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Posted Date: 6 November 2024

doi: 10.20944/preprints202411.0143.v1

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Enhancing Silvicultural Practices: A Productivity and Quality Comparison of Manual and Semi-Mechanized Planting Methods in Commercial Forestry in KwaZulu-Natal, South Africa

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Abstract: Planting plays a significant role in commercial forestry. Labour-related issues (scarcity, increased wages, absenteeism, ageing and high turnover), inconsistent work quality, increased operational costs, and poor ergonomics prompted the development of innovative planting techniques. This study aimed to assess the productivity (plants/PMH), worker productivity (plants/worker PMH), work quality and tree survival of a manual and a semi-mechanised planting method. Two study sites at Flatcrown and Kwambonambi, consisting of 37 plots, were planted at 1333 stems per ha, alternating across the study sites. Block-level and elemental-level time studies were conducted, followed by work quality assessments. The manual method planted 7.23 ha/shift (Flatcrown) and 5.89 ha/shift (Kwambonambi), whilst the semi-mechanised method planted 4.72 ha/shift (Flatcrown) and 3.19 ha/shift (Kwambonambi). The manual method was 50 to 60% more productive (plants/PMH) than the semi-mechanised method. In terms of plants/worker PMH, higher worker efficiency of 30 - 40% was observed at the Flatcrown site, which was characterised by level terrain and low residue presence compared to the Kwambonambi site, which had a gentle (< 20%) terrain and medium residue presence. Planting quality was conducted according to planting specifications. The two methods did not significantly differ, although the study suggests that the proportion of good-quality plantings could be somewhat higher for the manual method. There was no significant difference in tree survival across methods and sites after one month.

Keywords: regeneration; productivity; planting methods; planting quality

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1. Introduction

The global forest area managed for timber production is estimated to be 1.15 billion ha, producing about 4 billion m^3 of wood annually [1,2]. To meet the growing timber demands, harvested forests must be regenerated efficiently. However, regeneration activities are costly, time-consuming, and labour-intensive [3,4]. Regeneration practices are treatments carried out on a site post-harvesting to successfully establish and tend trees [5]. These practices affect tree survival, growth, and uniformity [6]; therefore, appropriate early-stage regeneration activities are required to achieve high yields at the rotation end [7,8].

Globally, the forestry industry has several labour-related issues such as an ageing workforce, high absenteeism, labour shortage, increasing labour costs, and high labour turnover [9–11]. Consequently, the industry has been forced to test and introduce efficient technological solutions to counter the challenges and reduce operational costs [12]. While soil preparation is predominantly mechanised globally; tree planting activities are still manually orientated. Furthermore, unlike soil preparation (e.g., earth auger) and stand tending (e.g., brush cutters), which offer motor manual

 doi:10.20944/preprints202411.0143.v1

technology options, the planting activity is limited to either manual, semi-mechanised or mechanised technology options [13].

Planting methods are affected by climate, physiography, stand size and country-specific terrain factors (ground conditions, ground roughness and slope), labour availability and management regimes, influencing planting costs and method efficiency [14,15]. Planting can be performed by using manual (e.g., with the aid of trowel/hoe and planting tubes), mechanised (e.g., excavator-based and wheeled machines) and semi-mechanised methods (e.g., tractor-drawn planting rigs). Of the planting methods, manual methods are the most commonly used in replanting approaches globally. Manual planting with a tool (e.g., hoe/trowel) requires the worker to bend when planting seedlings, which is strenuous and increases worker fatigue [16,17]. Planting tubes counter this as planters can work in an acceptable posture position.

There are different planting tube configurations available, but popularly known are the Finnish-produced Pottiputki and Swedish equivalent Sisuputki, where the planter carries a sturdy plant bag and, upon identifying a planting position, pushes the steel tube into the ground, pressing the pedal and dropping the plant onto the tube before firming it by the feet [18]. Unlike conventional planting tools, these prevent workers from bending but struggle to plant efficiently in slash-laden sites because the foot pedal is obstructed [19].

Mechanised tree planting machines have historically been developed and used in Scandinavian countries [20,21]. In recent times, more mechanised planting devices have been introduced and researched internationally (e.g., Komatsu Bracke excavator-based single and double head planters, Triple head planters, PlantMax and Risutec planting machines) [13]. These tree planting machines are tracked or wheeled and typically perform soil preparation, planting and irrigation [22,23]. Although the technology is still in its infancy, particularly in Africa, the most noticeable adoption of mechanised planting machines has taken place in Brazil (<10%) and Nordic countries (<5%) [13]. Compared to manual planting, mechanised planters achieve acceptable planting quality but still struggle to compete with manual operations in terms of costs [24,25].

Semi-mechanised methods are predominantly used in Southern Africa and South America. In these tree planting methods, the vehicle acts as a primary carrier of water and seedlings, relieving the planter of carrying these resources required for planting and easing the planting operation logistics [26]. Further technical advances have resulted in planting implements that can deposit water/hydrogel into the planting hole [27]. The high-pressure water planting rig (Wasserplanter), which uses high-pressure water for soil preparation and irrigation, and several other tractor towed/mounted planting vehicles (e.g., KISS planter), as well as the self-driven Fiori machine, exemplifies such innovations [28]. The latter requires soil preparation before planting, usually done by mechanised pitting machines.

Semi-mechanised planting methods enable planting and irrigation by single or multiple workers in a single sequence [29]. However, deployment of these planting methods is limited to relatively level terrain areas [13]. Adaptations have been made (e.g., extended pipes between carrier machine and planting tube) to extend their application to moderately steep areas. The work quality and productivity of those methods have not been widely documented.

There have been several reviews of existing planting technologies [30,31], but those reviews did not cover South African forests. [28] found that about 52% of the current commercially afforested area in South Africa is replanted using planting tubes and tractor-towed methods. Nonetheless, there is little information available in South Africa on using those methods. Therefore, this study aims to compare the planting productivity (plants/PMH), worker productivity (plants/worker PMH), work quality and plant survival of a manual and semi-mechanised planting methods currently employed in South Africa.

2. Materials and Methods

2.1. Study Site

Two trials were conducted in the Kwambonambi area of KwaZulu-Natal province in South Africa (28°36′17″S 32°05′11″E). This province experiences a subtropical climate with a mean annual temperature (MAT) and mean annual precipitation (MAP) of 22°C and 1155 mm, respectively [32,33]. Afforested areas are predominantly covered with deep sandy Fernwood soils with good ground conditions. The two experimental sites (Kwambonambi and Flatcrown) were previously planted with *Eucalyptus grandis x urophylla* and harvested using the mechanised (harvester and forwarder) cut-to-length method. Controlled burning of eucalypt residues was carried out in all the study areas before planting. The Kwambonambi site was characterised by medium residue with weed regrowth, while at Flatcrown, residue presence was low (Table 1). Planting positions were determined using previous rotation stump lines; after that, planting followed, which in the Kwambonambi area is mostly conducted between March and October.

Table 1. Study site information.

Site information	Kwambonambi	Flatcrown
Size (ha)	33.6	38.1
GPS Coordinates	-28.672676, 32.178478	-28.589121, 32.112583
Slope %	Gentle (11 to <20)	Level (<11)
Previous crop rotation age (years)	10.19	11.02
Burning date	24 May 2023	25 April 2023
Ground roughness	Uneven	Smooth
Planting date	04-05 July 2023	06-07 July 2023

Note: Slope class, ground conditions, and ground roughness were assessed using the forestry. National Terrain Classification Method [34]. Surface conditions were classified according to the silvicultural procedures manual [35].

2.2. Manual Method

A crew of 15 workers ran the manual method. Twelve workers, consisting of a planter and an irrigator, were paired up during the planting exercise with no soil preparation required (Table 2). The planter carried a bag of seedlings, and a planting tube was used to make a planting position and insert a seedling into it. Before the planter had firmed the soil around the seedling with his/her feet, the irrigator immediately followed up by applying hydrogel (about 2 l/seedling) on the planting position using a watering can (10 l capacity). The irrigator was also responsible for replenishing the hydrogel from a bowser towed by a four-wheel 98 kW agriculture tractor, moving slowly ahead of the planting front (Table 3). The bowser carried two tanks with a total capacity of 6000 l and a mixer, where superabsorbent hydrogel polymer and water would be mixed into hydrogel ready for dispensing. A single worker replenished seedlings from a seedling trailer parked at the compartment edge to the different planters. One supervisor managed the whole team.

Table 2. Planting process sequence and worker roles.

Planting method	Role	Activities				
		Walk	Soil preparation	Plant	Irrigate	Firm
Manual	Planter	✓	Use planting tool to open planting position	✓	-	✓
	Irrigator	✓	-	-	✓	-
Semi-mechanised	Planter	✓	Use high-pressure water to open planting position	✓	✓	✓

Table 3. Machine specifications and planting attachment adapted from [36].

Specifications	Manual method tractor	Semi mechanised method
Make and model	Landini DT135 Cab	Landini DT145 Cab
Engine power (kW)	98	104
Weight (kg)	5514	5519

Max. torque	590 Nm/1400 rpm	625 Nm/1400 rpm
PTO with ground speed	540/1000 rpm	540/1000 rpm
Fuel tank capacity (lt)	260	260
Drive system	4-wheel drive	4-wheel drive
Ground clearance (mm)	520	550
	Planter implements	
Make and model	-	ANCO GP3000, MP3000
Number of planting tubes	-	6
Attachment type	-	High-pressure planting unit

2.3. Semi-Mechanised Method

A crew of nine workers ran the semi-mechanised method. Six planters were working as a unit behind a steadily driven four-wheel 104 kW agriculture tractor towing the high-pressure planting unit (Table 2). The high-pressure planting unit consisted of a trailer carrying a pump and three tanks for a total of 9000 l of water capacity. The planting process used a high-pressure hydraulic driven pump supplying water to a discharge manifold through the connected six rear tubes (Table 3). A planter independently controlled each tube. Through a small diameter (51 mm) opening and about 40 - 50 bar pressure, water was pushed into the ground aimed at one position, thereby loosening the soil for planting [37]. This was followed by the planting tube inserted into the puddle cavity to deposit a seedling. The seedling was firmed using the displaced soil. Each operator carried a bag of seedlings, regularly replenished by an additional worker tasked with that job.

2.4. Seedling Quality Assessment

Eucalyptus grandis x urophylla (E. g x u) seedlings used in this trial were produced from cuttings in 128 plug-type trays. The plant quality assessment ensured that planted seedlings adhered to good quality specifications. Various factors such as site quality, the timing of planting, site preparation, planting quality, tending activities and biotic factors strongly influence plant survival and growth [38]. The plant quality assessment was executed using the grower company's plant quality standards (PQS). Each seedling was checked for the following quality specifications: height (25 – 40 cm); root plug consolidation and activity (fully consolidated with active white roots); leaf sets (>4 leaf sets); shoot tips (no cutback tips); stem form (no multiple leaders); pest and diseases presence (no presence of disease or pest damage) [39]. The seedlings that did not meet the prescribed specifications were rejected at the roadside, where the final sorting was conducted. All seedlings were planted at a density of 3 x 2.5 m (1333 stems ha-1).

2.5. Experimental Design

Manual and semi-mechanised planting methods were observed simultaneously on both compartments (Figure 1) divided into six-row wide strips (18 m) for the trial (Table 1). Strips were marked at the roadside with numbered pegs, which were used as a starting point for planting. Each strip represented one observation, and the experiment was organised as a blocked factorial design, with two treatments (e.g., manual and semi-mechanised) randomly distributed at each of the two blocks (e.g., Flatcrown and Kwambonambi) (Figure 2). Overall, the experiment contained 37 observations, distributed as follows: Flatcrown semi-mechanised = 13; Flatcrown manual = 9; Kwambonambi semi-mechanised = 7; Kwambonambi manual = 8.

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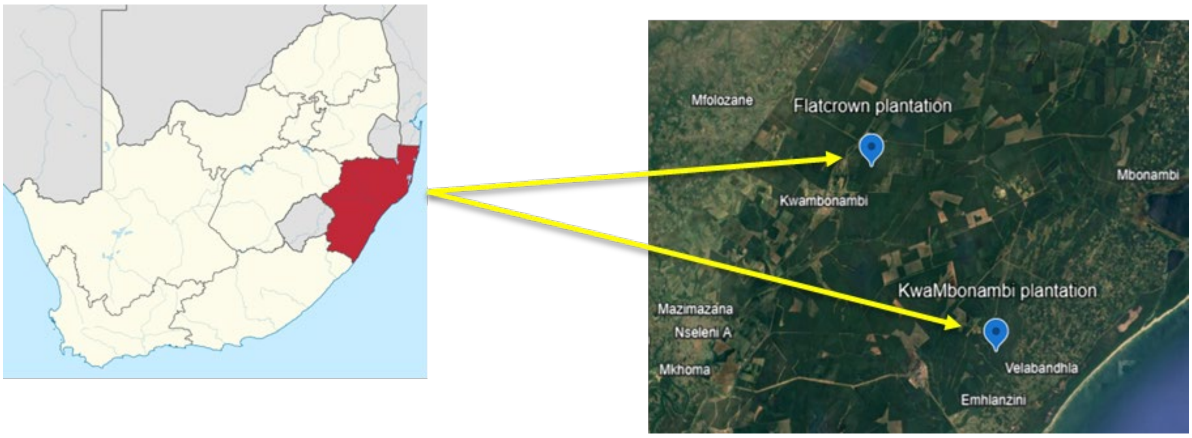

Figure 1. Research sites in KwaZulu-Natal.

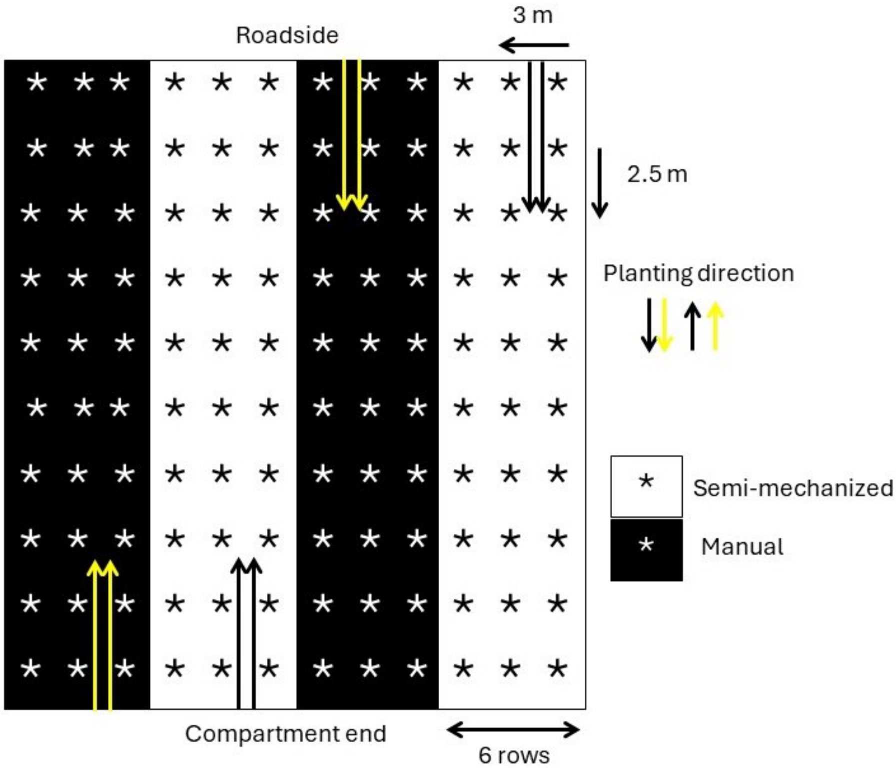

Figure 2. Study design plot layout for the two methods applied in both research sites. The 3 m represents the distance between rows and 2.5 m is the distance between planting positions. The arrows show the planting direction of each method which alternated across each site.

2.6. Data Collection

Three researchers followed the planting methods, conducting time studies, while another assessed the planting quality with the supervisor. The planting weather averaged 21.5°C for the duration of data collection. The nominal shift length was nine hours with a scheduled hour break. A total of 49.5 hours of time and motion data was collected from both methods while planting on both study sites (Table 1). Time data was collected according to classic time-and-motion study techniques described in [40]. Delay time was recorded separately from productive work time. The length of all strips was measured with a measuring wheel. While the equipment and methods used at the two sites were identical, the crews were different; therefore, two different crews were tested for each method at the two sites. Crews were selected by the site managers, who reputed them to be equally competent (six to seven planting seasons experience) and representative of the general pool of plant workers.

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2.7. Block Study Productivity Assessment

Block-level and elemental-level time study data were collected using a stopwatch for each planting method on both sites. The block time study measured the time it took for each method to complete planting a single strip separately for productive time and delay time [40]. The average strip length was 400 m at Kwambonambi and 430 m at Flatcrown. The block study determined the productivity measured as plants and ha per productive hour. Individual worker productivity was also determined to assess the effect of each site and method on worker efficiency by dividing the productivity of each method by the number of workers per method (plants/worker PMH).

2.8. Elemental Time Study Assessment

The elemental time study was carried out to determine the work sequence and the different levels of interdependence associated with different methods. The other reason for conducting an elemental time study was to determine the amount of time-lapse for each work element. The researchers used the Work-study (+7) application, and a Trimble Nomad handheld computer configured with UMT manager time study software to collect elemental time data. Work cycles were split into the following functional tasks, consistent with the two methods: walk, work, wait, replenish, and other delays (Table 4). Turning time was included as part of the walk element. Delays data were collected for both methods and classified into operational (for example, running out of seedlings, waiting for tractor/colleagues), mechanical (for example, tractor breakdowns) and personal (for example, answering a cell phone).

Table 4. Descriptions of elements used for the elemental study.

Method	Worker	Elements	Description
Manual	Planter	Walk	Starts when the planter begins walking towards the next planting position, ends when the planting tube tip touches the ground the ground
		Work	Starts when the planting tube touches the ground, ends when the planting tube is lifted
		Wait	Starts when the planter stops for the irrigator and/ seedling supplier while they approach, ends when the planter inserts the seedling into the planting tube
		Replenish	Starts when the planter stops to refill seedlings into the bag, ends when the planter inserts a seedling into the planting tube
	Irrigator	Walk	Starts when the irrigator begins moving towards the next planting position, ends when the irrigator reaches it
		Work	Starts when the irrigator lifts the watering jug to irrigate, ends when the irrigator moves towards the next planting position
		Wait	Starts when the irrigator stops to wait for the tractor to move closer, ends when the irrigator moves towards the hydrogel tap
		Replenish	Starts when the irrigator walks towards the tractor to refill hydrogel, ends when the irrigator reaches the planting position
Semi-mechanised	Planter	Walk	Starts when the planter starts walking towards the next planting station, ends when the planter reaches it
		Work	Starts when the planting tube touches the ground, ends when the planting tube is lifted by the planter

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Wait	Starts when the planter stops to wait for seedling replenishing and ends when the planter starts inserting the plant into the planting tube
Replenish	Starts when the planter stops after a signal to refill seedlings from the seedling replenisher, and ends when the planter inserts a seedling into the planting tube

2.9. Work Quality and Plant Survival Assessment

After planting, the researcher and team supervisor immediately assessed the work quality. The planting quality assessment application was used to assess the planting quality across all plots. For consistency, one researcher performed all the assessments. This assessment aimed to ensure uniformity in planting quality between the treatments. A zig-zag sequence was adopted where an assessor would start on the first planted line in a plot, assess 10 trees, then take a 90-degree turn to the next line and assess another 10 trees until the required number of trees was achieved, following the planting direction to attain a good representation of the planted seedlings across the plot. A sample of 105 planting positions was assessed on each of the 37 strips (approximately 10% of the total number of planting positions). The conditions encountered in each inspected position were recorded according to the codes in Table 5. The applicable criteria were adapted to meet the best operating practices for South African forests considering the planting position, depth (too deep or too shallow), defects (damaged) and soil compaction around the seedling as indicators for planting quality [30,41,42]. Water for irrigation was drawn from plantation reservoirs near the research sites. The irrigation status was checked to assess whether the planted seedlings had received water.

In the same plot areas where planting methods worked, pegs marked with spray paint to enhance visibility were used to mark 16 plots for plant survival assessments. Each plot consisted of two parallel plant row segments (15 trees x 2 rows), making a rectangular shape with 30 trees per plot. Tree survival was assessed after one month on 480 seedlings evenly distributed across 16 plots, where all trees were checked and assessed as either dead or alive.

Table 5. Planting quality assessment: codes and descriptions.

Code		Description
0	Good	Planting quality is good, seedling is straight, on right depth, and compaction around seedlings is according to given instruction
1	Deep	Planting quality is good but too deep (root collar is >10 cm below ground level). Seedling is expected to grow
2	Shallow	Seedling is planted too high. The root plug may dry out if exposed above ground level, seedling may not survive
3	Loose	Planting is good, but soil compaction is insufficient. Seedling is expected to survive but growth will be affected
4	Compact	Planting is good, but compaction is too much. Seedling is expected to survive but growth slowed due to damaged root method and dry root plug
5	Side	Seedling is planted straight, but not directly in the centre of the planting position but on one side of the planting station
6	Slanted	Seedling is planted but slanted instead of being straight
7	Broken	Seedling is planted, but the stem is broken
8	Fallen	Planting position is unplanted, but the seedling is visible and has fallen on or near the planting position
9	Missing	Planting position is unplanted, and seedling is not visible near planting position

2.10. Data Analysis

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Data were analysed to evaluate and compare the productivity and planting quality achieved by the different planting methods on both sites. First, the data was checked for outliers and other blatant errors. In particular, all data points that were two times the interquartile range below the lower quartile or above the upper quartile were considered suspected outliers and inspected: if the inspection could not find a reasonable explanation why the data point was so far off the cloud, then the datapoint would be removed (which did not occur). Then descriptive statistics were extracted, including means, medians, standard deviation, standard error, minimum and maximum. The significance of any productivity differences between the two planting methods at the system level (e.g., whole team) was tested using the classic analysis of variance since data were normally distributed.

In contrast, the significance of any differences in worker productivity, delay incidence, and elemental time incidence was tested using non-parametric techniques (Mann-Whitney U test, Kruskal-Wallis test) as the data violated the normality assumption. Finally, the chi-square test was used to determine if the distribution among different planting quality classes significantly differed between planting methods and sites. The same test was used to assess the effect of planting method and site on plant survival. The selected statistical significance level was α =0.05 for all analyses.

3. Results

3.1. Block Study Productivity

The results (Figure 3) showed that the mean productivity for a semi-mechanised tree planting method at Flatcrown was 1 049 plants per productive machine hour (PMH = productive work, excluding delays – cfr. [40]) and 709 plants per productive machine hour at Kwambonambi. In a manual method, the mean productivity was 1608 plants/PMH and 1 310 plants/PMH at Flatcrown and Kwambonambi, respectively (Figure 3). Statistical results showed significantly higher productivity for the manual planting method on both sites ($p<0.0001$). The semi-mechanised method was between 50 to 60% less productive than the manual method.

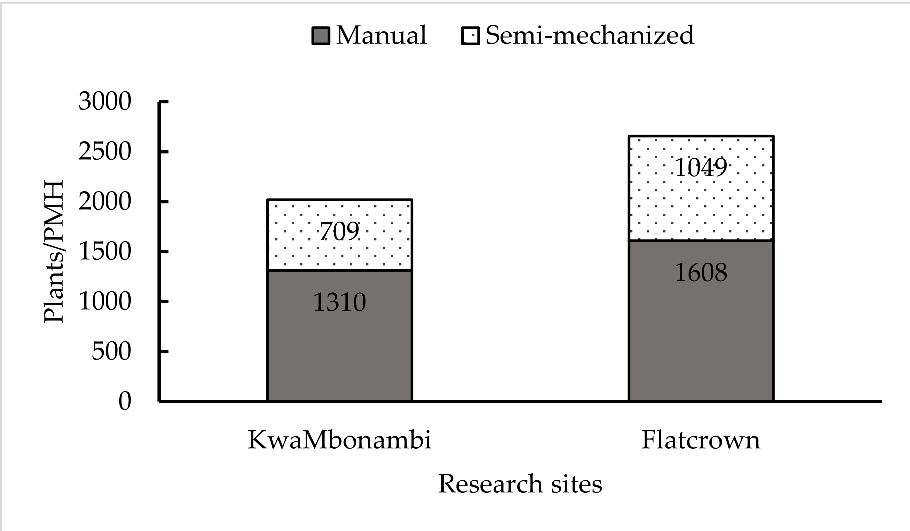

Figure 3. Manual and semi-mechanised planting method productivity at different sites.

The overall worker productivity was 30 – 40% higher at Flatcrown than at Kwambonambi. At Flatcrown, the semi-mechanised team achieved higher productivity (117 plants/worker PMH) than the manual team (107 plants/worker PMH), whereas the contrary was true at Kwambonambi (87 plants/worker PMH for the manual team and 79 plants/worker PMH for the semi-mechanised team). Mann Whitney U test revealed that workers' productivity between methods was not significantly different across both sites (Kwambonambi, p-value = 0.08; Flatcrown, p-value = 0.09).

The semi-mechanised method had a higher utilisation than the manual method; that is, it incurred fewer method delays, i.e., those delays when the whole method stops performing productive work (Figure 4). The highest method delays, the lunch and rest breaks, were recorded with the manual method (67% of the total method delay time). Resupplying of hydrogel and seedlings also had a much higher incidence in the manual method (31%) compared to the semi-mechanised method (15%). However, the semi-mechanised method had a large incidence of mechanical delays, which accounted for 46% of the total delay time or 12% of scheduled work time. The Mann-Whitney U-test indicated that those differences were not significant at the 5% level but at the 10% level. Given the high variability that typically characterises utilisation data, a 10% significance could be highly suggestive [43].

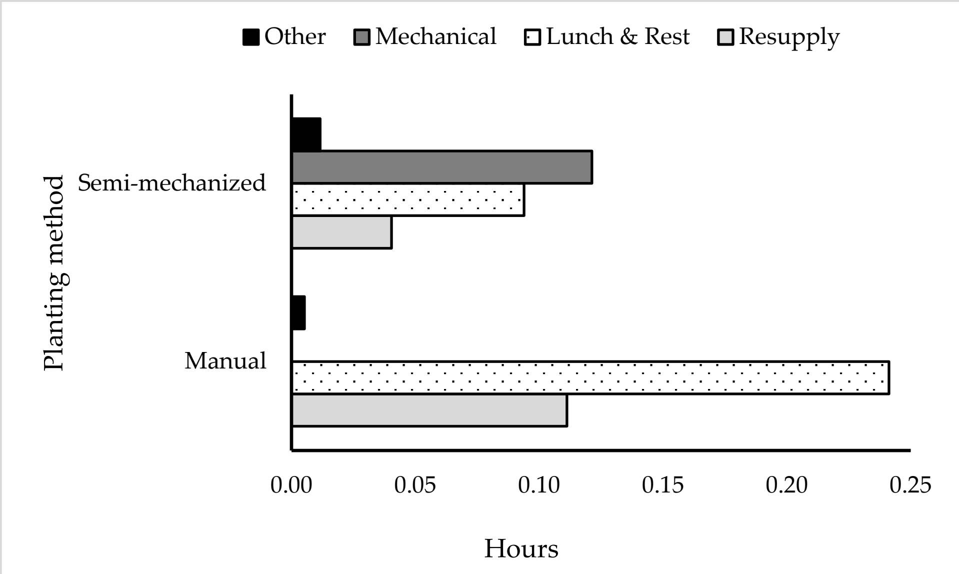

Figure 4. Delays composition of manual and semi-mechanised planting methods.

3.2. Elelemental Study Productivity

The mean cycle times for the manual planter, manual irrigator and semi-mechanised planter were 11.6s, 12s, and 25.1s, respectively. In the manual method, planters spent the highest proportion of time doing actual planting work (53.8%) and walking (19.3%). Waiting time was split between waiting for irrigators (10.5%) and seedling replenishing (7.8%). The results show that manual irrigators performed actual productive work only 1/3 of their work time. The remaining time was spent refilling the hydrogel, waiting for the planters to drop the seedlings, driving the tractor with hydrogel closer, and performing other ancillary tasks (Figure 5). In the semi-mechanised method, most of the cycle time was taken by actual work: boring planting holes, inserting the planting tubes, and depositing the seedlings. Semi-mechanised planter's actual planting work accounted for 63.3% of the total cycle time. Moving between planting positions took 15.1% of cycle time. Delay time was highest with semi-mechanised planters (17.3%) than for manual planters (8.7%) and irrigators (5.9%). The Kruskal-Wallis test revealed that the proportion of time spent on each task was significantly different for both treatments, except for delays (Table 6).

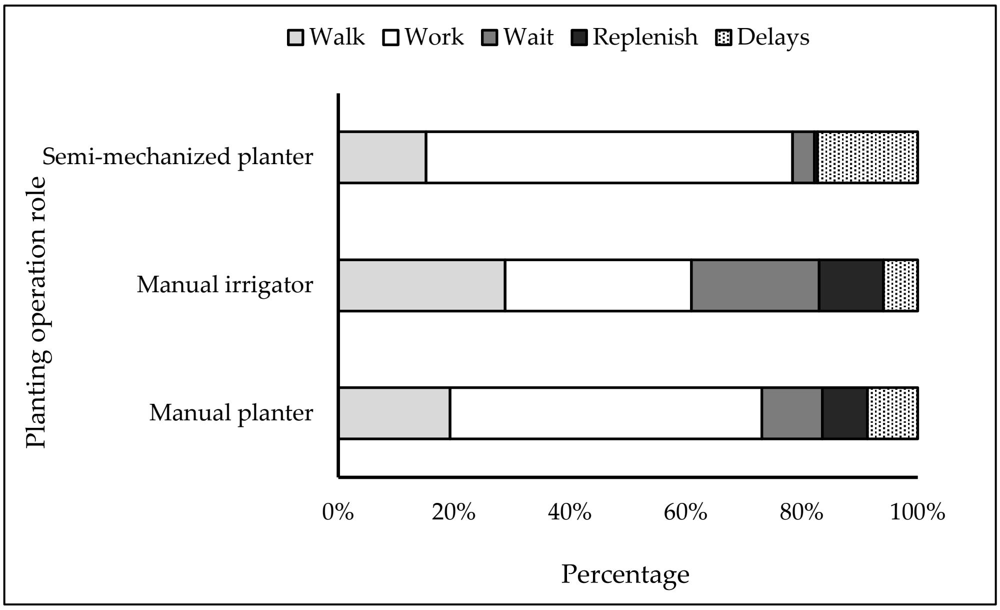

Figure 5. Elemental time distribution for various planting operation roles.

Table 6. Summary analysis of the proportion of time spent on each task by the different planting methods.

	Manual method		**Semi-mechanised method**	
Element	Planter (%)	Irrigator (%)	Planter (%)	*P*-values
Walk	19.3	28.8	15.1	<0.001
Work	53.8	32.1	63.3	<0.001
Wait	10.5	22.1	3.7	<0.001
Replenish	7.7	11.1	0.6	<0.001
Delays	8.7	5.9	17.3	0.9432

3.3. Planting Quality and Tree Survival

A total of 2 037 seedlings were assessed for quality after planting at all the study plots and for both methods. The Chi-Square test (x^2 = 1.68; df = 1; p-value = 0.19) did not detect any significant difference in planting quality between the two treatments across both study sites (p-value = 0.19). The success rate (i.e., good planting quality) was 96% for the manual method and 93% for the semi-mechanised method, but the difference was insignificant (p-value = 0.07). For both methods, no seedlings were planted shallow, inadequately compacted, or slanted. The percentage of seedlings planted on the side (2.5%), fallen (2.3%), loose (1.2%) and planted deep (1.2%) were higher with the semi-mechanised method than the manual method (Figure 6). There was no significant difference in the proportion of good-quality plantings between the four teams working at Flatcrown and Kwambonambi in both treatments (Manual, p-value = 0.58; Semi-mechanised, p-value = 0.81). Survival was 100% at Kwambonambi and 98% at Flatcrown, regardless of planting method; Chi-square analysis failed to find any significant differences in 30-day plant survival between methods or sites (p-value = 0.25).

Figure 6. Planting quality assessment for manual and semi-mechanised methods.

4. Discussion

In a six-row work swath, the manual method was 50 - 60% more productive (plants/hour) than the semi-mechanised method. The manual team worked in pairs (irrigator x planter), but each pair was independent of the other pairs. This setup allowed for ease of movement and removed most interaction delays, meaning that one pair would not be slowed by another pair. The only dependency was with the tractor carrying the water tank, which moved with the team to enable irrigators to replenish their hydrogel supplies and the seedling replenisher to collect new seedlings. The semi-mechanised method consisted of a tractor fitted with six planting tubes connected to the same manifold, which constrained workers to move at the same pace. Therefore, faster workers would be limited by slower workers. On burnt pine stands, [44] reported the productivity of a similar six-person tractor-drawn semi-mechanised method planting to be 1.20 ha/hour at 1667 stems per ha compared to 0.79 ha/hour (Flatcrown) and 0.53 ha/hour (Kwambonambi) achieved by the semi-mechanised method. The difference in productivity is probably because soil preparation was carried out prior to planting by a pitting machine [44] compared to high-pressure water used in this study, which increased planting time. The proportion of time spent walking and planting (68%) was >10% less than that recorded in this study.

[45] reported that the high-pressure water planting unit planted 0.89 ha per hour, a higher productivity than that recorded by the semi-mechanised method in this study at both sites (Flatcrown = 0.79 ha/hour and Kwambonambi = 0.53 ha/hour). In both of these studies, the semi-mechanised method faced challenges related to residue presence and terrain. The terrain conditions were not specified; hence, the comparison is made with caution.

The productivity of both methods was higher at Flatcrown than at Kwambonambi. Visual observation suggests that site conditions were a likely explanation, given that the Kwambonambi site was gentle, uneven, and especially much less clean than the Flatcrown site. The latter had achieved a relatively clean burn, which left the site with minimal residues, thereby increasing ease of access. That was not the case with the Kwambonambi site, where the presence of residue and weed regrowth negatively affected both planting methods. It is suggested that the amount of residue hindered the ease of movement, a conclusion [44] supports. Frequently, workers had to move residue aside before inserting the planting tool, and their advance was hindered on spots still covered with heavy residue.

 doi:10.20944/preprints202411.0143.v1

Consequently, worker productivity was higher on the cleaner site (Flatcrown) than on the site with more residue (Kwambonambi).

Termed as the planting tube method by [46], a manual planter planted 171 plants/hour compared to 107 and 87 plants/hour recorded in this study by the manual method. In their study, productivity was affected by increased tamping time due to rigid gleysol clay soils, while in this study, areas had sandy Fernwood soils, which facilitated easier penetration and compacting. Differences in site preparation and planting practices between the two studies exist in the method of marking a planting position (tractor ploughing and 1.78 m measuring stick attached to the planting tube vs. burning and use of old stump lines), planting density (1666 vs. 1333 stems per ha) and irrigation (absent vs. present). The planting tool (Pottiputki planting tube) features used in [46] were also different in that the planter had to step on the pedal to create a hole for a seedling to be deposited, an absent procedure in the planting process in this study. It can be suggested that better terrain agility and adaptability of the manual method allows workers to move freely and easily, avoiding hurdles; therefore, the more suitable method for sites with uneven conditions. In this study, worker productivity (plants/worker PMH) between methods was similar, suggesting that method selection had limited influence on individual worker efficiency. This finding is consistent with values reported by [47] who found manual planting productivity to be 95 plants per man hour.

Across all sites for both methods, teams spent over half the time doing productive work. The semi-mechanised method had a higher proportion (+4%) of time where workers were doing actual productive work. This might be attributed to semi-mechanised operators having the water connected to the tubes, eliminating time spent replenishing and refilling water/hydrogel. As part of the manual method sequence, irrigators were repeatedly refilling the watering cans with hydrogel from the tractor. The extended distance increased the walking time for irrigators to refill. Due to planter–irrigator interdependence, that delay affected the planter's efficiency and, subsequently, the whole operation.

Concerning delay types, the manual method incurred much larger resupply (64%), and lunch/rest (63%) delays compared with the semi-mechanised method. This suggests that delays associated with resupplying (hydrogel and seedlings) may be higher for a method with more workers and where water is not delivered automatically to the tubes. The manual method had no mechanical delays during the trials, potentially due to the minimal use of equipment that could break down. In contrast, mechanical delays were a common occurrence with the semi-mechanised method (12% of total work time). However, the study was too short (49.5 hours, including delays) to produce conclusive figures on such an erratic phenomenon as delay incidence, and therefore, the information reported just above must be taken as (highly) suggestive only.

The manual method exhibited a slightly better performance 3% in planting quality compared with the semi-mechanised method, possibly due to each team's ability to maintain their best work pace. Operators engaged with the semi-mechanised method were subjected to a higher time pressure, as they needed to keep pace with their colleagues, which may have caused occasional hurried work. Manually planted seedlings with different tools and innovations in other areas present similar [24,47] or superior planting quality [41]. Tree survival was relatively high for both methods at an acceptable industry rate of > 90% [48], consistent with results reported by [47] when comparing the survival of manually (98.6%) and mechanically (96.7%) planted seedlings. Planting quality may have long-term consequences on tree survival, growth and, ultimately, on the financial performance of a forest investment [49].

5. Conclusion

The drive to improve productivity and work quality and counter labour challenges has led to increased modernisation of replanting work in the South African forest industry. Findings from this study indicate that the manual method performed better than the semi-mechanised method under different ground conditions. The latter did affect the performance of both methods, which was higher on the cleaner site. As it relies on independent worker pairs, the manual method enjoys higher agility and is less affected by unfavourable work conditions, but it also relies on a much larger workforce to achieve the same production. Therefore, deploying such a method requires carefully analysing labour availability and cost. The semi-mechanised method is probably a better choice on clean sites and gentle terrain. Assigning the planting and irrigation tasks to the same operator reduces labour costs and removes the interaction delays inevitably created when assigning the two tasks to two separate workers. Although manual planting methods present superior work productivity and quality, semi-mechanised methods have the potential to supplant this dominance owing to improvements in method configurations and application.

Future studies should investigate the impact of both planting methods on the cost, growth, and uniformity of planted seedlings. This study provides valuable information for forest growers to plan and make decisions based on the efficiency and work quality expected from both planting methods.

Author Contributions: Conceptualization, M.M.R. and M.J.K; methodology, M.M.R, R.S. and N.M formal analysis, R.S.; Resources M.M.R.; writing – original draft preparation, M.J.K.; writing – review and editing, M.M.R., R.S. and N.M.; visualization, M.J.K. and M.M.R. supervision, M.M.R.; funding acquisition, M.M.R.

Funding: FP&M SETA; NRF; Nelson Mandela University

Data availability statement: Data can be obtained from the authors upon reasonable request.

Acknowledgments: The authors would like to acknowledge the Nelson Mandela University, FP&M SETA and NRF for the research funds. Mondi (grower company), Mondi Siyaqhubeka and Amahlathi Ethu (contractor) are thanked for making it possible for this study to be conducted.

Conflicts of Interest: The authors declare no conflict of interest.

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