the two conditions lied in the crops present before the mechanized planting operation. In the area with higher productivity, planting occurred in a grass field without stumps or slashes.

Regardless of the slope, the average productivity in the area with harvesting slash was 208 seedlings hour^{-1}, a similar value being reported by Nieuwenhuis and Egan (2013) under these conditions: 200 seedlings hour^{-1}. Hallongren et al. (2014) reported a minimum level of 190 seedlings hour^{-1} for mechanized planting equipment to be competitive with standard mechanized soil preparation and manual planting operations under Scandinavian conditions.

An adaptation of an automatic system to recharge the seedlings into the carousel on the Bracke Planter P11.a equipment, called MagMat, was reported to result in an increase of up to 10% in productivity depending on the unit used (Ersson et al. 2014). Using this system would reduce the difference between the productivity with and without seedling reloading up to 24%, highlighting a possible improvement to be implemented in mechanized tree planting machines.

The slope factor within the analyzed classes, undulating and undulating hilly, did not significantly impact productivity. No relationship between slope and productivity has been reported in the bibliography available on mechanized planting with any equipment. However, other factors include the amount of driver experience and harvesting slash and stumps in the area to be planted (Laine et al. 2016).

Maintenance and repairs are the most significant contributor to the total variable cost (Table 6). Some alternatives are considered feasible to reduce this cost, such as the Total Productive Maintenance (TPM) inserted into the World Class Manufacturing (WCM) program that aims to structure organizational maintenance processes through leadership and good practices (Yamashina 2000). Using some premises from WCM, Brazilian researchers concluded that it could reduce harvesting machine maintenance costs by 9% (Dinizet et al. 2018). Due to the high social charges applied in Brazil, the influence of labour-related costs is 18% of the total cost, as confirmed by a study that evaluated a P11.a planter in Brazilian conditions (Guerra et al. 2019). On the other hand, the seedling production cost is low, 11% of the total, despite the number of seedlings per hectare, 1333 seedlings. In an analysis of soil-preparation operations carried out in 2010 by a Brazilian forestry company, 14% of the area required manual operation, resulting in an average cost of € 398.46 ha^{-1} (Bortolas and Rosa 2014).

Using hydraulic excavators with digging equipment or shank implements to carry out soil preparation in sloping areas is more expensive than without soil preparation tools (Souza 2014). However, ergonomics are improved when using hydraulic excavators compared to manual and semi-mechanized activities. Indeed, there are fewer accidents related to the exposure of workers to venomous animals (Cenibra 2016). Using heavy machinery, and combining other activities with planting, such as applying fertilizer or even spraying herbicides, may reduce the logistics and operational costs (Souza 2014, Cenibra 2016). Planting *Pinus taeda* seedlings in previously subsoiled areas had an estimated operational cost of approximately € 186.00 ha^{-1} (Pires 2014).

A mechanized tree planting machine in Brazil, consisting of a hydraulic excavator and P11.a equipment, that carried out planting, fertilizing, and seedling irrigation in previously subsoiled areas, incurred costs of € 630.57 ha^{-1} and € 457.81 ha^{-1} for 3x1 m and 3x1.5 m spacing, respectively (Guerra et al. 2019). The cost calculated in this study is € 472.96 ha^{-1}, and the 3x2.5 m spacing lies within the range obtained by studies in Brazil for the same conditions, which emphasizes that the soil-tillage activity was performed only in the present study. In a study conducted in Latvia, using planting equipment from a different manufacturer, and considering 200 seedlings h^{-1} and a planting density of 1600 seedlings ha^{-1}, the authors reported a cost of approximately € 350 ha^{-1} (Lazdina et al. 2019). However, the equipment did not perform the mounding and the total cost would practically double if it did. In addition, the purchase price of the base machine and the equipment are considerably lower in these countries (Lazdina et al. 2019). Experienced operators and their availability in the market are fundamental for high-cost competitiveness (Laine et al. 2016, Ersson et al. 2018). Nevertheless, the origin countries of the leading manufacturers of these types of equipment still face the same difficulties found in Brazil in achieving high-cost competitiveness, such as low-profit margins for service providers (contractors), which creates little interest in this market; accordingly, manual planting still presents a higher profit margin for most contractors. In Finland, some contractors have a maximum of two mechanized tree planting machines, and in Sweden, only one tree planting machine (Ersson et al. 2018).

Due to the recent arrival of this equipment in Brazil, the availability of experienced operators is still low (Guerra et al. 2019). The replacement of manual planting with machines, especially in sloping areas, may be a viable option, considering the ergonomic/human aspect of this operation and the complexity of the diverse landscapes. However, the current cost competitiveness creates a barrier to adopting this technology.

5. Conclusions

While the presence of residues negatively influenced the productivity of the mechanized tree planting machine, the slope did not have a significant impact on its performance. Additional research needs to be done to determine if this negative influence of slash on productivity and cost can be overcome through a new approach that would remove more of it during the harvesting operation.

The cost of adopting this multifunction equipment to carry out soil preparation, planting, and irrigation is still higher than the other options available in Brazil. However, adding functions to its operation, such as fertilizing and applying herbicides, maybe the most cost-effective way to enable the use of fully mechanized planting equipment. By combining functions, there would be a decrease in the number of machine entries into a site, reducing soil impacts and increasing sustainability. Mechanized planting also provides ergonomic and safety benefits to operators, as compared to manual methods.

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