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Research article

Reforestation success can be enhanced by improving tree planting methods

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ABSTRACT

Successful cost-effective reforestation plantings depend substantially on maximising sapling survival from the time of planting, yet in reforestation programs remarkably little attention is given to management of saplings at the planting stage and to planting methods used. Critical determinants of sapling survival include their vigour and condition when planted, the wetness of the soil into which saplings are planted, the trauma of transplant shock from nursery to natural field soils, and the method and care taken during planting. While some determinants are outside planters' control, careful management of specific elements associated with outplanting can significantly lessen transplanting shock and improve survival rates. Results from three reforestation experiments designed to examine cost-effective planting methods in the Australian wet tropics provided the opportunity to examine the effects of specific planting treatments, including (1) watering regime prior to planting, (2) method of planting and planter technique, and (3) site preparation and maintenance, on sapling survival and establishment. Focusing on sapling root moisture and physical protection during planting improved sapling survival by at least 10% (>91% versus 81%) at 4 months. Survival rates of saplings under different planting treatments were reflected in longer-term survival of trees at 18–20 months, differing from a low of 52% up to 76–88%. This survival effect was evident more than 6 years after planting. Watering saplings immediately prior to planting, careful planting using a forester's planting spade in moist soil and suppressing grass competition using appropriate herbicides were critical to improved plant survival.

1. Introduction

Half of the global area previously covered by trees has been cleared since human civilization began (Crowther et al., 2015) contributing to an increase in atmospheric greenhouse gases (IPCC, 2022b). Human pressure continues to damage ecosystems, with 19% of Earth's terrestrial ecosystems deteriorating between 2000 and 2013 and only 6% improving (Williams et al., 2020). Tropical forest cover continues to decline (Pugh et al., 2018) and is anticipated to continue under global warming and land use pressure (Zeng et al., 2013). Restoring forests is challenging but essential to slow global warming (IPCC, 2022a). Global efforts to restore forests include the Bonn Challenge that aims to restore 150 M ha of degraded and deforested lands by 2020 and 350 M ha by 2030 (https://www.bonnchallenge.org/; accessed April 3, 2022) and the Aichi Biodiversity Targets of the Convention on Biodiversity, particularly Target 15 with the specific goal of restoring at least 15% of degraded lands by 2020 (https://www.cbd.int/sp/targets/: accessed April 3, 2022). Neither of these targets were achieved during the United Nation's *Decade on Biodiversity* 2011–2020 (Xu et al., 2021) and the world has entered the *UN Decade on Ecosystem Restoration 2021–2030* where science has been identified as a necessary contributor (Gnacadja and Vidal, 2023). Implementing landscape-scale reforestation has proved to be difficult, partly because of the inadequacy of practical methodologies and the lack of empirical evidence to support best practices (Chazdon and Guariguata, 2018) and it has been recognised that multiple mistakes have been made in restoring forests and planting trees by using inappropriate species and methods (Marshall et al., 2022).

Restoring forests is expensive, time-consuming and fraught with species selection, propagule collection, propagation, and seedling establishment issues (Engert et al., 2020; Martínez-Ramos et al., 2016; Palma and Laurance, 2015) as well as poor sapling survival and growth (Banin et al., 2022; Evans and Turnbull, 2004; Summers et al., 2015, 2015van Oosterzee et al., 2020). In tropical forest regions, survival and growth characteristics of most species remain untested (Plath et al.,

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2011) or are poorly monitored (Palma and Laurance, 2015), resulting in a legacy of poor survival rates that persist for decades (e.g. Evans and Turnbull, 2004, p. 223). For example, plantings in south-east Asia reported mortalities of 18% in the first 12 months increasing to 44% after 5 years (Banin et al., 2022), and others have reported 30–40% initially (Yang et al., 2013; Yeong et al., 2016). Survival rate is a common metric of early success (Le et al., 2012) and maximising survival of planted saplings is essential for the economic and environmental success of reforestation plantings.

Guidelines on species selection, nursery culture, and planting methods are usually based on well-grounded first-hand experience (e.g. Goosem and Tucker, 2013; Peel, 2010), but even so provide only limited guidance on specific best planting methods (or techniques). Species' selection and suitability for reforestation are often based on desired traits of adult trees within forests such as wood density (Asanok et al., 2013), growth rate, foliage structure (Close et al., 2005; Preece et al., 2015), resilience to herbivores (Moles and Westoby, 2004) and whether or not they are light-demanding or shade-tolerant (e.g. Hubbell, 2005). For example, high wood density has been shown to increase survival rates, but results in slower growth (Larjavaara and Muller-Landau, 2010; Nguyen et al., 2014; Preece et al., 2015). Adult traits do not necessarily reflect sapling traits of the same species and adult-stage species attributes are arguably less critical than other factors such as initial soil properties and conditions (Cheesman et al., 2018; Martínez-Garza et al., 2016) and their influence on sapling survival (Plath et al., 2011).

Recent neotropical nursery and outplanting studies recommend handling plants with utmost care and that 'moisture, temperature, and physical stresses are damaging and cumulative' (Wilkinson et al., 2014, 2016). Regardless, most reforestation studies and practices accept that a proportion of planted saplings will succumb to transplant shock (Close et al., 2005). Here we investigate how transplant shock can be mitigated by paying attention to three critical aspects of outplanting: the treatment of tubestock in preparation for planting; the wetness of field soils; and the physical method of planting saplings. Particularly important is the early "coupling" of saplings to soil by growing seedlings in nursery tubes until they have sufficient root volume to access soil water when outplanted (Grossnickle, 2005), critical to avoiding water stress and reducing risk of either hydraulic failure or carbon starvation due to reduced photosynthesis (Dalling et al., 2022; Grossnickle, 2005, 2012; McDowell et al., 2008). Low soil moisture and increased vapour pressure deficit, which plants perceive as atmospheric drought (even a few days of no rain) (Dalling et al., 2022; Engelbrecht et al., 2006), can significantly decrease survival of both temperate (Adams et al., 2009, 2017; Will et al., 2013) and tropical species (Dalling et al., 2022; Engelbrecht et al., 2007; Liu et al., 2020). Experiments on tropical species that demonstrate this effect have not been conducted (Dalling et al., 2022), even though soil water potential in some tropical soils can decline significantly at 20 cm below the surface ($<\sim -2$ MPa) during even short drought periods, with the greatest decline above 10 cm ($<\sim -3$ MPa) (Engelbrecht and Kursar, 2003; Grossnickle and MacDonald, 2018). Few plants can survive in soil with water potential of -3 MPa (Buckley, 2019) and soil moisture is probably the most important factor in tree sapling survival and growth (Liu et al., 2020). Directly associated with soil moisture is the wetness of the tubestock roots just prior to planting, both of which we address here.

The most careful selection of species for their functional and other attributes, and care with growing out seedlings to the sapling stage can be undone by poor planting practices. Although the effect of individual planters introducing bias or confounding factors has been recognised in experiments (e.g. Pinto et al., 2011), it has not received adequate attention in the restoration methods literature.

The best way to control grasses is with herbicides (e.g. Thaxton et al., 2012) which are used regularly in reforestation projects where established species, such as exotic grasses, out-compete planted trees. On our study site the original forest was cleared in the 1940s and replaced with three exotic pasture grasses, *Urochloa decumbens* (Stapf) R.D. Webster, *Setaria sphacelata* (Schumach.) Stapf & C.E.Hubb. Ex Moss. And *Melinis minutiflora* Beauv. These grass species are resilient and aggressive, characteristics that can be detrimental to a reforestation project. Practitioners use different approaches to controlling grasses, with some spraying out the whole planting area, others in strips along contours to reduce erosion and the amount of herbicide applied. Concerns about herbicide use include their potential long-term effects on natural regeneration, soil biota and reduced carbon sequestration (e.g. Druille et al., 2013; Griscom, 2020).

We established a large-scale restoration experiment in the wet tropics of Australia to examine several aspects of reforestation practice. The study was prompted by experiments we conducted in 2010 (Preece et al., 2013, 2015, 2017) which resulted in high survival rates of saplings compared with a subsequent much larger experiment in 2011 (van Oosterzee et al., 2020), which showed substantially lower survival rates. This difference in survival rates was unexpected, so the third experiment examined herbicide treatments, the effects of sapling treatments in the field prior to planting and the effects of individual planters' techniques (planter effect) on survival rates of saplings. The aims of the experiments were to improve reforestation and provide evidence-based practical guidance that will enhance sapling survival.

2. Methods

2.1. Thiaki Rainforest Restoration Project

All experiments were conducted on-site as part of the Thiaki Rainforest Restoration Project for carbon and biodiversity, located on the southern Atherton Tablelands (17.43° S, 145.51° E), at elevations between 900 m and 1000 m ASL in the Wet Tropics Region of north Queensland, Australia. The region has a humid tropical climate with mean winter and summer temperatures of 15.6 °C and 25.3 °C, respectively. Median annual rainfall is 1234 mm and is seasonal with peak rainfall months from December through April, declining in the cooler months (Kairi Weather Station #031034, Bureau of Meteorology, 2016, http://www.bom.gov.au/climate/; accessed April 15, 2022). Soils are derived from Atherton Basalt and are deep, well drained, red-brown pedal, uniform clay soils with basalt coarse fragments and quartz pebbles and excellent structure and moisture holding capacity (Malcolm and Nagel, 1997). Rainforest was the predominant original vegetation. Most of the study site was cleared prior to the mid-1940s and some in the late 1980s (Preece et al., 2017) and is typical of much of the surrounding grazing properties except that the site abuts intact (but logged) rainforest (Fig. S3). The site is steep with slopes ranging from 20 to over 40° with generally north-westerly and south-easterly aspects. Exotic pasture grasses were planted across the property and beef cattle intensively grazed the land until six months before planting.

A common method of reforestation is to plant saplings. The terms 'seedling' and 'sapling' have different meanings but are often mis-used, even in articles discussing sapling survival (e.g. Grossnickle, 2012; Hau and Corlett, 2003; and Preece et al., 2015 use 'seedling' and 'sapling' inconsistently to refer to the same growth stage). The term 'sapling' refers to one life stage of trees which include germinant, seedling, sapling, young-mature, old growth (Day and Greenwood, 2011). There is no consensus on what constitutes a 'seedling' (Eriksson and Ehrlén, 2008; Hanley et al., 2004), but we have adopted the definition of a young plant still dependent on seed nutrient reserves (Kitajima and Fenner, 2000). This is more than a pedantic argument, as a seedling grown in a nursery and intended for planting grows from a seed to a stage at which it is likely to survive in the planted location, commonly (but not always) after the nutrient source of the seed has been exhausted (Kitajima and Fenner, 2000). We assume that the young trees we planted were saplings as it was likely that, after 6 months or more in forestry tubes, as in other studies (Slot and Winter 2018), most had lost reliance on their seed reserves and were using nutrients in the potting matrix, having reached an autotrophic stage (Kitajima and Fenner, 2000).

2.2. Experimental plantings

The three landscape-scale experiments on the site were planted in 2010 (Expt. 1), 2011 (Expt. 2) and in 2013 (Expt. 3) (Table S1, Fig. S3), in the most reliable rainfall months (Jan–Mar) using 30 local-provenance species in various mixes across three experiments (Table S2). Planted species are native to the remnant forest on the property and have a broad range of adult functional attributes we considered important in reforestation. Species selection was based on advice from researchers and practitioners for their availability from nurseries and their effectiveness in reforestation plantings. Saplings were nursery grown from seed through the seedling stage in 'forestry tubes' 12 cm deep and 5 × 5 cm wide (300 cm^3) to approximately 20–30 cm high, for 6–12 months, and were all acclimatised (Close et al., 2005) (or 'sun-hardened'), where plants are exposed to more natural conditions than in nurseries prior to planting. Due to nursery shortfalls in experiment 2, about 2000 (of 26,000) small saplings of *Flindersia brayleyana* were harvested locally from the wild, potted and matured for at least six months prior to planting stage and grew in the nursery as well as nursery-germinated plants.

Plots were separated by at least 5 m. Soil moisture was recorded at 11 weather stations across the property using Hoboware recorders. Water content was measured as $m^3\ m^{-3}$ (soil water vol. To soil vol.) combining ECH2O Dielectric Aquameter probe (EC-5) from Decagon Devices with Onset smart sensor (S-SMC-M005 or S-SMC-M003) technology, with probes buried in soil to 40 cm. Results are shown in the Supplement.

In all experiments, the planting rows were sprayed with glyphosate (Roundup®) before planting and with fluazifop-p-butyl (Fusilade® or Fuzilier®) after planting, according to manufacturers' instructions. Spraying was applied according to best practice to prevent drift of herbicide and over-application. This was successful as the sprayed rows were all straight and separated by unsprayed living grassed inter-rows for the duration of the experiments and until saplings had established. While herbicides are considered essential in wet tropical regions to eliminate competitive grasses, their use has costs and long-term negative effects (e.g. Botten et al., 2021; Griscom et al., 2005). To reduce these effects we stopped herbicide use when saplings were sturdy enough to out-compete grasses, generally above 60 cm tall. Saplings were planted so that soil covered the root collar and the deepest roots were 12 cm (tube length) below the surface. In all experiments, saplings were planted after rains had saturated the soils during the mid-summer growing season and were not watered after planting.

In experiment 1, sapling tubes were fully wetted shortly before planting and planted in saturated soil. In experiment 2, saplings were initially mist-sprayed with a hose (but not immersed in water) on site for the first half of the planting week, and then fully wetted from mid-week prior to planting. We were alerted on day 3 by planters that plants had not been fully wetted and some root boluses in the tubes were dry. Commercial planters planted the saplings over a week in saturated soils to begin with, but the site experienced no rain for 5 of the 6 days of planting due to the build-up of Cyclone Yasi, after which there was heavy persistent rain for at least two months (see Fig. S2 for rainfall data for all three experiments). We also observed that some plants in trays had been left overnight before planting, so they probably dried to a point that affected early survival. We were unable to correct this at the time as the plants were planted before we knew they had been left out. We discuss this in the discussion.

We used survival information from experiments 1 and 2 to provide the baseline for experiment 3 which we report on here. In experiment 3, fifty-six saplings from 13 species were planted randomly in each of 16 paired plots (Table S1). There were two objectives of experiment 3. One was an experimental design to test for the effects of spraying method on early survival rates; one plot of each pair was fully sprayed out, and the other sprayed in 1 m wide strips along contours 3 m apart, leaving unsprayed grassed strips 2 m wide. Paired plots were immediately adjacent to each other (separated by 5 m buffers) to reduce effects of site factors varying due to more distant location. Each sapling tube was fully immersed in water an hour or so prior to planting. Saplings were planted over three consecutive days in late March 2013.

The second objective was to monitor sapling survival for each planter, based on our prior experience with planters. The seven planters operated as individuals or in teams of 2–4 (Table S3). Planters in their team combinations were discreetly monitored for technique (by authors NDP & PvO) to avoid influencing how they planted. We controlled for potentially confounding factors by obtaining all plants from one nursery, controlling sapling water condition, planting in saturated soils and avoiding locations with flood potential so that we could isolate the effects of different planters' techniques which we expected might result in different survival rates. Our specific interest was planting technique as the other causal factors are well known to affect survival in reforestation activities.

2.3. Analyses

In experiment 2, species-level differences in sapling survival (binary response, 1 = living, 0 = dead) at 4 months (Fig. 1) and for more than 6 years after planting (Fig. 2) was modelled (Table S4) using generalized binomial proportions linear mixed-effect models with logit link function; sapling survival was modelled as a function of planting treatment (monoculture, six or 24 species per plot), landscape- and site-scale variables (plot slope, plot aspect, days of sun exposure immediately after planting), and species' wood density. Plot nested within block was included as a random effect in all models. Variance component analysis indicated that most of the variance in the fixed effects occurred between and within families as opposed to between species. Most of the within-family variation was captured within the Lauraceae and Moraceae (Fig. S1). Thus, species-level differences in the fixed effects were examined separately from the final models. Maximal models containing all relevant explanatory variables for each of the measured time periods for each experiment were simplified according to the protocol for mixed effects modelling in Zuur et al. (2013, p.122). In experiments 1 and 3, species-level difference in survival at 4 months (Fig. 1) and for more than 6 years after planting (Fig. 2), was modelled (Table 1 and S4; Supplement Model summaries) using generalized binomial proportions linear mixed-effect models with logit link function.

In experiment 3, herbicide treatment, planter identity and sapling species were included as fixed effects and plot identity as a random

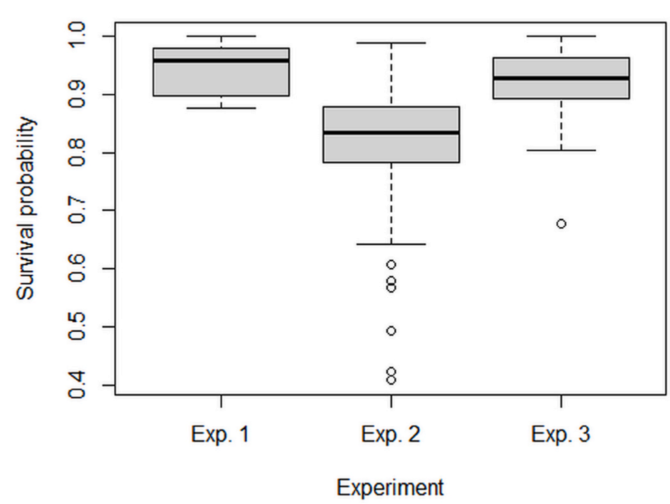

Fig. 1. – Box plot representation of individual survival probability at 4 months after planting. Whiskers indicate the maximum or minimum relative to ±1.5*the interquartile range (grey box). Open circles are potential outliers and the absolute min or max values; Exp. 1 data from Preece et al. (2013); Exp. 2 data from experiment 2 tree data; Exp. 3 data from this study).

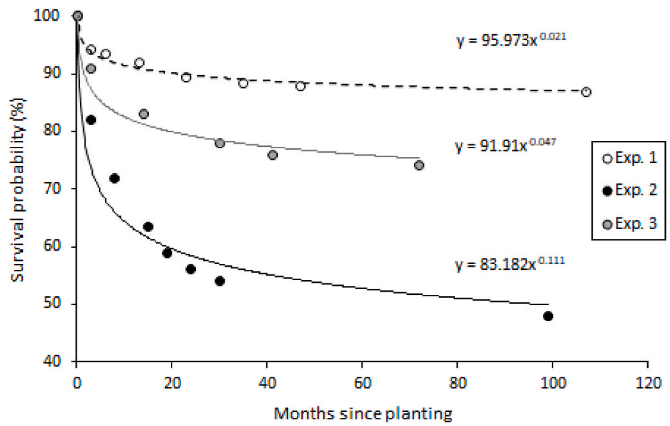

Fig. 2. Survival probability of saplings since planting in 3 experimental plantings. See Table 1 for description of each experiment.

effect. Data analysis for all of the above was conducted in the R statistical software package version 4.0.1, using the nlme and lme4 package (Bates et al., 2015; Pinheiro and Bates, 2023; R Core Team, 2020).

We applied split-line regression to determine the breakpoint (months since planting) at which sapling mortality rate slowed substantially. This analysis was conducted using the R package 'segmented' for estimating breakpoints (see https://CRAN.R-project.org/package=segmented) (Muggeo, 2003, 2008). We used survival rates as an indication of the success of the methods in increasing survival, and mortality rates as an indication of how poor methods can cause higher mortality.

3. Results

3.1. Survival rates among the three experiments

Survival rates at four months after planting differed significantly among the three experiments ($F_{2,82} = 59.8$, $P < 0.001$; Fig. 1). The 2011 planting (experiment 2) exhibited the lowest sapling survival (81%) compared with the other experiments' survival rates ranging from 91 to 94%. Careful planting methods in experiment 3 improved sapling survival over experiment 2 by at least 10% and was similar to experiment 1 in the first few months after planting.

Applying split-line regression to determine the breakpoint, at which sapling death rate slowed substantially, shows that careful planting methods resulted in significantly better sapling survival in the longer-term (70 to over 100 months) (Table 1).

In experiment 3 (2013), sapling survival after approximately 20 months since planting was increased by at least 23% compared with experiment 2 results. Time to establishment when saplings are growing well, interpreted here as the breakpoint, was shortened by 1–3 months. The mortality rate in experiment 2 was 1.95% of saplings per month compared to 0.5%–1.09% per month under careful planting methods in experiments 1 and 3, respectively.

Sapling survival rates generally stabilised beyond 20 months after planting and were similar among the three experiments (Fig. 2). However, the mortality rates in the first 4–5 months differed significantly and had a long-term effect on sapling survival, with factors affecting survival

Table 1
Breakpoints (point at which survival rates asymptote) for survival probability and month of establishment after planting for each of the three experiments.

	Breakpoint		Mortality Rate	% Variance
Experiment	Survival prob.	Month	% saplings/month	
Expt 1	88.2 ± 4.6	17.9 ± 0.8	−0.54 ± 0.17	85.1
Expt 2	52.7 ± 3.2	20.6 ± 2.9	−1.95 ± 0.35	89.8
Expt 3	76 ± 1.7	19.8 ± 4.3	−1.09 ± 0.28	91.5

in experiment 2 resulting in only 53% of saplings surviving in the long-term whereas 76–88% of saplings survived in experiments 1 and 3.

3.2. Effect of planting spacings, species mix and days since rain on sapling survival

In experiment 2, sapling survival in the first four months after planting did not differ between planting spacing treatments or between the low (6 species) and high (24 species) diversity treatments but was significantly lower in monocultures of *Flindersia brayleyana* ($P = 0.023$). Sapling survival was significantly different among families ($P < 0.0001$) and species ($P < 0.01$), with species in the Lauraceae having the lowest survival (74%) and those from the Moraceae the highest (96%). Some species including *Cryptocarya oblata* (43%; $P < 0.001$), *Melicope jonesii* (69%; $P < 0.001$), *Flindersia brayleyana* (76%; $P < 0.001$), and *Syzygium (Acmena) resa* AR (79%; $P < 0.01$) showed lower survival rates than others. Sapling survival at four months after planting increased significantly with wood density ($P = 0.0012$).

At four months, there was no difference in survival between planting spacing treatments ($P = 0.4$), plot aspect ($P > 0.2$), days the saplings were exposed to drying soils due to lack of rain before the next rainfall ($P > 0.35$), and the slope of the plot ($P > 0.3$). Sapling survival in the monoculture plots was 49%, lower than in the high (24 species) diversity treatment plots (61%, $P = 0.061$), and significantly lower (65%; $P < 0.02$) than in the low (6 species) diversity treatment plots. At 18 months, differences in survival among families were less pronounced than at 4 months, although the survival of species in the Lauraceae was significantly less (38%; $P < 0.0001$) than any other family (range = 54–77%). As observed at 4 months, species with greater wood density displayed greater sapling survival at 18 months ($P < 0.002$).

Soil water content and rainfall at the time of planting cannot be predicted in any experiment. In experiments 1 and 3, rain preceded, continued through and followed the plantings with the result that soils were very wet and planted saplings experienced no short-term drought. In experiment 2, planting occurred in saturated soils to begin, but rain ceased the night before the first day of planting and no rain occurred until day 6. This was followed by persistent heavy rainfall associated with Cyclone Yasi for several months (Fig. S2). Moisture content of soil (soil water content as proportion of soil volume) during this dry week in experiment 2 was significantly less (0.24 ± 0.02 m3 m−3; x ± s.d.) than either the soil moisture in the week prior to planting (0.29 ± 0.02 m^3 m^{-3}; $P = 0.0009$) or the long-term average (0.29 ± 0.08; $P = 0.0002$). Despite this drying period and contrary to expectation, the duration of exposure of newly planted saplings to drying soils did not significantly affect sapling survival at four months (range = 77–92%; $P > 0.1$).

3.3. Herbicide and the planter effect on sapling survival

In experiment 3, survival probability of saplings at 4 months was 0.92 (±1 SE = 0.02) for both herbicide treatments, and there was no difference in sapling survival between herbicide treatments, either overall ($t_{2,14} = 1.33$, $P < 0.2$) or as blocked pairs at 4 months ($t_{1,7} = 2.12$, $P < 0.07$) or at 18 months (0.90–0.92 survival probability; $t_{1,7} = 0.66$, $P < 0.5$).

Significantly greater sapling mortality rates at 4 months were associated with planter E (group number 3) when working alone (Fig. 3), but not when with group 4. This illustrates the negative effect that a single planter can have on sapling mortality.

4. Discussion

Reforestation programs aim to maximize tree survival, regardless of the objectives. Here we examine how tree survival can be improved. Survival rates in the first few months clearly affect longer term survival to establishment. Our study shows that by 18–20 months after planting, overall survival stabilised in all experiments, the saplings probably

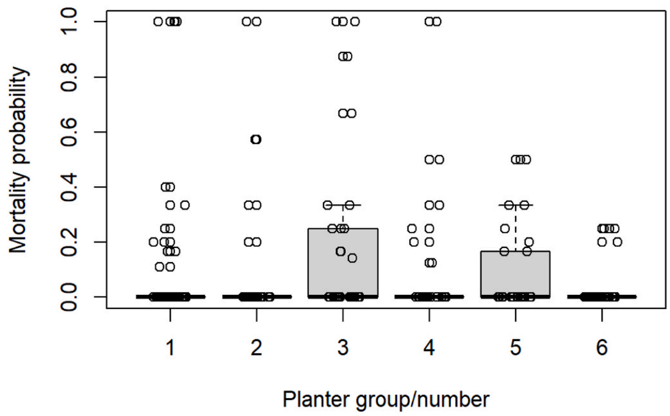

Fig. 3. Effect of planters on mortality rates of saplings in 16 plots in Experiment 3. Planter groups 1,3,6 were individuals, and 2, 4 and 5 were groups comprising different combinations. Planter E worked alone in group 3 and with another planter in group 4, but in no other groups, and was associated with significantly greater sapling mortality at four months ($t_{5,189} = 2.82$, $P < 0.005$).

having overcome initial planting shock, hydraulic failure and carbon starvation (Grossnickle, 2012). This is consistent with other studies such as in tropical Mexico where mortality rates declined from 6 months to 24 months after planting, after which mortality rates stabilised (Martínez-Garza et al., 2013). Our findings reinforce the value of post-planting monitoring (Dumroese et al., 2016), without which we would not have discovered some critical factors that affect survival.

Key findings could help improve survival rates of plantings.

a) Planting spacing and mixes of species have no real effect on survival (lower survival of monocultures was probably due to other factors);
b) Avoid damaging the root stock during planting by carefully extracting saplings from planter tubes and planting with care to prevent root damage. We demonstrated a noticeable planter effect on sapling survival and conclude that it was due to observed rougher planting technique than other planters;
c) Grass must be removed prior to and for sufficient time after planting for the young trees to escape competition from grass. We found, however, that whether spraying herbicide in planting rows or across the whole area had no significant effect on survival, and
d) The root bolus of saplings in nursery tubes must be saturated with water immediately prior to planting to provide the newly planted sapling the necessary moisture to avoid hydraulic failure. Planting by planter spade to a depth of at least 12 cm enhances the potential of the newly planted saplings to access soil moisture.

Species' functional traits or performance in remnant forests is not a reliable guide to sapling survival (Martínez-Garza et al., 2013; Ruiz-Jaen and Potvin, 2011). We suggest choosing species based on both experience with sapling survival and adult functional traits, together with the attention usually paid to provenance, germinability, storage and handling of seeds, culturing of plants in nurseries (Grossnickle, 2012; Grossnickle and Ivetić, 2022; Kimball et al., 2015; Palma and Laurance, 2015) and morphological and physiological attributes of seedlings (Grossnickle and MacDonald, 2018).

We showed that spacings of trees and species mixes had no effect on survival, other than for monocultures, which we consider was due to there being more monocultures than either of the mixed species plots and that by chance they were affected more by dried tubestock, not an inherent property of monocultures or the species.

We found a substantial planter effect due to one planter working alone causing significantly lower sapling survival (10–20% lower) than others. The effect of this planter seems to have been masked while working with others, perhaps because they were more careful in company or planted a small proportion of plants. Planting rates varied among planters from approximately 600 to 1500 stems per day, so a fast planter with a defective technique can have a significant negative effect on a whole planting, but conversely, a good, fast planter can produce a large positive result. Poor technique can cause damage to roots when removing the sapling from the tube and when inserting saplings into the ground. Most planters pressed the plants firmly into the soil with pressure exerted through the ball of the foot (as suggested in Evans and Turnbull, 2004, p216; and Haase et al., 2014, p324) and we refer to this as 'good' technique. The planter whose success rate was lower than other planters was observed on numerous occasions to kick the mounded soil around the planted sapling with visible force, rather than press the soil to hold the plant, and we refer to this as 'poor' technique. We speculate that kicking the soil caused damage to the lateral and tap roots. Such trauma could be enough to set back the establishment of the sapling during the "coupling" phase by reducing the ability of the roots of the newly planted saplings to bind with the soil and obtain vital carbon and moisture (Grossnickle, 2005, 2012; McDowell et al., 2008) and root damage leads to electrolyte leakage (Grossnickle, 2012). Early root growth during the first days after planting, which is the result of root system size, morphology, lateral roots and fibrosity (Davis and Jacobs, 2005), is critical to establishment and survival immediately after saplings are planted in the field (Grossnickle, 2012; Grossnickle and MacDonald, 2018). Our finding that planter techniques are important contrasts with those of a previous study on the site because Charles et al. (2018) assumed that the composition of the planter teams was fixed, whereas we (authors NDP & PvO) observed that planters of experiment 2 swapped among teams. Specific training of planters to explain potential damage to roots and demonstrate correct technique is warranted.

Our observations show that how planters treat plants, including the preparatory watering of saplings, planting when soil water potential is high, and careful planting techniques, have a measurable effect on long-term sapling survival. Separating the relative importance of each factor is not possible without a controlled field experiment designed to examine these effects further, but the combination of these factors provides a parsimonious explanation for differences in sapling survival among the three experiments.

There was no significant survival difference between whether whole plots were sprayed out or sprayed in strips along contours with herbicide, leaving grassed rows between planted rows of saplings. Limiting the amount of herbicide used reduces establishment and maintenance costs, reduces erosion and reduces negative effects of persistent use (Druille et al., 2013; Griscom et al., 2005). Leaving unsprayed grassed strips also helps to maintain a more hospitable micro-climate in the planted rows by reducing wind-assisted evapotranspiration and is worth further investigation.

Water stress can be caused by insufficient watering of tubestock prior to planting, damage during planting, planting into dry or drying soils or short-term drought of only a few days' duration immediately after planting (Buckley, 2019; Engelbrecht et al., 2006; Engelbrecht and Kursar, 2003). Water stress reduces the ability of newly planted saplings to bind their roots to the soil, leading to carbon starvation and hydraulic failure (Grossnickle, 2005, 2012; McDowell et al., 2008). The more favourable soil moisture conditions at the time of planting in experiments 1 and 3 likely contributed to >90% survival at 4 months, compared to experiment 2 (which was affected by the dry week during planting) with 81% survival. That the differences due to days after and before rain alone were not statistically significant (Fig. 2) requires more explanation. The tubestock for experiment 2 was delivered from the nurseries over a series of days and the plants that were planted in the first couple of days of drying soils may have been wet enough from the nurseries to survive. Poorly watered tubestock that were planted midweek received follow-up rain a few days after planting, whereas those properly saturated over the last three days, likely ameliorated the effect of dry conditions. Therefore it was more likely in experiment 2 that the causes of lower early survival were inadequate watering of tubestock prior to planting and poorer planting techniques by one or two planters. The higher early mortality in experiment 2 led to a striking difference in survival in the longer-term (18–20 months), from high survival in experiments 1 and 3 (88% and 76%, respectively), to low (53%) in experiment 2.

A demonstration that saplings with dry root boluses have a lower chance of survival due to moisture shock (Grossnickle, 2005, 2012; Rietveld, 1989) can be seen in experiment 2 where one set of adjacent plots (both facing south-south-east and at the same altitude) planted with *F. brayleyana* monocultures. Plants in tubes for one of these plots were accidently left out in the hot sun the day before planting and these were planted without being freshly watered. Only 41% of plants survived to four months in this plot, whereas 80% of plants in the adjacent plot (planted wet) survived to four months. The very low survival rate was atypical of most plots and a statistical outlier that skewed overall survival results, as most monoculture plots of *Flindersia* retain high survival rates.

Three further observations are worth mentioning. First, flooding rains followed Cyclone Yasi and continued for months, flooding four plots and drowning most of the saplings. Flooding is known to affect survival (Palma and Laurance, 2015), but is generally poorly addressed in the literature. Avoiding planting in floodways if they can be determined in advance of site selection would reduce this problem.

Secondly, aspect and slope may play a role in the long-term survival of the plants but were not important in the early stages of tree establishment. Our findings contrast with Charles et al. (2018) who used incorrect aspects (Table S5). In addition, they based their interpretation on the effects of aspect at much higher latitudes (e.g. 32° S) (e.g. Armesto and Martínez, 1978) than the study site (at 17.43° S). At high latitudes (greater than ~23° S), the sun is always north. Tropical insolation differs from temperate insolation by a substantial amount (Kumar et al., 1997) and is much less variable throughout the year. At 17.43° S, the sun's declination at the study site is south for 5 months, and for another 5 months is the equal and opposite declination north. Further modelling of the effect of aspect and insolation on medium to long-term survival is warranted.

Third, higher wood density was significantly associated with higher survival rates in both the short and long term, which is consistent with other findings (Nguyen et al., 2014; Preece et al., 2015). We show however that poor planting technique which can damage roots and inadequate watering can lead to lower overall survival, which from other studies can lead to poor nutrient and water uptake and that these factors are more critical than functional traits of adults. Wood density also is an inherent property, whereas planting practices can be manipulated and therefore improved.

Maximising survival of plants is critical to all reforestation activities. While mortality rates in our experiments are not unusual when compared with other plantings, the loss of 20% of saplings in the first few months in our second experiment amounted to approximately 4800 plants, at a financial value of AU$14400 at AU$3 per plant (2011 values), and approximately 12,000 plants in the first 20 months. Finally, this paper contributes to understanding the early-stage establishment of trees in reforestation projects in the wet tropics and demonstrates the value of longitudinal studies that consider multiple aspects of real-world situations.

Credit author statement

All authors made a substantial contribution to conception and design, acquisition of data and drafting and revising the article; MJL, NDP undertook data analyses and statistical analysis; MJL undertook the statistical modelling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jenvman.2023.117645.

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