PROCCEDINGS OF THE INTERNATIONAL SYMPOSIUM "*FOREST AND SUSTAINABLE DEVELOPMENT*"
9TH EDITION, 16TH OF OCTOBER 2020, BRAȘOV, ROMANIA

ANALYTIC HIERARCHY PROCESS AND BENEFIT COST ANALYSIS FOR THE SELECTION OF SUITABLE EUCALYPT RE-ESTABLISHMENT METHODS: A CASE STUDY IN KWAZULU-NATAL, SOUTH AFRICA

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Abstract: *Deciding which re-establishment methods to apply has become increasingly complex due to the expanding range of options and the numerous criteria that need to be fulfilled to support any chosen options. The objective of this study was to develop a decision model for the selection of the best method to perform different re-establishment activities, based on stakeholder preferences. The Analytical Hierarchy Process (AHP) was used in conjunction with Benefit Cost analysis to facilitate the process of selecting the best re-establishment method. Results from the case study carried out in Kwazulu-Natal on eucalypt re-establishment showed that the mechanized and semi-mechanized re-establishment alternatives were best for all criteria assessed, except for cost efficiency, where manual methods offered improved financial returns.*

Key words: *Decision-making, technology, alternative.*

1. Introduction

The main hardwood species grown commercially in South Africa are eucalypts, wattle and poplars [70]. South Africa has 521,325 ha of eucalypt plantation, of which 57.8% is located in the KwaZulu-Natal province [23]. Depending on site quality, eucalypt stands are grown over a rotation ranging from 6 to 12 years [41]. Eucalypts are commercially significant plants because they are fast growers of good form and can be used for various purposes—such as pulpwood, poles, saw timber, mining timber, biomass and essential oils [5].

Pulpwood is an important commodity for the South African economy. In 2017, the value of the pulp round wood production amounted to 6.9 billion Rands [23]. For South Africa to sustain and increase the supply of fibre, precision

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forestry is required in pulpwood re-establishment [49]. The use of technology in silviculture is important because it can improve productivity [10, 54] and decrease negative environmental impacts [32].

Globally, advancements in technology influence the way in which tasks are performed across various industries such as agriculture, mining, manufacturing, construction and forestry [15]. The introduction of new technology or innovation results in both opportunities and uncertainties [44]. In forestry, stakeholders responsible for intensively managed plantations continually make site-specific decisions regarding the best methods for site preparation, planting, weed control and fertilization [4, 54]. Moreover, they are faced with making complex evaluations regarding the choice of the most appropriate technologies so as to remain competitive and increase returns to the company [35].

According to Prisecaru [53] the complexity associated with decision-making is expected to increase as industries transition and adapt to the Fourth Industrial Revolution. Within forestry, modernisation (entails using the most up-to-date techniques and equipment to perform task) will result in technological changes, especially where digital solutions, connectivity, robotics, and big data sets are used [79].

In South Africa, most re-establishment activities are conducted manually, and include practices such as the management of harvesting residues, site preparation, planting, fertilisation, and weed control [70, 74]. Over the past decade, various new re-establishment technologies have been tested operationally (mainly associated with mulching, stump treatment, preparation of planting positions and planting), with some adopted into current practice. Examples are the preparation of a planting position through the use of a pick, earth auger, single pitting head machine, multiple pitting head machine and tractor, or dozer-pulled ripper [6, 7, 16]. The modernisation of re-establishment activities in South Africa is in response of the need to improve operator health and safety, increase productivity whilst reducing costs, improve work quality, and mitigate labour related risks [42, 50, 63, 75]. Due to the increase in available options, forestry grower companies and contractors are faced with the difficult task of having to consider numerous alternatives before selecting appropriate re-establishment methods to use in their operations.

The complexity in forestry decision making is exacerbated by multiple criteria—including economic, social, environmental, and technical factors—that have to be taken into account [52]. Furthermore, some tasks may entail diverse stakeholders (small private growers versus large corporate companies) [28], and conflicting objectives and constraints [4]. Therefore, decision support systems that incorporate multiple criteria and information from various sources are important to improve the quality of decision making in forestry.

Multi-criteria decision analysis (MCDA) is used to describe a collection of formal approaches which take explicit account of several criteria when assisting individuals or groups making important decisions [3]. Some of the most popular MCDA methods are Goal programming, PROMETHEE, ELECTRE, MACBETH, MAUT (Multi-Attribute Utility Theory), ANP (Analytical

Network process) and AHP (Analytical Hierarchy Process) [30]. Each method has its advantages and disadvantages. The Analytical Hierarchy Process is defined as a theory of prioritization that derives relative scales of absolute numbers, known as ‘priorities’, from judgements expressed numerically on an absolute fundamental scale [58]. AHP can be described as a multi-criteria optimization methodology that includes the risk factors to be considered when making a decision. It is a versatile and robust tool because it can deal with qualitative and quantitative attributes [33].

Decision support systems (DSS) such as the analytic hierarchy process (AHP) have been tested in numerous studies related to forest engineering [13, 51] and forest planning [2, 17, 31, 48]. In forest operations, DSS models have been used for making decisions about optimal harvesting methods and systems [22, 29, 68]. However, there has been no published study related to operational criteria and alternatives to assist forest stakeholders to decide on the best re-establishment methods to use.

To address this, a study was conducted to:

- Develop a decision model for selection of the best method to perform different re-establishment activities (residue management, preparation of a planting position, weeding before planting, planting, fertilising and weeding after planting) based on stakeholder preferences; and

- To use benefit cost analysis for selecting re-establishment methods that generate the highest return on investment.

2. Materials and Methods

A two-phased approach was adopted for this study. The first approach made use of AHP for the selection of the most appropriate re-establishment method based solely on the non-financial benefits thereof. Where complex decisions involving multiple facets are made, it is recommended that costs are excluded until all the associated benefits of the alternatives have been assessed, especially were decision makers may disqualify an alternative, based on the costs alone [27]. The second approach combined the results of the non-financial benefits (from the AHP model) with cost hierarchies, with output ratios analysed as described by Wedley et al. [76]. The complete decision process involved eight key steps (Figure 1).

2.1. Multi-Criteria Decision Analysis - Analytic Hierarchy Process (AHP)

For this study, the AHP method was identified as the most appropriate method based on the parameters of the method itself, the modelling effort required and the output required based on the study objectives. For AHP, the main factors considered when making a decision are first identified and then arranged in a hierarchic structure that includes (in the descending order): overall goal; criteria; sub-criteria; alternatives [57]. Analytic Hierarchy Process is based on pair wise comparisons and relies on the judgements of experts to derive priority scales (priorities are numbers associated with the nodes of an AHP hierarchy) to be used to measure intangibles in relative terms [59]. The comparisons are further structured according to a scale of absolute judgements that represent how much more one element (criteria/sub-criteria) dominates another with respect to a given attribute. The derived priority scales are multiplied by the priority of their parent nodes (upper level nodes).

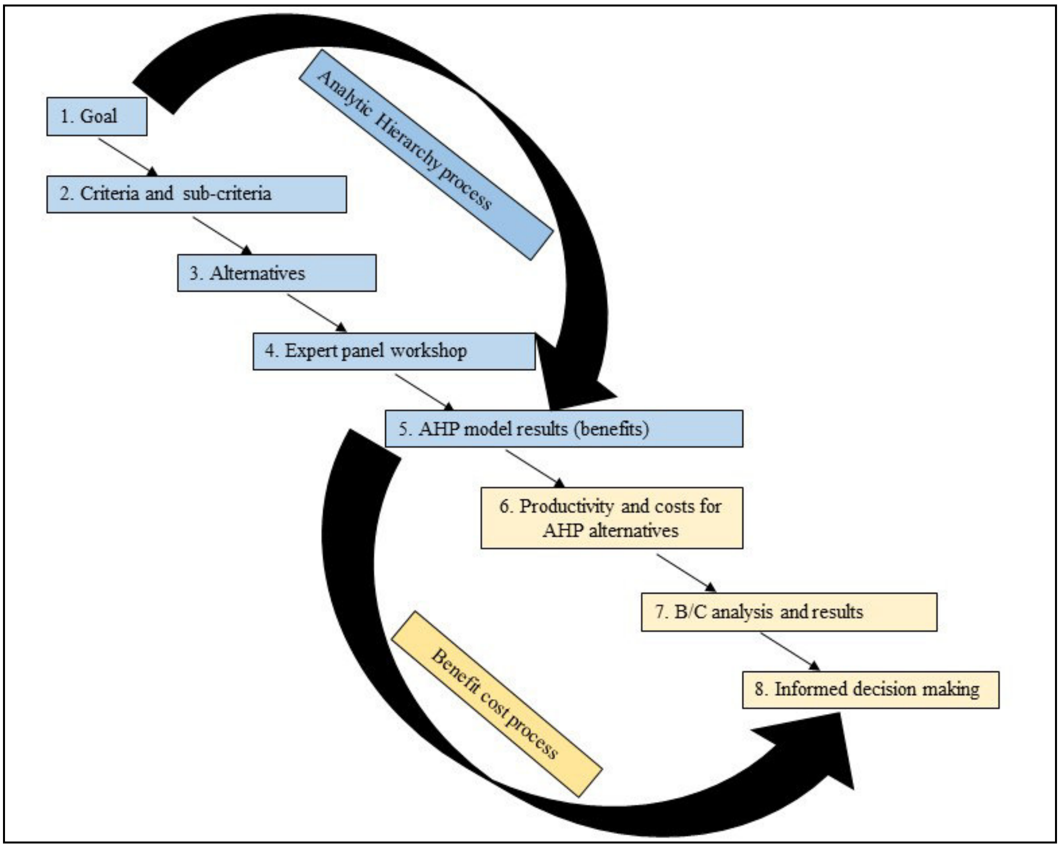

Fig. 1. *Schematic diagram of the steps followed in the decision-making process*

The fundamental scale (Table 1), which is used in AHP to make judgements, has been validated for effectiveness in many applications and through theoretical comparisons with a large number of other scales [57]. AHP has already been used successfully in forest engineering [13, 68], which further supports the method choice made by the researcher.

In this study the ratings mode was used to obtain priorities for selection of the alternative methods. The ratings mode identified priorities by establishing rating categories for each criterion and prioritised the categories by pair-wise comparison for preference. Alternatives were then evaluated by selecting the appropriate rating category for each criterion [59].

2.2. AHP Model Design

The AHP model was constructed based on key objectives provided by the experts.
The model is illustrated in the form of a hierarchy value tree (Figure 2).

Table 1

The fundamental scale [57]

Intensity of importance on absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	Evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	When compromise is needed
Reciprocals	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity, then j has the reciprocal value when compared with *i*	
Rationals	Ratios arising from scale	If consistency were to be forced by obtaining n numerical values to span the matrix

2.2.1. AHP Hierarchy Goal

Adopting the AHP developed by Saaty [59], a case study was used to illustrate the application of the decision model. The case study goal was to select the best re-establishment method for a large commercial company that grows eucalypts for pulp and paper in the KwaZulu-Natal forestry region of South Africa. The extent of the case study was limited to the collection of opinions from silvicultural experts currently active in this region. The selection of a re-establishment method can be classified as a complex decision process due to the number of factors that need to be considered (for example: ergonomic friendliness, output/ha, employment opportunities etc). The decision-making process involved evaluating all possible alternatives based on the “importance criteria”, such that the best re-establishment method(s) would be chosen.

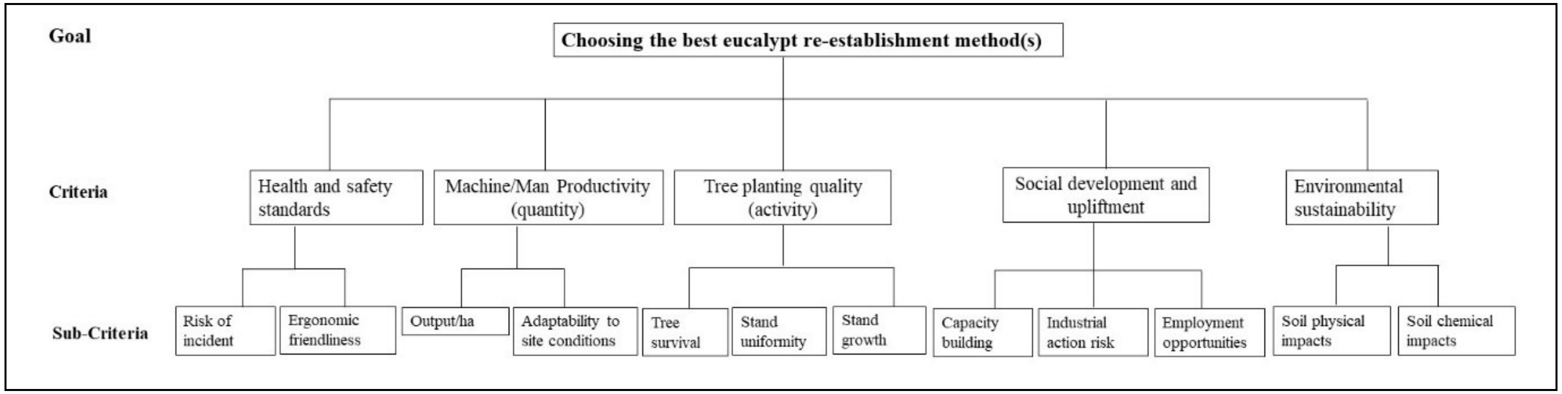

Fig. 2. *Hierarchy of decision maker's goal, criteria, and sub-criteria for selecting the best re-establishment method*

2.2.2. Importance Criteria

Five attributes of a good re-establishment method were identified by conducting a literature review and interviewing experts. These were subsequently used as main criteria and sub-criteria in this study. A benefits hierarchy was used to generate priorities for non-financial benefits of each re-establishment activity. The benefit priorities were then compared to the cost priorities to determine then the highest ratio of benefit to costs. Costs were considered as separate attribute against which the results obtained from the non-financial benefits using AHP were plotted to give the final trade-offs so as to find best re-establishment system [69].

The main criteria were:

i. Health and safety standards - referring to the safety level of the method, taking into consideration the potential health risk of the individual or team using it.
ii. Machine/man productivity - referring to the effectiveness and efficiency of the re-establishment method in terms of the output (e.g. trees planted per hour)
iii. Tree planting quality – referring to the ability of the re-establishment method to meet the tree planting specifications in terms of tree performance (survival, growth and uniformity).
iv. Social development and upliftment – referring to the effect of the method in terms of considering community needs, providing employment, empowering people and dealing with labour related risks
v. Environmental sustainability – referring to the extent to which the method resulted in a reduced impact on the site and ensured a sustainable future crop.

2.2.3. Sub-Criteria

The main criteria were divided into sub-criteria. The sub-criteria helped the experts to have a more detailed understanding of each of the main criteria and they are described in Table 2.

2.2.4. Alternatives: Re-Establishment Methods

Various methods (alternatives) within each re-establishment activity were identified by the researcher based on interviews with various experts. The alternative methods were derived from the main re-establishment activities, namely: harvesting residue management, preparation of a planting position (POPP), weeding before planting, planting, fertilising and weeding after planting (Table 3). For example, the alternative methods considered under residue management were burn, broadcast and mulch.

2.3. Decision Making Panel

Due to the lack of local scientific studies investigating relationships between re-establishment methods and the criteria for their selection, the ratings used in the AHP model were predominantly based on the experiences of the experts, research from other countries (such as Brazil [25] and Sweden [19]) and reports from company research studies. A panel of nine local experts involved in re-establishment of eucalypt plantations in KwaZulu-Natal were invited to participate in a workshop so as to rate the main and sub-criteria.

According to Ishizaka and Nemery [30], when various experts are consulted, bias present when judgements are made by one expert is eliminated. The experts who participated possessed relevant knowledge (all had greater than 10 years' experience in re-establishment) and were engaged in the following roles: grower company silviculture specialists (2), silviculture management forester (1), silviculture product and equipment manufacturers (2), contractors (CEOs) (2), business development manager (1) and researcher (1).

Table 2

Sub-criteria used for selection of the best re-establishment method

Main criteria	Sub-criteria	Description of sub-criteria
Health and safety standards	Risk of incident	Likelihood and impact of incident
	Ergonomic friendliness	Reduction in musculoskeletal disorders such as carpal tunnel, back and neck strain, and fatigue
Machine/man productivity	Output/ha	A measure of efficiency of a person or machine in converting inputs into useful outputs.
	Adaptability of the method or system	Ability to adjust to new working conditions e.g. terrain
Tree planting quality	Tree survival	Percentage mortality of plants
	Tree uniformity	Limited stand or state of being consistent e.g. Height and DBH
	Tree growth	increase in size and numbers of vegetative structures of plants
Social development and upliftment	Capacity building	Education and skills training for the work
	Industrial action risk	Labour and politically related instability
	Employment opportunities	Jobs, opportunity to secure paid work
Environmental sustainability	Soil physical impacts	Soil displacement, soil compaction and soil loss
	Soil chemical impacts	Nutrient availability and organic matter

Before the workshop, the experts were sent background information about the research and literature about the AHP method used for decision-making. At the workshop the experts were further orientated about the AHP method and the expectations (desired outcomes) for their participation in the workshop. The experts' task was to conduct pairwise comparisons to derive weightings for the main criteria and sub-criteria. The main criteria (Table 2, left column) were individually compared against each other in the form of a matrix to establish which was more important with respect to the goal of selecting the best re-establishment method.

Using the 9-point scale typical of AHP studies, the experts assessed the extent of dominance of each element over the others. When the experts could not reach consensus on a specific rating, the geometric mean [59] was used to combine their individual ratings and derive a single score. The consistency ratio of the pairwise comparison was calculated at the end of the process. When the pairwise comparison matrix is consistent, the normalized sum of each criteria score indicates how much each criteria dominates the others in relative terms. Consistency checking helps to detect possible contradictions in the pairwise entries [30]. A consistency ratio of 10% or less is considered valid for a 4 by 4 (or higher) matrix.

To normalize the data so as to obtain idealised priorities for the ratings [59], the score for each priority was divided by that of the largest of the priorities. For each re-establishment method, the total overall rating score was calculated and then compared to the overall scores for the other alternatives within the re-establishment category (activity).

Table 3

Re-establishment activity alternatives available for selecting best re-establishment methods

Activity	Residue management	Preparation of planting position	Weeding before planting	Planting	Fertilizing	Weeding after planting
Methods	Mulch Broadcast Burn	Single pitting head machine Earth auger Pick	Tractor boom spray Chemical with knapsack Manual clearing	Wasserplanzer (high water pressure planter) Tractor planter Planting tube Manual (trowel)	Fertilizer tablets Fertilizer backpacks Fertilizer fork	Tractor spray rig with lances Manual (hoe/slash) Chemical with knapsack

2.4. Benefit Cost Analysis

Equipment manufacturers and grower companies were contacted to gather cost and productivity information for the different re-establishment methods identified as alternatives (Costing assumptions Annexure 1). The South African Forestry Contractors Association (SAFCA) costing model was used to accurately estimate the costs for conducting different re-establishment methods. To ensure consistency in all costings, only direct costs were used, with indirect costs (overhead and administrative costs) excluded from the cost calculation. Furthermore, costs of material inputs such as seedlings, chemicals and fertilizer where excluded in the costings because they are standard costs regardless of re-establishment methods assessment.

The costings of each method were conducted independently of each other to allow for accurate comparisons between different methods. In reality, the cost of different re-establishment activities are costed out together to derive labour/machine rates to ensure the labour and vehicle resources are used efficiently. The same re-establishment resources (e.g. labour) can perform various activities depending on the re-establishment needs at a specific time (e.g. labour can perform pitting and broadcasting). The common cost denominator used was the cost per ha of each of the alternatives. The projects with B/C (benefit cost) ratios greater than one are considered to yield positive net benefits and they are the ones that can be undertaken [77]. The relative differences between the total AHP ratings and B/C ratios were used to graphically compare the findings.

3. Results

3.1. Using the AHP for Selecting the Best Re-Establishment Method

The weights for the main criteria and sub-criteria were derived from the pairwise comparisons scores provided by the experts (Table 4).

Table 4

Relative ranking of criteria

Criteria	Priorities (%)
Health and safety standards	38.7
Tree planting quality	27.6
Environmental sustainability	19.1
Machine/man productivity	9.2
Social development and upliftment	5.4
Total	**100**
Sub-criteria	***Global alternative priorities (%)***
Risk of incident	32.3
Tree survival	15.8
Soil physical impacts	9.6
Soil chemical impacts	9.6
Tree growth	7.9
Man/machine output/ha	7.7
Ergonomic friendliness	6.5
Tree uniformity	3.9
Capacity building	2.8
Employment opportunities	1.6
Adaptability of the method/system	1.5
Industrial action risk	0.9
Total	**100**

The re-establishment method associated with the highest level of health and safety standards had the highest weight (38.71%), with the need to provide social development and upliftment, the lowest weight (5.36%). A valid consistency ratio of 9% was derived from the pairwise comparisons. Amongst the sub-criteria, the level of incident risk associated with the re-establishment method had the highest weight (32.26%), and the risk of industrial action had the lowest weight (0.92%). The consistency ratios of the sub-criteria were all 0%.

By using the rating categories for each of the sub-criteria, the priority outputs were determined by pair-wise comparing them for preference. For example, the rating categories for risk of incident are high, moderate and low risk. These categories were compared for preference using the pair-wise comparison method (Table 5). Table 6 gives the corresponding numerical ratings from Table 5 for each re-establishment activity alternative.

The preferences of the decision makers involved when rating each method was sucessful in indicating the best method for each re-establishment activity (Table 7). For residue management, POPP, weeding before planting and weeding after planting, mechanised alternatives had the highest rating priorities. Based on the objective of selecting the best re-establishment method (based on the algorithm used by the researcher), the output from the model indicated the following preferred options: mulching (Figure 3a) to manage the residues, a single pitting head machine (Figure 3b) to prepare planting position, a tractor-mounted boom sprayer (Figure 3c) to apply chemical (herbicide) before planting, and tractor spray rig with lances to conduct inter-row weeding after planting (Figure 3f). The Wasserplanzer (Figure 3d) and fertilizer fork (Figure 3e) were rated as the preferred methods for planting and fertilizing respectively.

3.2. Benefit Cost Analysis

The results from the B/C analysis (Table 7) indicated that burning (Figure 3a) and manual pitting (Figure 3b) had the highest B/C ratios compared to the other options within their activity category. Of interest was that both methods (burning and manual pitting) were the second most preferred residue management and POPP method when non-financial benefits were taken into consideration. The use of a tractor-boom sprayer generated the highest B/C ratio, which was consistent with the most preferred weeding before planting method when considering non-financial benefits. Manual planting with a trowel and tubes generated the two highest B/C ratios for planting, although the Wasserplanzer method was the most preferred in terms of non-financial benefits. The application of fertilizer tablets was the most viable method for fertiliser application compared to other alternatives, although the use of fertiliser forks was the preferred option when considering non-financial benefits. When comparing weed control methods following planting, the tractor spray rig with lances method generated the highest B/C.

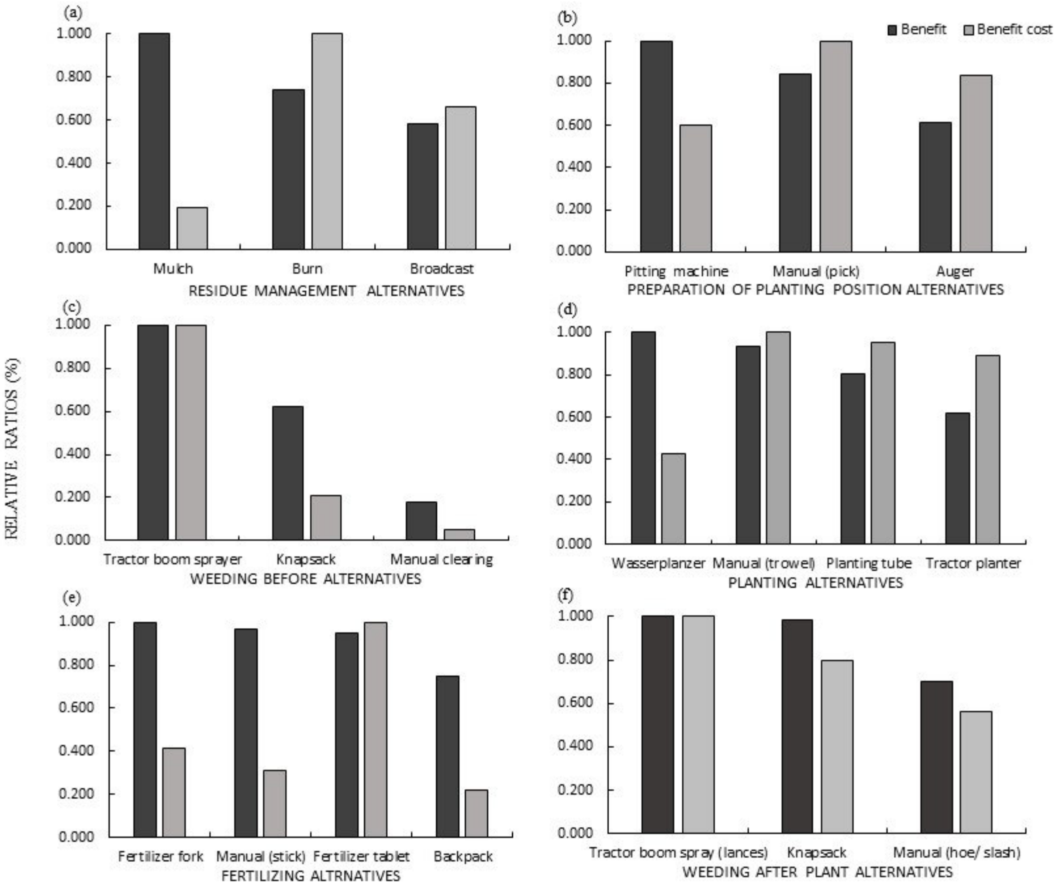

Fig. 3. *Relative non-financial benefit and benefit cost ratios for each re-establishment activity alternative:(a) Residue management (b) Preparation of a planting position, (c) Weeding before planting, (d) planting, (e) fertilizing and, (f) weeding after planting*

Table 5

Prioritised ratings categories for all criteria

Health and safety standards		Machine/man productivity		Tree planting quality			Social development and upliftment			Environmental sustainability	
Risk of incident	Ergonomic friendliness	Output/ha	Adaptability	Survival	Uniformity	Growth	Capacity building	Industrial action risk	Employment opportunities	Soil physical impacts	Soil chemical impacts
High risk	Good	High	High	>90%	Highly uniform	High m^3/ha	Advanced	High likelihood	>5 people	High risk	High risk
0.071	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.071	1.000	0.085	0.085
Moderate risk	Moderate	Moderate	Medium	70–89%	Moderately uniform	Moderate m^3/ha	Intermediate	Moderate likelihood	2-5 people	Moderate risk	Moderate risk
0.304	0.298	0.304	0.411	0.304	0.402	0.316	0.454	0.304	0.500	0.298	0.298
Low risk	Poor	Low	Low	<70%	Poor uniformity	Low m^3/ha	Basic	Low likelihood	1 person	Low risk	Low risk
1.000	0.084	0.071	0.168	0.079	0.111	0.074	0.087	1.000	0.148	1.000	1.000

Table 6

Numerical values for alternative ratings for each re-establishment category

ACTIVITY	SUB-CRITERIA / METHOD	Risk of incident	Ergonomic friendliness	Output/ha	Adaptability to site conditions	Tree survival	Stand uniformity	Tree growth	Capacity building	Industrial action risk	Employment opportunities	Soil physical impacts	Soil chemical impacts
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Residue management	Burn	0.304	0.084	1.000	1.000	0.295	1.000	1.000	0.454	0.070	1.000	0.084	0.084
	Broadcast	0.304	0.084	0.070	0.411	0.295	0.401	1.000	0.087	0.304	1.000	1.000	1.000
	Mulch	1.000	1.000	0.070	0.411	0.295	1.000	0.315	1.000	1.000	0.147	1.000	1.000
Preparation of planting position	Manual (pick)	1.000	0.084	0.070	1.000	1.000	1.000	1.000	0.087	0.304	1.000	1.000	1.000
	Auger	0.304	0.084	0.304	0.411	1.000	1.000	1.000	0.454	0.304	0.499	1.000	1.000
	Single pitting head machine	1.000	0.298	1.000	0.411	1.000	1.000	1.000	1.000	1.000	0.147	1.000	1.000
Weeding before planting	Manual clearing	0.070	0.084	0.070	1.000	0.079	0.110	0.073	0.087	0.304	1.000	1.000	1.000
	Chemical application with knapsack	0.304	0.084	0.304	1.000	1.000	1.000	1.000	0.454	0.304	0.499	0.298	1.000
	Tractor boom sprayer	1.000	0.298	1.000	0.167	1.000	1.000	1.000	1.000	1.000	0.147	0.298	1.000

Table 6 (continuation)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Planting	Manual (hoe/trowel)	1.000	0.084	0.070	1.000	1.000	1.000	0.315	0.454	0.070	1.000	1.000	1.000
	Planting tube	1.000	0.298	0.304	1.000	0.295	0.401	0.315	0.454	0.070	1.000	1.000	1.000
	Tractor planter	0.304	1.000	1.000	0.411	0.295	0.401	0.315	0.4543	0.304	0.499	1.000	1.000
	Wasserplanzer	1.000	0.298	0.304	0.411	1.000	1.000	0.315	1.000	0.304	0.499	1.00	1.000
Fertilising	Manual (stick/trowel)	1.000	0.084	0.070	1.000	1.000	1.000	1.000	0.087	0.070	0.499	1.000	1.000
	Fertilizer fork	1.000	0.298	0.304	0.411	1.000	1.000	1.000	0.087	0.070	0.499	1.000	1.000
	Fertilizer backpack	0.304	0.298	0.304	0.411	1.000	1.000	1.000	0.454	0.304	0.499	1.000	1.000
	Fertilizer tablet	1.000	0.298	1.000	1.000	1.000	1.000	0.315	0.087	0.304	0.147	1.000	1.000
Weeding after planting	Manual (hoe/ slash)	0.070	0.084	0.070	1.000	0.295	0.401	0.315	0.087	0.070	1.000	1.000	1.000
	Chemical application with knapsack	0.304	0.084	0.304	1.000	0.295	0.401	0.315	0.454	0.070	0.499	1.000	1.000
	Tractor spray rig with lances	0.304	0.298	0.304	0.411	0.295	0.401	0.315	0.454	0.070	0.499	1.000	1.000

Table 7. *Re-establishment methods: non-financial benefits calculated using the AHP method and benefit cost ratios*

Activity	Method	Non financial benefit (AHP)	Rate/ha	Normalised costs	Benefit cost ratio
Residue management	Mulch	0.430	R 4 770.23	0.759	0.949
	Burn	0.318	R 687.96	0.109	4.854
	Broadcast	0.252	R 828.00	0.132	3.199
Preparation of planting position	Single pitting head machine	0.407	R 2 302.31	0.513	1.798
	Manual (pick)	0.344	R 1 174.32	0.261	2.981
	Auger	0.249	R 1 015.40	0.226	2.494
Weeding before planting	Tractor boom sprayer	0.557	R 274.09	0.132	6.928
	Knapsack	0.346	R 818.46	0.393	1.441
	Manual clearing	0.098	R 990.42	0.475	0.336
Planting	Wasserplanzer	0.413	R 3 576.13	0.487	1.467
	Manual (trowel)	0.385	R 1 419.13	0.193	3.448
	Planting tube	0.331	R 1 285.02	0.175	3.278
	Tractor planter	0.256	R 1 060.70	0.144	3.069
Fertilizing	Fertilizer fork	0.370	R 548.30	0.244	3.152
	Manual (stick)	0.359	R 711.61	0.317	2.357
	Fertilizer tablet	0.352	R 216.55	0.096	7.592
	Backpack	0.278	R 769.35	0.343	1.686
Weeding after planting	Tractor spray rig with lances	0.372	R 729.23	0.287	1.135
	Knapsack	0.367	R 898.56	0.354	0.908
	Manual (hoe/ slash)	0.261	R 909.39	0.358	0.637

4. Discussion

Based on the criteria tested in this study, the AHP and B/C analysis were successful as decision aids for the selection of the best re-establishment method from a range of options (The corresponding author can be contacted for a copy of the Decision support tool). The AHP method applied in this study focused on identifying the non-financial benefits of various re-establishment methods and the benefit cost analysis included cost considerations in order to identify the method(s) that generate the highest return on investment. To create a valid reference for the points discussed in the following paragraphs, it is important to highlight a limitation of the study. It is imperative to recognise that the outcomes could be different if a different group of people were used and if the objectives of the landowner were different. For example, the panel comprised of people with technical and business expertise and did not have a social expert who could have influenced the priority weighting of the social development and upliftment criteria.

4.1. AHP

When ranking the criteria priorities, the re-establishment method's ability to meet health and safety requirements was ranked the highest (38.71%) by the experts. For large corporate companies; employee work-related injuries lead to legal liabilities and to a poor reputation. This can make it difficult for a company to attract and retain skilled employees, adversely affect company morale and have significant cost implication [73]. In South Africa, some large corporations are mechanising silviculture activities to reduce risks related to performing physically demanding work [11].

In this study, the risk of an incident occurring was rated by the experts as the highest (32.26%) amongst the sub-criteria. Thissub-criteria was highly rated because of the strict safety regulations surrounding safety and the need for punctual adherence to safety regulations whenever an incident occurs. Literature findings indicate that silviculture workers are at risk of various occupational health issues, some of which are similar to those in harvesting operations and some of which are more specific to the task being performed [38, 72]. Musculo-skeletal problems are associated with carrying out certain manually orientated work. For example, the manual planting of trees requires prolonged and repetitive non-neural postures, which can cause musculoskeletal problems. According to Sullman and Byers [66], manual planting can be classified as hard continuous work. Further, silviculture crews are exposed to a range of potentially harmful chemicals, such as fertilizers, pesticides, lubricants, diesel and petroleum fuels and their emission. Although mechanising forest operations may significantly improve safety, the use of machines also introduces new hazards [55], such as neck, shoulder, arm and hand problems, caused by an operator using control levers, machine keyboards and display units [21, 71].

Tree planting quality was ranked the second highest (27.62%) criteria, and the ability of a re-establishment method to achieve the best tree survival rate was considered the second highest (15.85%)

sub-criteria. According to Löf et al. [36], low seedling performance (survival and tree growth) may lead to significant financial losses. The experts who participated in this study agreed that tree survival is critical for the sustainability of any grower company because poor survival during the establishment phase can lead to sub-optimal use of resources on the site and, ultimately, to a lower timber yield at rotation end. Using mechanised re-establishment methods does not guarantee positive tree performance (survival, tree growth and uniformity). This is based on the results from numerous studies conducted on various re-establishment activities globally (refer to examples provided below).

When comparing various manual and mechanised land preparation methods in re-establishing hardwoods in South Africa, Smith et al. [61] found insignificant differences in survival and tree growth. In fact, complete site preparation by machines led to a reduction in growth in some sites. More studies conducted in Europe found that the effects of the use of mechanised site preparation on tree performance varied considerably, depending on the site and type of treatment. Generally, reported responses were positive [37, 67].

When comparing manual and mechanised planting in Ireland, Nieuwenhuis and Egan [47] found that manual planting was significantly better than mechanised planting for plant positioning and planting quality, although mechanised planting was within the acceptable range. Furthermore, no differences in tree growth were found in the first growing season between manual and mechanised planting operations in the same study. In Sweden, Ersson 19] observed that seedlings planted by the planting machines showed higher survival rates than manually planted seedlings. However, another study [39] found that survival rates in mechanised planting varied, depending on the re-establishment area, machine and planting period.

Tree planting quality is closely linked to environmental sustainability, which in this study comprised of two sub-criteria (soil physical impact - 9.6%, and soil chemical impacts - 9.6%). The experts agreed that an optimal re-establishment method should have a reduced negative impact on both physical and chemical components of the soil. According to Nambiar [45], to maintain site productivity, the soil quality must be preserved and the impacts of management on resource depletion should be minimized. The impacts of soil disturbance on forest productivity have been well studied, with several studies showing loss in productivity because of topsoil disturbance [23, 45, 62]. The use of heavy site preparation equipment can cause soil compaction, churning, rutting, mixing, displacement, and soil removal, which in turn can limit tree root growth because of damage to soil physical, chemical, and biological properties [43]. According to Löf et al. [36], the relationship between a re-establishment method and tree performance is difficult to quantify because of the interactions of the method selected on soil physical and soil chemical properties that affect plant performance.

The man/machine productivity criteria was ranked fourth (9.31%) by the expert participants. The experts believed that achieving high man/machine productivity without health and safety, tree planting quality and environmental sustainability would result in detrimental inefficiencies to the whole re-establishment system. In the past in South Africa, due to the availability and low cost of labour, there has been little focus on significantly improving man/machine productivity in re-establishment operations [64] which contrasts with a much greater attention to productivity in harvesting operations. However, over the past decade new semi- and fully-mechanised technologies have been developed to improve the output/ha of various re-establishment methods, mainly due to labour related factors such as high turnover [7, 14].

Pitting is an example of an activity that has experienced a significant increase in productivity because of progressive mechanisation. When pitting on similar conditions, a person using a pick can achieve 494 pits/shift [46], a single operator using an earth auger can achieve 1243 pits/shift [60] and a single pitting head machine can complete 2500 pits/shift [65].

However, mechanised options do not always produce a higher output compared to manual methods. For example, when clearing harvesting residues, a mulcher can clear 2.5 ha/shift [26] whilst a burning team of six people can clear an area of 4.2ha ha/shift (based on 1.4 man days per ha). Regardless of whether an activity is performed manually or mechanically, the man/machine productivity maybe directly affected by factors such as terrain (ground conditions, ground roughness and slope), weather, residues (slash and stumps), stand density, delays (personal, operational or mechanical) and human factors (such as experience) [20, 34, 56].

The ability of a re-establishment method to provide social development and upliftment (5.4%) was ranked the least important criteria. The experts consulted in this study argued that the main goal of a corporate company is to make a return in the most sustainable and cost-effective manner possible. However, companies need to be conscious of the socio-economic needs of the local communities, such as employment needs and capacity building. Globally, the involvement and consideration of local communities in forest management decisions is becoming more important [1, 18]. This is because local communities may be current or future land owners [78], dependent on the land and forest resource (e.g. employment, biomass resources, practice of culture and heritage needs etc.) [9], and impacted negatively or positively by changes in forest operations. According Marchi et al. [40], sustainable forest operations should promote socially acceptable and responsible activities which enhance community values and wellness. In South Africa, most re-establishment activities are still predominantly performed manually, although there is slow progression to semi- and fully-mechanised methods. In certain instances mechanisation of traditionally manual operations can lead to some job losses. However, new work opportunities can be created through enterprise development programmes within the surrounding communities [12]. According to Charnley [9], decision makers in forest re-establishment and management need to consider the advantages and disadvantages of socio-economic changes (e.g. mechanisation) to local people to avoid displacement and exclusion of already poor communities living in and around the plantation areas.

4.2. Benefit-Cost

The study found that when considering the non-financial benefits of different re-establishment method, mechanised options within each category were found to be the best. This outcome was due to favourable ratings (based on criteria) associated with mechanised options compared to manual alternatives. For example, the experts' rating found mulching to be the best residue management method because when mulching the operator works from an ergonomically friendly cab which has a lower health and safety risk compared to burning and broadcasting slash manually. The experts believed that mulching yields excellent tree survival, highly uniform stands and moderate tree growth. However, they considered mulching as a low production method because of the hectares that can be cleared in a day [8]. In terms of social development, the experts believe that mulching provides the operator with advanced skills and training and the likelihood of industrial actions is low even though the employment opportunities are very low. Due to the organic matter mulch retained on the site, the experts considered mulching as a low impact method in terms of risk on the physical and chemical components of the soil. The AHP findings were based on this specific expert group's knowledge and landowner objectives. Irrespective of the non-financial benefits of a method, the costs had to be considered because in reality some methods may possess good overall benefits but may not be economically viable.

In general, mechanised alternatives are associated with improved safety and productivity compared to manual ones. However mechanised alternatives are more capital intensive. When including cost considerations in the rankings, then burning became the preferred option among all residue management techniques, because of its cost effectiveness. Even though mulching is safer, its cost-effectiveness is restricted by the high capital costs and low machine productivity. The benefit cost analysis results of the POPP activity were similar to those of residue management. Although manual pitting is ergonomically unfriendly and not as productive as its mechanised counterpart, it was the preferred method because of the lower costs (almost half) of the mechanised options. The earth auger method had the lowest cost, but the poor non-financial benefits generated by the method made it unfavourable.

The outcomes of the benefit cost analysis of the weeding before planting activity showed that the tractor mounted boom sprayer method was preferred. Despite the high capital costs, the operational costs (cost per ha) of using this method were found to be less than those of the knapsack and manual clearing methods. The high B/C ratio of the tractor boom sprayer can be attributed to the high productivity, which dilutes the fixed costs. The selection of this method over the other alternatives needs to be carried out after careful planning and consideration of its limitations (especially terrain). Where suitable, a combination of this method with other alternatives may be considered. Manual planting with a trowel and tubes generated the highest B/C ratios. When considering non-financial benefits, the Wasserplanzer method would be preferred. However, because this planting method incorporates the POPP process, it incurred higher costs and had lower productivity compared to other conventional planting methods. When deciding on the preferred planting method to use, the decision maker needs to assess the Wasserplanzer method holistically.

The results of the benefit cost analysis of the fertilization activity indicated that the use of fertilizer tablets generates the highest returns compared to the other methods. The high B/C ratio can be attributed to the relatively low costs because fertilizer tablets are integrated with the planting activity, whereas conventional fertilization methods (granular fertilizer) occur as a separate activity after planting. When selecting the preferred fertilization method, the decision maker needs to consider the suitability of using fertilizer tablets compared to using granular fertilizer to remedy nutritional needs of the site.

The outcomes of the benefit cost analysis of the weeding after planting activity showed that the tractor spray rig with lances method was preferred. This method generated the greatest non-financial benefits and the highest return on investment. Despite high capital costs, the operational cost (cost per ha) of using this method was found to be low because of the high productivity, which dilutes the higher fixed costs. Although the model developed in this study considers the tractor spray rig with lances method as the best, the decision maker needs to consider the limitations of using this method (especially terrain). Where applicable, a combination of this method with other alternatives may be considered. It is important to note that if labour costs increase drastically in future the outcomes of the B/C ratios may shift from manual to mechanised alternatives.

5. Conclusions

The study proved that AHP combined with benefit cost analysis can be used by forestry decision makers to select the best re-establishment method for eucalypt plantations. The criteria and sub-criteria weightings guide the decision maker in prioritizing important characteristics that need to be fulfilled by the alternatives. Results from the illustrative example showed that when considering non-financial benefits only, the mechanised and semi-mechanised re-establishment alternatives were the best, mainly because they acquired better ratings compared to manual methods based on the specified criteria. However, when it came to the benefit cost analysis, manual methods in all re-establishment activities except weeding before and after planting generated better returns economically because of the generally lower cost of performing manual activities.

In South Africa, re-establishment activities performed manually are progressively being mechanised. Decisions to change from manual to semi- or fully-mechanised methods are complex and require in-depth analysis of the various factors involved. The AHP decision model will assist decision makers to choose the best re-establishment methods to use in their plantations based on their specific criteria (risk factors) and landowner objectives. Although AHP is reliable, it requires accurate data to guide the decision maker correctly. Scientific data on a specific subject area may not be available which may lead to unreliable or incorrect predictions. However, this shortcoming is overcome by using a well experienced panel of experts who can make well informed recommendations where there are data gaps.

Future research on this subject area would benefit from focussing on using different expert groups and comparing their findings. In addition, the AHP could be compared to other multi-criteria decision analysis (MCDA) tools.

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ANNEXURE 1. MACHINE COST ASSUMPTIONS

Note: Only direct costs included in the costing – excludes overheads

1. Forest resource

Annual re-established area for costing	1200 ha
Average compartment size	40 ha
Tree spacing (planting density)	3 x 2m (1 666 trees ha^{-1})
Average slope	Flat (0 – 20%)

2. Capital costs

Interest	10% (prime 11/12/2019) +3% = 13% (South African Reserve bank 2019)
Exchange rate	1$ = R14.75 (11/12/2019)
Profit and overheads	0%
Licensing and insurance	2% of machine price per year
Resale value	10% - forestry equipment 20% - labour carriers
Depreciation period	60 months

3. Running cost of machines

Diesel price	R14.59 /litre
Diesel consumption	MPAT: 3/mhr (38KW) Tractor: 16l/mhr (65KW) Mulcher Tigercat M726: 35l/mhr (275KW)
Oil price	R62/litre
Oil consumption	MPAT: 5% Tractor: 7% Mulcher Tigercat M726:5%
Repair and maintenance cost* *Repair and maintenance cost used in the costings include **total cost** of purchasing and running a full workshop and doing daily infield maintenance on the machines. However, the repair and maintenance figure does not distinguish between labour cost, back-up vehicle cost and cost of spare parts	80%

4. Running cost of machines (cont'd)

Equipment purchase costs	MPAT: R1 144 478 Tractor New Holland 6610 : R546 560 Planting trailer ANCO GP3000: R335 000 Mulcher Tigercat M726: R6 603 900 Tools Stihl earth Auger: R11 500 Planting backpack unit: R2 695 Fertilizer forks (galvanized): R2 000 Fertilizer backpacks R7 000 Tractor boom spray rig R50 000 Tractor mounted windbox rig R95 000
	MPAT: Tracks Life: 4000mhrs, R30 000 (set) Tractor New Holland T160: Front tyres 6 000/tyre @ 4000 hrs Rear tyres R10 217/tyre @ 4000 hrs Trailer ANCO GP3000: R335 000 Trailer tyres 9 000/tyre @ 6000 hrs Mulcher Tigercat M726: Life: 6000mhrs, R250 000 (set)
Equipment life	15 000hrs
Machine moves per year	10 moves @ R5,000 per move, MPAT only Assumption is that tractor, trailer and wheeled mulcher will drive to various compartments

5. Wages and work days

Wages per month	Manual labour R3 500 (R18/hr national minimum wage 2019) Machine operator R7 800
Production days per year	260
Shifts per day (9-hour shifts)	Manual operations x 1 shift Tractor trailer planter x 1 shift MPAT x 2 shifts Mulcher x 1 shifts
Days per working week	5 days

6. Productivity

(i) Manual operations	*Productivity assumptions**
○ Residue management • Burning • Broadcast	Average man-days per hectare (m/ha): ○ 1.4 m/ha ○ 2.4 m/ha
○ Preparation of a planting position • Manual (pick) • Earth auger	 ○ 4.2 m/ha ○ 2.4 m/ha
○ Weeding before planting • Manual clearing • Chemical application with knapsack	 ○ 2.4 m/ha ○ 2.1 m/ha
○ Planting • Manual (hoe/trowel) • Planting tube	 ○ 3.9 m/ha ○ 3.3 m/ha
○ Fertilizing • Manual (stick/trowel) • Fertilizer fork • Fertilizer backpack • Fertilizer tablet	 ○ 1.9 m/ha ○ 1.4 m/ha ○ 1.9 m/ha ○ 1 m/ha
○ Weeding after plant • Manual (hoe/slashing) • Chemical application with knapsack /(cones)	 ○ 3.1 m/ha ○ 2 m/ha / 2.8m/ha

(ii) Semi- and fully-mechanised operations	*Productivity assumptions*
○ Residue management • Mulch	 ○ 2.5 ha/ shift
○ Preparation of planting position • MPAT single pitting head machine	 ○ 1.5 ha/shift (2500 plants/ shift)
○ Weeding before planting • Tractor-mounted boom spray	 ○ 3.92 ha/shift
○ Planting • Tractor-trailer planter	 ○ 5.94 ha/shift (9902 trees)
• Wasserplanzer	○ 1.73 ha/shift (2884 trees)
○ Weeding after plant • Tractor-mounted windbox	 ○ 7.3 ha/shift (0.82 m/ha)