

ORIGINAL ARTICLE

A forecast of future silviculture re-establishment technologies in plantation forestry

Previsão das tecnologias futuras na silvicultura de florestas plantadas

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Abstract

Technology is rapidly advancing and in forestry new innovations are increasingly being integrated into operations such as silviculture re-establishment (regeneration), harvesting and processing. The goal of this study was to identify eucalypt re-establishment technologies which will become important from 2018 to 2040 and to forecast the date on to when 50% of the technologies would be adopted in new forest machinery. The Delphi technique was used to systematically elicit expert opinion on possible future re-establishment technologies which have the highest probability of being adopted in operations. The process involved the distribution of a questionnaire to 24 experts in the field of silviculture re-establishment in plantation forestry. Results from the Delphi revealed that future technology development in re-establishment would be directed to four main areas, namely: (i) machine development (ii) material input innovations (iii) machine operator advances and (iv) computerized technology applications. Within these broad technology areas, 18 specific technologies were identified and forecasted. 15 technologies were forecasted to reach 50% adoption by 2025 and one technology was identified as already adopted. Two technologies were identified as highly unlikely to be adopted in future. Forecasting future technological advances in re-establishment is important because it enables forest growers to plan, strategize and take decisions to deal with future changing environments.

Keywords: Technology; Re-establishment; Adoption.

Resumo

A tecnologia está avançando rapidamente e as inovações florestais estão cada vez mais integradas às operações silviculturais, como a talhadia, colheita e processamento. O objetivo deste estudo foi de identificar tecnologias de condução florestal que serão importantes de 2018 até 2040, além de prever a data em que 50% das tecnologias serão adotadas em novos equipamentos. A metodologia Delphi foi utilizada para obter, sistematicamente, a opinião de especialistas sobre a probabilidade de as novas tecnologias serem adotadas nas operações florestais. O processo envolveu a distribuição de um questionário a 24 especialistas em silvicultura de florestas plantadas. Os resultados do Delphi revelaram que o desenvolvimento de tecnologias futuras seria direcionado a quatro grandes áreas: (i) desenvolvimento de máquinas (ii) novos materiais (iii) aperfeiçoamento nos operadores de máquinas (iv) adoção de tecnologias computadorizadas. Dentro dessas grandes áreas, 18 tecnologias específicas foram identificadas e previstas. Quinze tecnologias foram previstas para atingir 50% de adoção até 2025 e, uma tecnologia foi identificada como já adotada. Duas tecnologias foram identificadas como altamente improváveis de serem implementadas no futuro. A previsão de futuros avanços tecnológicos na condução florestal é importante porque permite aos produtores, planejar, elaborar e tomar decisões num futuro com incertezas ambientais.

Palavras-chave: Tecnologia; Plantio; Adoção.

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INTRODUCTION

Globally, the total area of planted forests is 291 million ha which represents seven percent of the world's forest area. Even though the area covered by plantations is relatively small, it contributes 50% to the total global wood supply, which relieves pressure on native forests (Payn et al., 2015; Sands, 2013). Between 2010 and 2015 the average annual rate of increase in planted forests was 3.2 million ha year⁻¹ (Food and Agriculture Organization of the United Nations, 2016). Some of the main change drivers putting pressure on the forest resources globally are population growth, growth in per capita income and climate change (Blaser & Gregersen, 2013). It is therefore important that planted forest areas that are harvested for commercial purposes are re-established shortly after harvesting in order to meet the growing timber demand. One of the main aims of silvicultural re-establishment in pulpwood stands is to achieve full tree stocking at the lowest possible cost (Pallett, 2005). Due to the length of the rotation, it is important that labour and material costs invested in silviculture work during stand establishment result in maximum returns at the end of the rotation (Uusitalo & Pearson, 2010).

In plantation forestry, re-establishment activities include practices such as site preparation, tree planting and stand tending (Theron, 2000; Viero & Du Toit, 2012). Site preparation encompasses the treatment of harvesting residues (e.g. burning, broadcasting, mulching, biomass harvesting etc.) and soil preparation (ripping, pitting, sub soiling, scarifying etc.) before and at planting (Gonçalves et al., 2008; Theron, 2000). Tree planting is the practice of inserting the plants roots into the soil up to the root collar and ensuring the tree is upright and firm (Evans & Turnbull, 2004). Coppice regeneration is an alternative to replanting, it is common to coppice eucalypt plantations because it is cost effective even though the yields maybe lower in some instances (Viero & Du Toit, 2012). Stand tending is an important part of re-establishment. It involves activities such as weed control, fertilization, management for tree protection (biological/physical e.g. ant control in Brazil), pruning and pre-commercial thinning (Schönau, 1989; Zanetti et al., 2003). In this research, stand tending operations considered did not include post planting activities such as pruning, commercial thinnings, or ant control (in Brazil).

To follow current and future technology developments during re-establishment, it is important to assess what happened in the past. In 2018, it is estimated that about 85 percent of re-establishment operations around the world were conducted manually (Choudhry & O'Kelly, 2018). Out of the total mechanised portion, soil preparation is the re-establishment activity that has the highest level of mechanisation (Evans & Turnbull, 2004), primarily due to the use of machinery such as rippers, moundsers, scarifiers, disc trenchers and pitting machines (Hechter, 2019; Hjelm et al., 2019). Efforts to mechanise silviculture re-establishment operations began during the mid to late 1900s (Armitage, 1979; Baker, 2018; Germishuizen & Vos, 1979; Silversides, 1984). During this period, countries like Sweden and New Zealand focused on silviculture mechanisation due to actual or perceived future labour shortages and increasing labour costs. However, as time progressed the forecasted labour shortages were not as high as predicted (Baker, 2018). When compared to site preparation, mechanised planting has not been widely adopted mainly because of low cost competitiveness compared to manual planting. This is mainly due to low productivity, terrain constraints, regular relocation between sites and the need for frequent reloading of the planting head with seedlings (Ersson, 2014).

Re-establishment practices differ around the world because of variables such as: regional preferences, terrain conditions, physiography, climate, labour availability and capacity, tree properties and management regimes (Silversides, 1984). For instance, soil preparation is conducted by ripping in Australia (Dickinson et al., 2005); scarifying, disc trenching and mounding in Sweden (Royal Swedish Academy of Agriculture and

Forestry, 2015; SVEASKOG, 2015); ploughing, harrowing, terracing and pitting in China (Richardson, 1990; Turnbull, 2007) and predominantly pitting in South Africa (Smith et al., 2000). Due to research and technology improvements, these methods have evolved and progressed over time to how they are currently practiced, however, the lack of uniformity in re-establishment activities globally has led to fragmentation and limited mechanisation in silviculture (Silversides, 1984).

Globally, technology is widely available across different industries and it is continually evolving to improve the manner in which various activities are performed (Hetemäki & Nilsson, 2005). Over the past decade, investment in new technologies in forestry and other industries (e.g. agriculture) has been revolutionizing the manner in which forests are managed. Even though forestry has lagged behind in adopting technologies which improve efficiencies, there is now progress in “precision forestry” and the need to improve efficiency and remain sustainable (Choudhry & O’Kelly, 2018). According to Taylor et al. (2002), precision forestry is defined as “planning and conducting site specific forest management activities and operations to improve wood product quality and utilization, reduce waste, increase profits, and maintain the quality of the environment”.

Advancements such as the use of geospatial technologies (GPS and GIS) (Husband, 2010) to improve efficiency and reduce the costs of wood production have become more important in managing forest operations (Taylor et al., 2002). Other advanced precision technologies that have been investigated in re-establishment operations include automation of regeneration machines (Lideskog, 2018) and the use of remote sensing technologies to accurately measure forest structural characteristics (Dubayah & Drake, 2000). Merging these technological advances with the ecological characteristics of the forest site (e.g. soil characteristics, competing vegetation dynamics and stand nutrient needs) provides support for strategic, tactical and operational silviculture decision making both currently and in the future (Rubilar et al., 2018). In contrast, even though precision technology is available, the forestry industry presents unique physical challenges which restrict technology adoption such as: steep terrain, sensitive soils, and remote locations (Parker et al., 2016). Despite these challenges, optimal use of technology can support higher productivity, increase quality of output, and improve working conditions (International Labour Organisation, 2019).

The increasing economic, environmental and public demands from plantation forests necessitate the use of technology (Buvanewaran et al., 2015). Unfortunately, the external environment in which the forestry industry exists currently presents a complex web of interrelated and interdependent factors which are broadly categorised under technology, economic, social and political (Twiss, 1992ba). Out of all these factors, the use of technology is a key factor that affects the ability of any organisation to survive and succeed in today’s competitive environment (Hansen et al., 2006). It is therefore important that forest owners are aware of existing technologies and are aware of any opportunities to innovate and improve efficiency in the manner in which trees are planted. Technology forecasting is a process whereby a systematic approach is applied to obtain a better understanding of the future in order to make sound decisions (Twiss, 1992b). Forecasting future technological changes in forestry is complex because a wide variety of technologies are expected to emerge in response to various needs (Nair, 2003) with very little historical evidence to draw upon. Regardless of the complexity and the uncertainty of future events, it is an important to forecast future technology advances as this will enable organisations to guide themselves in the correct direction instead of retrospective reactions to critical events (Twiss, 1992ba).

The Delphi technique is a method used to forecast future re-establishment technologies and their adoption dates. This technique achieves anonymous interaction between carefully selected experts by means of a questionnaire with feedback (Hasson et al., 2000; Twiss, 1992a). The success of any Delphi study is dependent on the selection of the panel participants (Gordon, 1992). According to Oh (1974), the

selection of experts to form part of the Delphi panel is a matter of judgement and discretion by the Delphi administrator or researcher. The optimal number of experts in a panel is dependent on the type of study (Hsu & Sandford, 2007; Ludwig, 1994), however for most purposes 15 to 40 participants is normal with 25 being acceptable (Twiss, 1992a).

The use of this technique was brought into practice by RAND Corporation in the early 1950s to address questions about the military potential for the update of future technology and has subsequently been used in various industries to forecast future technologies through the use of expert opinions (Loo, 2002; Woudenberg, 1991). Many forecasting techniques are available in literature, such as: time series, S-curve of progress, Fisher-Pry, expert judgement, cross-impact analysis, Pareto analysis, benchmarking, brainstorming, scenario building and environmental scanning (Gordon, 1992; Porter et al., 2004; Twiss, 1992b). However, the Delphi method is preferred because it is most suitable for making long range forecasts and determining new technologies (Twiss, 1992b) and has been used in several forestry studies (Brink, 2001; Egan & Jones, 1997; McEwan, 2016; Riala & Asikainen, 2012). The Delphi process comprises of three main processes, namely: preparation, survey in two or more rounds; and application.

Several studies have focused on forecasting future harvesting technology and systems (Brink, 2001; McEwan, 2016), but none have investigated future trends in silviculture re-establishment technologies. The goal of this study is to identify eucalypt re-establishment technologies which will become important from 2018 to 2040 and to forecast the date on to when 50% of the technologies will be adopted in new forest machinery. This study is important as it will create awareness about technologies that may impact the forestry industry in the future and also help forest practitioners to plan and strategize how they can integrate new and emerging technologies into their operations, thereby improving efficiency in the manner in which forest plantations are managed.

METHODS AND MATERIALS

Identification of emerging and future technologies

A comprehensive literature review on existing and future re-establishment technologies was conducted, however, due to gaps in the literature, 30 semi structured interviews were also conducted (face to face and Skype) to fill the gaps. The interviewed experts were from Australia, Brazil, Canada, China, South Africa, Sweden and the United States of America. The experts were from different professions, and because the interviews were semi structured the respondents could provide reasons why they thought a particular technology would become important in the future. Some of the interviewed experts were also invited to become part of the Delphi panel. To further identify key technologies the researcher attended equipment and technology exhibitions such as Expoforest in Brazil, Focus on Forestry and NAMPO in South Africa. Over and above identifying current and emerging technologies, the preparation work assisted the researcher to identify experts who would form part of the Delphi panel.

Delphi expert panellist selection

A total of 31 silviculture re-establishment experts primarily from the Southern hemisphere were invited via e-mail and telephone to form part of the Delphi panel: 24 of them were willing to participate and joined the study. An expert in the context of this study was described as a person with in-depth knowledge and skill in the specific area of silviculture re-establishment technology (Soanes, 2002). The experts were

assured of anonymity by explaining the Delphi process and informing them that none of their statements would be directly attributed to their name. The experts were identified through general industry contacts, reading literature, visiting exhibitions and through referrals from other experts. The panel comprised of experts from South Africa (63%), Brazil (33%) and Uruguay (4%). Because the focus of the research was on future re-establishment technologies used in eucalypt plantations, Brazilian experts were chosen as key contributors due to Brazil's large scale commercial eucalypt plantations and for leading technology developments in re-establishment (Gonçalves et al., 2008). All the experts were from diverse forestry professions such as equipment manufacturing and sales (33%), foresters (29%), forest machine technology development (17%), silviculture contractors (13%), forest consultants (4%) and academia (4%). The experts had experience ranging from a minimum of five years to over 30 years.

Questionnaire build up

The Delphi questionnaire was created in a Microsoft Excel spreadsheet and it contained an introductory part stating the objective of the questionnaire, the scope of the research, the structure of the questionnaire and the research design. A cover letter which accompanied each questionnaire described upfront what was expected from the expert. The main questionnaire was divided into two parts: part one required biographical information and the second part comprised of various technologies that the experts had to forecast (Table 1). The experts were required to forecast 50% adoption dates of the technologies provided only if they agreed that the technology was emerging.

Table 1: Delphi questionnaire main sections

Section no	Main section	Sub sections
	Introduction	Study information, name, gender, preferred e-mail address, main expertise, experience, country, main re-establishment method, rotation length, industrial use of plantation timber, silviculture knowledge background, Name reporting, feedback requirements
	Delphi questionnaire	Main technology categories which comprise of specific technologies which the experts had to forecast (Refer to Delphi questionnaire technology descriptions)

Delphi Questionnaire technology descriptions

The 18 technologies included in the first-round questionnaire were divided into four broad technology categories which were: machine specific technical innovations (five technologies), material input innovations (four technologies), machine operator specific innovation (four technologies) and computerized technology applications (five technologies) (Table 2). The results section is structured according to the technology categories specified in this section.

Pilot study

According to Skulmoski et al. (2007) a pilot study is important to estimate the scope of the research and the amount of time needed to complete it. Five participants (20% of the sample total) were used to test and adjust the Delphi questionnaire. The pilot sample was deemed sufficient by the experienced researchers (Hertzog, 2008). The pilot study participants were not part of the main Delphi study panel. Based on the feedback from the participants, improvements were made to the questionnaire to make the instructions clearer and certain technologies were described more comprehensively to prevent any obscurity in the questions.

Table 2: Description of re-establishment technologies in Delphi questionnaire

Technology category	Specific technology	Description
Machine specific innovations	Multifunctional machines	Integration of traditionally separate re-establishment activities into one or two pass practicable operations on a machine
	Machine terrain handling enhancements	Technologies to enable re-establishment equipment to handle poor soil conditions, rougher ground conditions and steeper slopes e.g. levelling machines
	Machine automation and robotics	Machine's ability to perform certain re-establishment tasks with minimal human assistance
	Application of drones to monitor and conduct some re-establishment activities	Drones with hyper-spectral, multispectral, or thermal sensors that can monitor the health and density of forest stands. Drones to perform re-establishment activities e.g. chemical spraying
	Machine self-diagnosis and maintenance	Remote monitoring, data collection and self-diagnosis which encompasses reconfiguration, troubleshooting and self-maintenance with very little human input
Material inputs innovation	Paper based plant pots	Containerised trays with degradable ellepot paper
	Advance chemical application	Optical and vision systems for weed sensing
	Nano fertilizers and fertilizer tablets	Nano meter regime that delivers nutrients to crops and compressed, nutrient-rich tablets that supply nutrients
	-Ultra low emission engines - Hybrid electric power systems	Tier 5 diesel particulate engines for re-establishment equipment and the development of electric and hybrid drives over traditional hydraulic and mechanical ones
Machine operator specific innovations	Ergonomically friendly cabs	Operator cab with improved lighting, low vibration, temperature control options, better posture and enhanced range-of-motion and positioning
	Simulation training	Virtual reality, augmented reality, mix reality integrated with artificial intelligence to train the operator
	Artificial intelligence	Simulation of human thinking and decisions by re-establishment equipment
	Advance human-machine interfaces	Multi-touch enabled interfaces, gesture recognition, eye tracking and voice control. Machines controlled by using the mind/ muscular electrical activity.
Computerized technology applications	Real time machine monitoring	Telematics for tracking machines performing at a remote location e.g. machine productivity, fuel usage and chemical applied
	Real time stand assessment	LIDAR data to apply precise quantities of various inputs required during re-establishment operations
	Operator behaviour and performance monitoring	Digital platforms on-board re-establishment equipment to monitor key operator variables such as work performance for benchmarking and machine usage
	Processing and application of big data	Supportive technology for processing and application of historic big data (from GPS and on-board systems) to improve overall performance of machines
	Remote-control of operating machines	Radio controlled devices use to remotely operate machines

Delphi rounds

The Delphi followed an iterative process in which responses from each questionnaire round were provided as feedback in a concise form to the experts. Therefore, after all responses from the first round were received, the researcher analysed the range of responses and presented it back to the group together with any comments (Davis, 2007). According to Hsu & Sandford (2007), the feedback process allows and promotes the selected Delphi experts to reassess their earlier estimations. Therefore, the results of previous estimations regarding certain technology predictions could be modified by an individual expert based on forecasts and comments provided by other Delphi panellists members. This cycle underwent three iterations. For those participants that could not agree, their reasons were made clear when reporting the results.

The first-round questionnaire comprised of 18 technologies derived from interviews and literature, but it made provision for the experts to add any other technologies which were considered to hold future promise. For each technology two questions were asked: (i) "Is this an emerging or possible future technology in re-establishment operations?"

The experts had the options to select: "Yes", "No" or "Already adopted". If the expert indicated that the technology was not a possible future technology, they were not required to proceed to the next stage of forecasting but had to move on to the next technology. However, if the expert indicated that the technology was already adopted, or it was a possible future technology, then the expert had to respond to the next question which was:

(ii) "In what year do you estimate that 50% of new re-establishment machines or systems will have adopted this technology? Provision was made for the expert to indicate earlier adoption years (before 2018) and to forecast later years (> 2040)."

The last section under each technology made provision for comments. The experts could use this section to provide reasons for their predictions or to add a general comment about the specific technology.

In the second round each expert received a questionnaire which was structured much like the first one. For this round the experts were asked to review the summary of forecasts and comments for each technology based on the information provided in the first round. The mode was used to show each expert where their forecast was laying relative to the rest of the panel. The upper limit year for each category year range was used as category descriptor because during the first round most of the experts forecasted the years of adoption in five year intervals (e.g. 2025, 2030, 2035) (Table 3).

Table 3: Adoption year categories and descriptions for Delphi 2 and 3

Category	Category range description
No	The technology will NOT be adopted at the 50% level anytime in future
2018	The technology has already been adopted at the 50% level in the past or will be adopted by 2018 latest
2020	The technology will be adopted at the 50% level between and including the years 2019 and 2020 latest
2025	The technology will be adopted at the 50% level between and including the years 2021 and 2025 latest
2030	The technology will be adopted at the 50% level between and including the years 2026 and 2030 latest
2035	The technology will be adopted at the 50% level between and including the years 2031 and 2035 latest
2040	The technology will be adopted at the 50% level between and including the years 2036 and 2040 latest
Future	The technology will be adopted at the 50% level in the far future after the year 2040

For each of the 18 technologies the expert was presented with three options: "(i) choose to alter the first round prediction by selecting a new adoption year range; (ii) if the first round prediction was different from the majority of experts, and the expert believed their prediction was more accurate, the expert could maintain the first round prediction but had to write a brief comment explaining the reasons for the prediction; (iii) leave the first round prediction unchanged and make no comments".

The third round questionnaire was structured as for the first and second round questionnaires but only included the summarised year forecasts and comments from round two. Likewise, the third round offered the same options as the second, and the experts had an opportunity to revise predictions and also provide reasons if their prediction lay outside the majority prediction.

The overall response rate was excellent, with only one expert not proceeding beyond round 1.

Data analysis

According to Hasson et al. (2000), when analysing response data from a Delphi study the aim is to detect convergence and change after each round. In Delphi studies there is no single definition of consensus and it is up to the researcher to create a definition (Jorm, 2015). For this study if over 50% of the experts forecasted a specific adoption year it was considered that the experts had reached consensus. For a collective opinion to be derived the use of descriptive and inferential statistics is required. Delphi studies are not intended to produce statistically significant results because the views provided by the expert panel do not predict the views of the larger population (Gordon, 1992).

Data from each round was summarised per item by producing frequency histograms which were circulated back amongst the experts as feedback in the third round. Central tendencies (mode) and percentage change in predictions between Delphi 1 and Delphi 3 iterations were carried out. The percentage change was calculated as a percentage of the respective percentages in order to balance for the different number of respondents. The qualitative data from the comments section was summarised for each round and used to substantiate the quantitative results. Histograms showing detailed 50 percent adoption frequencies for various years for all three Delphi rounds are attached as supplementary information.

RESULTS AND DISCUSSION

Study limitations

The study comprised of predominantly South African and Brazilian experts and therefore the forecast is more specific to these two countries. Unless otherwise mentioned in the results, the forecast predictions were for both South Africa and Brazil. Forest practitioners involved in plantation forestry in other countries can adapt the findings of this research based on technology adoption rates in their specific countries. Expanding the panel to include more countries would have likely resulted in a more extensive forecast, but it would also have also introduced additional country specific variables which could introduce inaccuracies to the forecasts.

The results are presented according to the categories used to classify the technologies. The four technology categories: machine specific technical innovations, material inputs innovation, machine operator specific innovations and computerised technology applications are described and the specific technologies relating to each category are then discussed. No additional technologies were suggested to the technology list supplied by the researcher.

Machine specific technical innovations

This specific category grouped technologies designed to improve the operational efficiency of equipment.

All 23 experts responded to the predictions for all five technologies in this category. The mode for 50% adoption of multi-tasking, improvement in terrain handling, drones and self-diagnosis technologies is “2025”. The mode for 50% adoption of automation technologies is “2030” (Figure 1). The percentage changes between the first and third iterations of multi-tasking and terrain improvement technologies indicate that as the discussions proceeded, predictions favoured earlier adoption years of “2020” and “2025” (Table 4). Most experts forecasted 50% adoption of automation further into the future, with 39% and 22% of the respondents predicting “2030” and “2035” respectively.

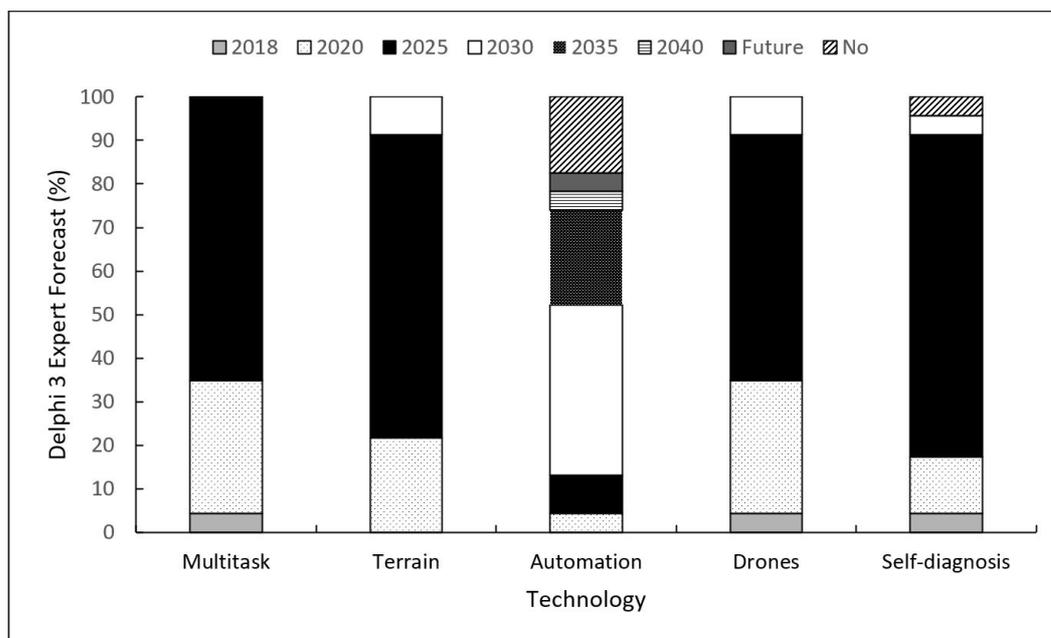


Figure 1: Delphi 3 forecasts for 50% adoption of machine specific technologies

Table 4: Change in preference for machine specific technologies between Delphi 1 and Delphi 3 represented as a percentage of Delphi 1 respondents

Category	Multi-task	Terrain	Automation	Drones	Self-diagnosis
No	0%	-100%	-40%	-100%	-48%
2018	-65%	-100%	0%	0%	-48%
2020	83%	67%	4%	40%	4%
2025	30%	33%	-48%	-7%	48%
2030	-100%	0%	17%	0%	-74%
2035	-100%	0%	74%	0%	-100%
2040	-100%	-100%	4%	-100%	0%
Future	0%	0%	0%	0%	0%

The respondents commented that multi-tasking technology is already in place within some operations in Brazil wherein soil preparation is done in conjunction with fertilizing and the application of pre-emergents but the integration of complete planting still needed time to fully develop. During Delphi 1 a few respondents believed that this technology had already been adopted at the 50% level whilst a total of five experts (21%) estimated it would only be adopted by “2030” and beyond, however by Delphi 3 most of these experts had revised their predictions to “2020” and “2025”. Regarding the 50% adoption of technologies to enhance terrain handling abilities, some respondents (13%) indicated that this technology

has already been adopted in harvesting equipment; but the major limitations in silviculture could be the cost of the equipment leading to a limited volume of sales for such equipment.

The respondents had various views about the adoption of automation technology in re-establishment equipment. The Brazilian experts were in favour of its early adoption “2030” and believe that as the agriculture sector uses it more, the forestry industry will adapt accordingly. The South African experts forecasted that this technology would be adopted five years later (“2035”) in South Africa. Those who argued that it would not be adopted said automation and the use of robotics in silviculture could be restricted by social responsibility challenges such as job losses, high investment costs and an overall resistance to change.

During the discussions around the future adoption of drone technology for re-establishment operations, the respondents commented that this technology can be used for two different purposes: (i) monitoring and (ii) conducting of re-establishment activities. In terms of forest monitoring (e.g. detecting of pests and diseases) most respondents believe drones have been tested and application is happening at a rapid rate, but the use of drones for re-establishment would mainly be limited to chemical or pesticide spraying operations. One respondent from South Africa cautioned that the use of drones could be delayed by barriers in entry by Civil Aviation Authorities (CAA) in acquiring pilot licenses and remote operator’s certificates.

Material inputs innovation

This specific category focused on future technologies that could be used with re-establishment material inputs (e.g. plants, chemical and fertilizer). These material inputs can be used independent of, or in conjunction with, modernised equipment.

All 23 experts responded to the predictions for paper-based pots and low emission engine technology, with 22 experts responding to optimised chemical application and Nano fertilizer technology predictions. The mode for 50% adoption of paper based pots, optimised chemical application, Nano fertilizers and low emission engines technologies is “2025” (Figure 2). For paper-based pots and optimised chemical application the experts forecasted earlier adoption years (“2018” and “2020”) in Delphi 1 but their opinions were swayed during the iterations to a later adoption date of “2025” (Table 5). The majority also predicted that 50% adoption will be achieved in the same time span for Nano fertilizers and low emission engines even though some of the experts doubt that this will ever be the case by “2025”. Interestingly, the reiterations led to very small prediction changes when it came to low emission engines which indicated that the experts had strong views about this technology.

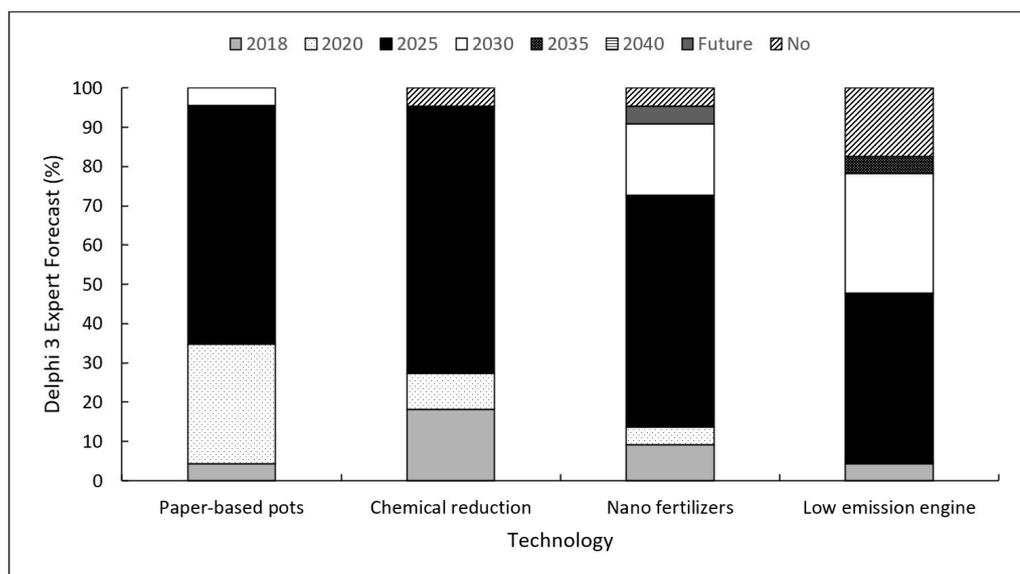


Figure 2: Delphi 3 forecasts for 50% adoption of material innovation technologies

Table 5: Change in preference for machine technologies between Delphi 1 and Delphi 3 represented as a percentage of Delphi 1 respondents

Year	Paper-based pots	Chemical reduction	Nano fertilizers	Low emission engines
No	-100%	0%	-67%	-9%
2018	-85%	-33%	-50%	0%
2020	265%	0%	0%	-100%
2025	33%	36%	30%	1%
2030	-48%	-100%	0%	-9%
2035	0%	-100%	0%	0%
2040	0%	0%	0%	0%
Future	0%	0%	0%	0%

The South African experts commented that paper-based pots technology would increasingly become adopted in South Africa resulting in better survival, growth and increased efficiency at the nursery due to the absence of traditional plastic tubes. However, the Brazilian experts indicated that this technology could take a bit longer to adopt, as old nursery structures would have to be depreciated before the full introduction of this technology. One respondent from South Africa mentioned that paper pots are a necessity if growers want to mechanise planting operations. Concerning the adoption of advanced chemical application technologies, most of the respondents commented that this technology would mainly be driven by certification and societal pressure to find more efficient ways to use chemicals and eradicate weeds. The respondents (18%) who considered the technology as already adopted, argued that the use of pre-emergents had drastically reduced the use of chemicals.

The respondents commented that the use of Nano technology is expensive and a 50% adoption of this technology could thus take some time. Meanwhile the respondents indicated that the use of fertiliser tablets where spot cultivation is practiced extensively will become important in the future, but with continuous soil cultivation, tablet technology would be complex to integrate. As the discussions proceeded there were no major forecast changes except for the reduction in respondents who believe that Nano technology and fertilizer tablets will never be adopted, or that it would be adopted by "2020".

Combining low emissions engines (Tier 5) and hybrid electric engines may have caused the diversity in predictions and opinions observed for engine technology, because these are in fact two different technologies. Nevertheless, some respondents commented that the use of low emission diesel engines such as Tier 4 and Tier 5 would be adopted by "2025" whereas the adoption of hybrid electric systems would not be practical for forestry in the near future. Two respondents (one Brazilian and one South African) added that they rather foresee technology improvements in this area being focussed in having more efficient hydraulic systems, pumps, valve and motors combined with the use of smaller engines because lighter duty forestry machines have historically been designed with oversize engines.

Machine operator specific innovations

This specific category focused on future technologies designed to improve operator efficiency and well-being when using a machine to perform any re-establishment operations.

All 23 experts responded to the predictions for all four technologies in this category. The mode for 50% adoption of ergonomically friendly cabs is "2018" (currently in place) and the mode for simulation training and machine learning is "2025". Interestingly, half of the Brazilian experts predicted that simulation training will be adopted in Brazil by "2020". The mode for advanced human interface technologies is "No" (Figure 3). When making predictions for the adoption of simulation training technologies the experts swayed more to "2025", as opposed to the initial views that the technology would never be adopted. The majority (74%) of the experts believe that advance human interface technology will never be

adopted in the future and as the reiterations proceeded more experts who forecasted later adoptions dates changed their predictions and supported the majority prediction (Table 6).

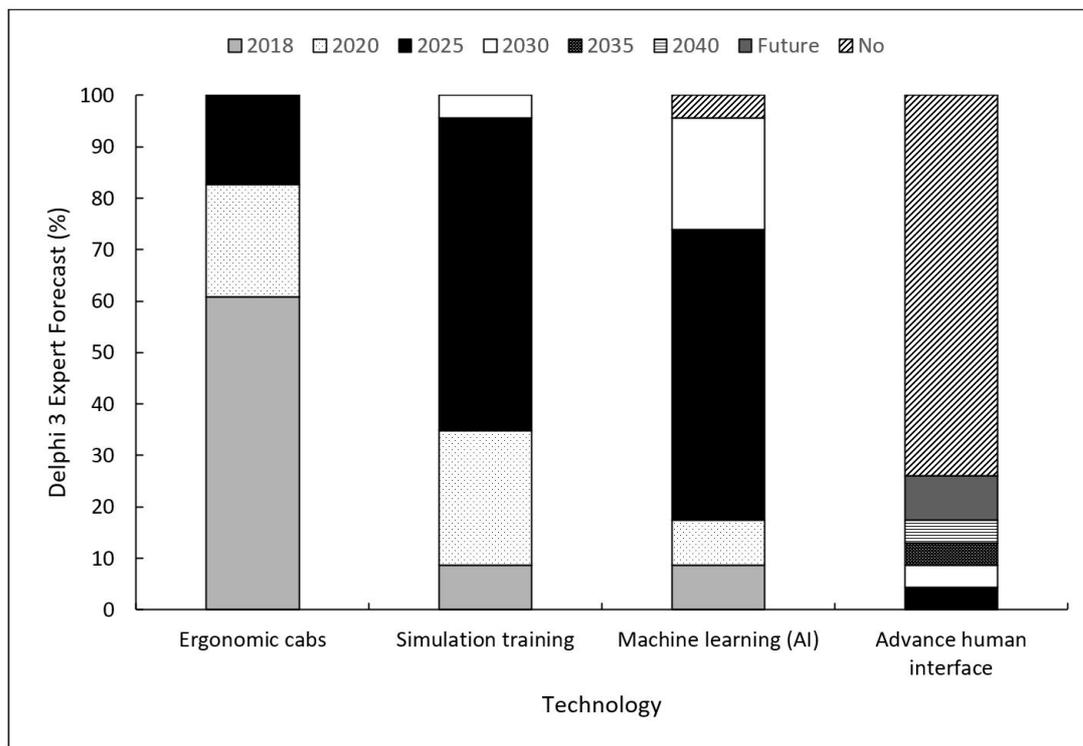


Figure 3: Delphi 3 forecasts for 50% adoption of operator specific technologies

Table 6: Change in preference for machine technologies between Delphi 1 and Delphi 3 represented as a percentage of Delphi 1 respondents

Year	Ergonomic cabs	Simulation training	Machine learning	Advance human interface
No	0%	-100%	-52%	25%
2018	8%	-52%	91%	0%
2020	67%	15%	-36%	0%
2025	-33%	34%	13%	-68%
2030	-100%	-52%	59%	-52%
2035	0%	0%	-100%	-52%
2040	0%	0%	-100%	0%
Future	0%	0%	0%	-4%

The experts commented that due to re-establishment operations using equipment adapted from agriculture, or purpose-built equipment, the use of ergonomically friendly cabs had already been widely adopted, even though some older machines do not meet all ergonomic standards. Respondents forecasting the adoption year of “2020” increased from three (Delphi 1) to five (Delphi 3) respondents. The respondents who forecasted “2025” decreased from six (Delphi 1) to four (Delphi 3). Concerning the adoption of simulation training, two experts (Brazilian and South African) commented that this technology is currently under development in countries such as Europe and North America, but there was a general understanding amongst the remaining experts that this technology would still require time to implement in the Southern hemisphere plantation forestry setting, even though this technology is used extensively in harvesting.

The experts also had strong views on the adoption of artificial intelligence and machine learning technologies. One South African expert said “machines are being developed to use these techniques to detect the positions of seedlings, obstacles and other trackable factors. This is only the beginning, when a technique as powerful as AI and machine learning emerges as a practical solution to some problems, it typically opens doors to other functionalities that were once deemed impossible or unimaginable. We saw this with the integration of electronics for machine controls, which snowballed into what seems to be endless possibilities for machine controls.” A Brazilian expert mentioned that this technology will improve considerably with the growth and development of purpose-built re-establishment machines. Most of the experts had extreme reservations about the adoption of advance human interface technologies and considered this technology as irrelevant and of no benefit in re-establishment operations. One South African expert commented that this type of technology would be the pinnacle of the fourth industrial revolution but there were still serious moral and ethical boundaries to its implementation.

Computerized technology applications

This specific category focused on future technologies that would be dedicated to modernising computer based digital platforms for mainly monitoring, management and remote accessibility.

The mode for 50% adoption of real time operation monitoring, real time stand assessment, real time operator monitoring and big data processing is “2025”. The mode for Remote-control of machines is “No” and “2025” (Figure 4). Even though the majority of experts predict that real time stand assessment, real time operator monitoring and big data processing will reach 50% adoption by “2025” some experts are of the view that these technologies will never be adopted or will only be adopted by “2030”. The iterations seemed to move the expert’s predictions towards “2025” as opposed to early (“2018” and “2020”) or later (“2030”) adoption (Table 7). There is a clear distinction between two groups with equal number of experts in the prediction of remote-control technologies, one group (35%) believes this technology will never be adopted whilst another group (35%) believes that 50% adopted will be reached by “2025”. The remaining experts (26%) believe that 50% adoption of this technology will be reached by 2030. As the discussions proceeded some experts changed their predictions from “No” to supporting a 50% adoption rate by the year “2030”.

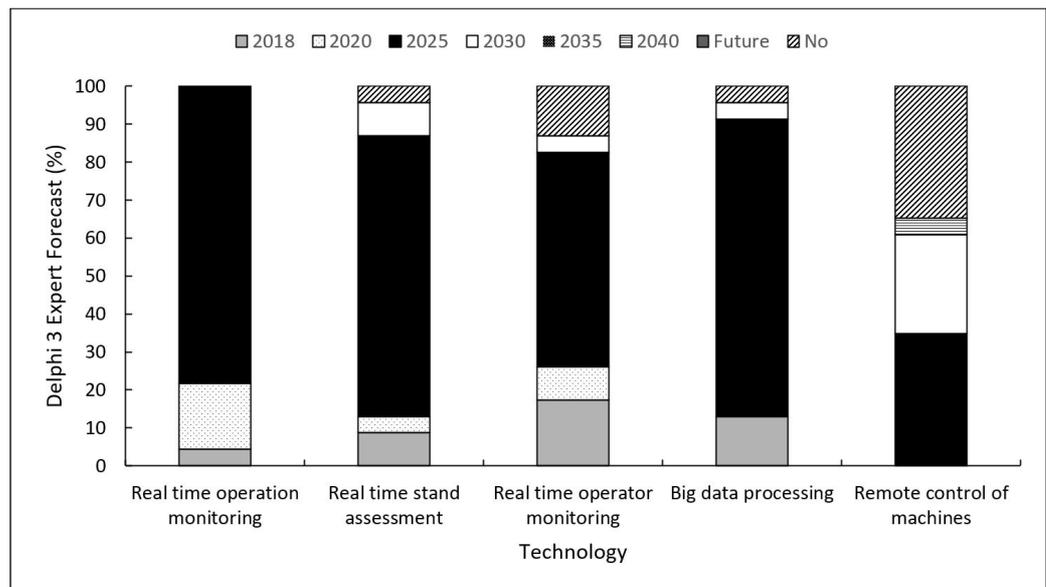


Figure 4: Delphi 3 forecasts for 50% adoption of computerized technologies

Table 7: Change in preference for machine technologies between Delphi 1 and Delphi 3 represented as a percentage of Delphi 1 respondents

Year	Real time operation monitoring	Real time stand assessment	Real time operator monitoring	Big data processing	Remote-control of machines
No	-100%	0%	0%	-50%	-11%
2018	-50%	-67%	-20%	-40%	0%
2020	-20%	-50%	0%	-100%	-100%
2025	50%	70%	18%	125%	14%
2030	-100%	-33%	-50%	-83%	50%
2035	0%	100%	0%	0%	0%
2040	0%	0%	0%	-100%	0%
Future	0%	0%	0%	0%	-100%

Comments about real time operation monitoring did not change, which was reflected in the lack of change in predictions. The experts believed that use of real time operation monitoring is already taking place but will increase in time due to improved efficiency and reduced costs. Similarly, the experts were confident that the use of real time stand assessment technologies will increase, as the need to improve efficacy in applying material inputs (e.g. fertiliser) on various sites increases; however the accuracy of the system would be dependent on the availability of soil data. In terms of real time monitoring of operators, the experts commented that the technology is still in its early stages of development, but is already being used to a certain extent, and therefore 50% adoption would occur over time. Examples include cameras and tracking devices which monitor operator behaviour. Some experts indicated that even though these technologies are currently being used (mainly as safety measures), in the future they will be used more in identifying operator problem areas and to help improve efficiency.

The experts believe the use of big data will become an important technology in the future, but only if relevant data is collected and it is synthesized with existing systems so that it is usable. With reference to the adoption of remote-control technologies the experts (South African and Brazilian) were divided in opinions and predictions. The experts who predicted that it will never be adopted to the 50% level indicated that the technology will be limited to only very steep terrain, and adoption will be restricted by high costs. Those in support of its adoption in the future believe that this technology will be applied at a limited scale, with more widespread adoption only happening once re-establishment operations are fully mechanised, and if virtual technology is integrated to it. One Brazilian expert commented that remote-control technology will only be relevant and applicable in conjunction with drone type technologies for monitoring and spraying.

CONCLUSION

The study identified eucalypt re-establishment technologies which will become important from 2018 to 2040 and also forecasted the dates when 50% of the technologies will be adopted in new forest machinery. The Delphi findings showed that by "2025" there is a high probability that machine specific technologies such as multi-functional machines, advance machine terrain handling enhancements, drones and machine self-diagnosis and maintenance will reach 50% adoption whilst machine automation and robotics may reach 50% adoption about five years later. By "2025" material input technologies such as paper-based pots, optimised chemical applicators, Nano fertilisers and low emission engines will likely reach 50% adoption. The adoption rates of these technologies will be influenced by the availability of infrastructure, social and environmental pressures as well as legislation imposed by various external stakeholders. Furthermore, the Delphi revealed that the

adoption of operator specific technologies is ongoing and progressive. The experts concluded that the adoption of ergonomically friendly cabs had occurred in “2018” and in “2025” the widespread adoption of simulation training and machine learning technologies can be expected. The Delphi results further indicated that by “2025” real time monitoring of operations, stands and operators as well as big data processing technology will reach 50% adoption. Despite several potential future technologies identified in this study, advance human interface technology and remote-control technologies were identified as highly unlikely to be adopted in the future.

Although one study is insufficient to completely reorient the industry as a whole, this study has exposed key new and relevant technologies that forest owners need to be aware of when they plan for the future. It is recommended that future studies monitor the adoption of the technologies identified in this study and determine if the forecasts were accurate and reliable. Furthermore, future studies can look at common technologies between harvesting, silviculture and agriculture to identify essential synergies.

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