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Early root development of field-grown poplar: effects of planting material and genotype

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Abstract

Background: Poplar trees (*Populus* spp.) are used widely for soil conservation. A key advantage is their ability to establish from unrooted stem sections of varying dimensions, ranging from small cuttings to large poles. This study determined root length and biomass of young trees from three different-sized stem sections and quantified clonal variation.

Methods: Two concurrent field trials were conducted: trial 1 compared root attributes of trees from cuttings, stakes, and poles of a single poplar clone, while trial 2 compared those of trees from cuttings of six poplar clones. Excavations of entire trees were conducted in autumn for three (trial 1) or two (trial 2) years after planting.

Results: Total root mass averaged over 3 years was in the order poles (364 g) > stakes (70 g) > cuttings (17 g), and total root length was in the order poles (73 m) > stakes (21 m) > cuttings (7 m). Maximum lateral root extension was approximately 2.6 m from poles, 1.7 m from stakes, and 0.8 m from cuttings. Clonal variation in trees from cuttings was found for both mean total root mass (10.4–45.9 g) and total root length (3.5–11.8 m). In both trials, root mass and length increased, decreased, or were unchanged with increasing 0.5-m increments of the distance from stem and soil depth, depending on year, planting material, root diameter, and their interaction.

Conclusions: Early root development from poles was greater than from cuttings, with development from stakes being intermediate. Different poplar clones exhibited large variation in root biomass development within 2 years of planting. The results provide an understanding of the differences in early root development of poplar planting materials and clones used for soil conservation and other purposes and guidance on appropriate tree spacings of different planting materials to achieve root interlock.

Keywords: Pasture-tree systems, Erosion control, Root systems, Root diameter, Tree spacing

Background

Soil erosion in diverse ecosystems and landscapes modified by human activity is a significant global problem (Toy et al. 2002; Blanco and Lal 2008; Liu et al. 2011). Methods to control various erosion types and processes comprise built structures (Gebrernichael et al. 2005; Posthumus and De Graaff 2005; Yang et al. 2009; Wang et al. 2012) or the use of biological solutions, principally the establishment of a live vegetation cover (Zuazo and Pleguezuelo 2008; Stokes et al. 2014). The choice of approach depends on factors such as the extent and severity of the erosion problem, initial and ongoing costs of implementation, anticipated maintenance requirements, and expected useful life of works. Vegetation reduces erosion through above- and below-ground mechanical and hydrological effects that are governed by factors including species (e.g. growth form, morphology, root depth, and distribution), age, and spatial and temporal configurations (Bischetti et al. 2005; de Baets et al. 2009; Stokes et al. 2009; Genet et al. 2010). Vegetation used in erosion control programmes ranges from indigenous or introduced herbaceous grasses, legumes, and herbs through to woody vegetation comprising assorted shrub and tree species (Blanco and Lal 2008; Evette et al. 2009; Kuzovkina and Volk 2009; Wu et al. 2010).

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Species and hybrids of the genus *Populus* (poplar) are important examples of trees used in erosion control and remediation programmes in many regions of the world (Wu et al. 1994; Lammeranner et al. 2005; Licht and Isebrands 2005; Reisner et al. 2007; Blanco and Lal 2008). The advantages of using poplar for erosion control include rapid growth, high evapotranspiration rates, extensive lateral root systems, abundant fine root production, and rapid tree establishment from vegetative material. There continue to be many above-ground attributes of poplars assessed, including in Europe (Pulkkinen et al. 2013; Toillon et al. 2013; Verlinden et al. 2013), China (Fang et al. 2013), and North America (Hart et al. 2013; Kaczmarek et al. 2013), mainly with respect to the rapidly developing use of short-rotation coppice systems for biofuels and other products. In contrast, fewer below-ground investigations have been conducted recently (Benomar et al. 2013; Berhongaray et al. 2013; Hajek et al. 2014; Phillips et al. 2014), and this imbalance needs addressing because root characteristics and their spatial and temporal changes are particularly important in determining efficacy for soil stabilisation (Stokes et al. 2009). Furthermore, in view of the many natural and bred poplar genotypes available (Eckenwalder 1996), variation in root characteristics between species/hybrids of poplar in the field has received scant attention (Al Afas et al. 2008; Benomar et al. 2013; Berhongaray et al. 2013; Phillips et al. 2014). Consequently, there is limited knowledge of the genetic variation in root attributes of populations of poplar which hinders identifying the most appropriate clones for stabilising soil.

Poplars have been planted in significant numbers in New Zealand since the 1960s to reduce the extent and severity of mass-movement erosion processes such as shallow landslides, earthflows, and gully erosion (Thompson and Luckman 1993). Plantings are particularly widespread on hill country supporting a pastoral cover for livestock (predominantly sheep and beef cattle) grazing enterprises, where established trees at densities of less than 100 stems per hectare (sph) provide effective slope stabilisation and enable understorey pasture production (Wilkinson 1999; Guevara-Escobar et al. 2007; Benavides et al. 2009). For example, the area of shallow landsliding was reduced by 50–80 % by trees of *Populus* spp. and species of other genera at 70 sph or greater (Hicks 1995), and trees of mostly *Populus* spp. at 32–65 sph reduced the occurrence of shallow landslides by an average of 95 % (Douglas et al. 2013). Annual pasture production beneath widely spaced poplars is reduced by 20–50 % depending mainly on tree spacing and tree size/age (Douglas et al. 2006; Wall et al. 2006; Guevara-Escobar et al. 2007).

In pasture-poplar systems, the growth and distribution of 'Veronese' poplar (*Populus deltoides* Marshall × *nigra* L.) roots on erodible slopes have been measured for entire trees aged 5–11.5 years (McIvor et al. 2008; McIvor et al. 2009), but there appear to be scant data for other clones, regardless of age. Nine months after establishing poplar clones from various planting materials (PMs) on flat, cultivated terrace soils, the mean root depth of Veronese was almost twice that of *P. deltoides* × *yunnanensis* clone 'Kawa' (Phillips et al. 2014). There were no significant differences between the clones in below-ground biomass, maximum lateral root diameter, and total root length. In a greenhouse study of up to 10 weeks, genetic variation was detected for number of root nodes, root mass, and root length among ten poplar genotypes established from 0.2-m-long stem sections (McIvor et al. 2014). Additionally, root development was reduced significantly with increasing soil bulk density, which has implications for likely field performance of the genotypes in different substrates.

Poplars can be established in the presence of grazing livestock by planting stem sections protected with a plastic sleeve (Wilkinson 1999), rather than using nursery-grown seedlings and ceasing grazing within at least the first few years following transplanting. In New Zealand, unrooted stems 3 m long, 50–70 mm diameter, and aged 2 years, henceforth referred to as poles, are typically planted vertically in grazed pastures. Smaller and younger vegetative material such as 1-m-long stems of 20–30 mm diameter and aged 1 year, henceforth referred to as stakes, may be planted where livestock are excluded (Wilkinson 1999). Stakes also have potential use in non-farm applications such as protecting roadside and railway embankments. Similarly, shorter and thinner stems, e.g. 0.4 m long and 15–20 mm diameter, henceforth referred to as cuttings, are used in agricultural and non-agricultural situations. The effect of the size of PM on early tree development, particularly in relation to root length and biomass, is poorly understood (Sidhu and Dhillon 2007; DesRochers and Tremblay 2009). It is hypothesised that over the first few years of tree establishment, poles will have significantly greater rates of above- and below-ground biomass development than stakes and cuttings.

The first objective of this study was to determine the effect of PM (poles, stakes, and cuttings) on above- and below-ground biomass development of Veronese poplar within the first 3 years after planting in the field. The second objective aimed to quantify the variation in root development of selected experimental and released poplar clones in the first 2 years after planting as cuttings. The results from two concurrent trials are reported.

Methods

Study sites

Two trials were conducted in a cultivated block on flat land at a commercial plant propagation nursery (175°39′ E, 40°21′ S), approximately 10 km from Palmerston North in the south-west of the North Island. A flat site was deemed likely to maximise tree growth and facilitate whole-tree excavation. The ground was cultivated 2 months before planting when soil water levels were high, so it did not develop a fine tilth. Data obtained from the National Institute of Water and Atmospheric Research (NIWA) showed that the site has a temperate climate, with mean monthly air temperature over the period 1981–2010 ranging from 8.6 °C in July (winter) to 18.3 °C in February (summer), and mean annual rainfall of 917 mm (NIWA 2013). The soil was a Manawatu fine sandy loam (Fluvial Recent soil, Dystric Fluventic Eutrochrept derived from greywacke alluvium) (Hewitt 1998). Soil samples from $0 < 25$, $25 < 50$, and 50–75 cm depth at the site were analysed for pH (1:2.1 v/v water slurry), Olsen phosphate (Olsen extraction), and sulphate-sulphur content (potassium phosphate extraction).

Trial 1: planting material comparison

Plant material and experimental design

Hybrid poplar clone Veronese was established from vegetative PM of three dimensions and ages: poles, stakes, and cuttings, as described previously. Veronese has been available commercially for 15+ years (Wilkinson 1999) and is used widely in erosion control programmes throughout New Zealand. Experience has found that the unrooted stems of Veronese are able to establish roots readily in a range of field and glasshouse conditions. Cuttings and stakes were removed from the middle of vertical stems of parent trees, and poles were obtained from lower-middle parts of stems. All PMs were dormant, obtained from a local nursery, and soaked in a water bath for 1–3 days before planting.

In August 2009, three units of each PM were planted in each of five randomised complete blocks that provided five replicates for destructive sampling in each of three consecutive years. Each PM unit was treated as an experimental unit, and in total, there were 45 experimental units in the trial. The volume (V) of each of the three PMs was estimated using the formula $V = \pi d^2 L 4^{-1}$ where d = diameter of PM and L = length of PM. A single value was calculated for each of the three PMs assuming all poles were 3 m long and 60 mm diameter (midpoint of 50–70 mm range), all stakes were 1 m long and 25 mm diameter (20–30 mm), and all cuttings were 0.4 m long and 17.5 mm diameter (15–20 mm). Units were at 2-m spacings within two adjacent rows 3 m apart, with two or three buffer rows of stakes planted either side to reduce any border effects. The PMs were planted vertically at depths of 0.3 m for cuttings, 0.5 m for stakes, and 0.8 m for poles to facilitate anchorage of the developing trees in the substrate. Soil surrounding the PM was compacted to reduce the likelihood of air pockets (van Kraayenoord et al. 1986). Weeds, principally grasses (mostly *Holcus lanatus* L.), but also legumes (e.g. *Lotus uliginosus* Schkuhr) and other broadleaf species (e.g. *Ranunculus repens* L.), were controlled by hand-weeding and application of herbicide (glyphosate at 1.8 kg a.i. ha^{-1}). For example, in the first year, weeds were sprayed once after planting and once in summer.

Measurements

Above- and below-ground attributes were measured in autumn 2010 (year (Y)1), 2011 (Y2), and 2012 (Y3). Five replicates of establishing trees from stakes and poles were measured each year whereas the death of several trees established from planted cuttings resulted in the measurement of four replicates of this PM in Y1 and Y2 and three replicates in Y3. Above-ground attributes measured were as follows: longest shoot length, henceforth referred to as shoot length (m, measured in Y1–Y3); diameter of the base of the longest shoot, henceforth referred to as shoot diameter (mm, Y1 and Y3); distance from ground level to the base of the longest shoot, henceforth referred to as shoot position (m, Y1–Y3); root collar diameter (mm, Y1); and shoot mass (g), comprising leaf and stem (Y1–Y3). All leaves and stems were severed from the PM units, and their total mass determined by oven-drying at 70 °C for 24 h. Mass of the destructively sampled PMs (g) was determined in Y1–Y3 by drying at 70 °C to a constant weight (up to 4 days).

Whole-tree root excavations were conducted using hand-held implements within a series of 0.5-m radial widths radiating outwards from the establishing trees and at 0.5-m soil-depth increments (Fig. 1). Width and depth each comprised three classes of $0 < 0.5$, $0.5 < 1.0$, and ≥ 1.0 m. Roots extending beyond 1.0 m laterally or vertically were followed to their end point, often characterised by a venation of very thin roots. Roots were removed from the original PMs and classified into diameters of <1 (fibrous), $1 < 2$, $2 < 5$, $5 < 10$, $10 < 20$, and ≥ 20 mm. The total length of roots in each diameter class, except fibrous, was measured, and all material was oven-dried (70 °C to a constant weight) to determine root mass.

Trial 2: clonal variation comparison

Plant material and experimental design

Cuttings from six different poplar clones (‘San Rosa’, ‘Fraser’, ‘Veronese’, ‘Kawa’, ‘Geyles’ and ‘PN471’) from various poplar species/hybrids (Table 1) (Van Kraayenoord and Hathaway 1986; MAF 2011) were planted in a randomised design with five replicate cuttings of each clone in each of 2 years. Spacings between cuttings were 2 m within rows and 3 m between rows and, as in trial 1, were planted in August 2009. Experimental units were as defined previously, and the total number of units in the experiment was 60 (6 clones × 5 reps × 2 years).

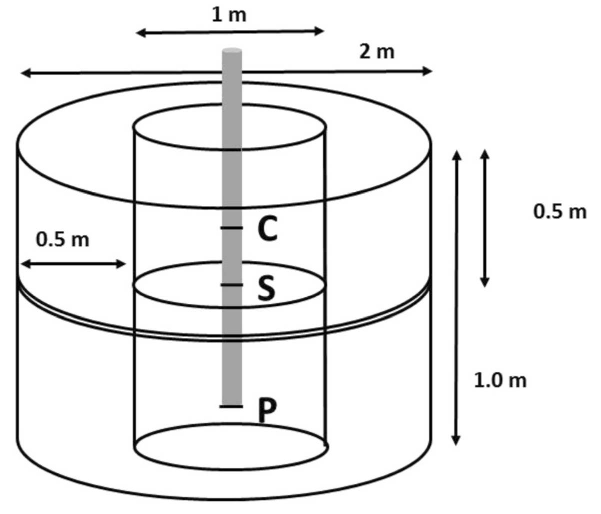

Fig. 1 Arrangement of sampling depths and widths around poplar trees established from cuttings (*C*), stakes (*S*), and poles (*P*). *Horizontal bars* on central axis represent depth of planting of cuttings (*C*, 0.3 m), stakes (*S*, 0.5 m) and poles (*P*, 0.8 m). Planting materials have different diameters (not shown). Excavations exceeded 1.0-m radius and depth when roots extended beyond shown dimensions

Planting method and depth, and plot management, were as in trial 1.

Measurements

Above-ground measurements were conducted in autumn 2010 (Y1) and 2011 (Y2) for shoot length (m), shoot diameter (mm, Y1 only), and shoot mass (g), as in trial 1. Mass of cuttings (g) was determined as previously. The number of replicates measured per clone varied in Y1 (three to five) and Y2 (one to four) because of inadvertent tree deaths occurring after planting.

Below-ground attributes were measured using the same protocol used in trial 1, including soil width and depth increments of 0 < 0.5, 0.5 < 1.0, and ≥1.0 m. Roots were classified into diameter classes of <2, 2 < 5, 5 < 10, and ≥10 mm. The total soil volume excavated for each clone was relatively low because of the small root systems developed over the initial 2 years of establishment compared to those for stakes and poles in trial 1.

Statistical analyses of data

All analyses were conducted using GenStat© 16th edition (VSN International 2014). Data for above-ground attributes were analysed using mixed effects models with a restricted maximum likelihood (REML) approach. In trial 1, data for root collar diameter, shoot mass, and PM mass were log-transformed to achieve variance homogeneity. Similarly in trial 2, shoot mass data were log-transformed. In trial 1 for above-ground attributes measured in each of 3 years, sources of variation in the model were block (4 degrees of freedom (df)), year (2 df), PM (2 df), year × PM interaction (4 df), and residual (28 df), giving a total of 40 df. The total df in models was reduced for attributes measured in one (13 df) or two (26 df) years. In trial 2, key sources of variation in the model were year (1 df), clone (5 df), and year × clone interaction (5 df). Significant terms in the fitted models were examined further using Fisher's protected least significant differences (LSDs) at the 5 % level. For transformed data, back-transformed predicted means and approximate standard errors are presented.

Root data in both trials were analysed using a two-step method, similar to that used previously (Douglas et al. 2010), comprising (1) analysis of the proportion of width × depth × year combinations (cells) with roots and (2) analysis of data for cells where roots were present. This method was used because of the large number of zero values in the datasets. Logistic regression was used to analyse presence/absence data for step 1. Data for step 2 were log-transformed and analysed using REML, and back-transformed predicted means and approximate standard errors are presented.

In trial 1, two separate analyses of root data (A, B) were conducted for step 1. Analysis A was for all PMs and

Table 1 Clones of *Populus* spp. established from cuttings

Clone	Description
Populus deltoides Marshall × *P. ciliata* (Wall. Ex Royle) clone San Rosa	New Zealand (NZ)-bred vigorous clone, best suited to drier regions because of rust susceptibility; copes well with wind.
Populus deltoides Marshall × *P. nigra* L. clone Fraser	NZ-bred, very narrow tree with a light open canopy that casts minimal shade; light stems are prone to breakage at windy sites.
Populus deltoides Marshall × *P. nigra* L. clone Veronese	European-bred, straight-stemmed, narrow-crowned tree that has good drought and wind tolerance.
Populus deltoides Marshall × *P. yunnanensis* (Dode) clone Kawa	NZ-bred, narrow-crowned tree, resistant to browsing by possums; well suited to moist slopes but not to strong winds.
Populus maximowiczii (A. Henry) × *P. nigra* L. clone Geyles	NZ-bred, straight-stemmed tree with a narrow crown, high rust resistance; grows well on moist sites.
Populus trichocarpa (Torrey and Gray) clone PN471	European-selected, American balsam poplar, narrow-crowned tree for slope stabilisation and gully plantings; not recommended for planting on windy and exposed sites.

comprised data for 3 years, two depths (0 < 0.5, 0.5 < 1.0 m) and two widths (0 < 0.5, 0.5 < 1.0 m). The data were restricted to a maximum of 0.5 < 1.0 m width because trees from cuttings did not produce roots beyond 1.0 m within the study time frame. Terms in the model comprised year, depth, width, PM, and depth × width, depth × year, and depth × PM interactions, with a regression df of 11 and total df of 35. Analysis B was for pole data only and was conducted because the roots of trees from poles extended frequently beyond 1 m. This enabled three (0 < 0.5, 0.5 < 1.0, ≥1.0 m) rather than two widths to be included in the analysis to obtain a greater understanding of variation between widths. The model used comprised terms of depth, width, year, and depth × year interaction with a regression df of 7 and total df of 89. For step 2, total values for root attributes were calculated in two ways. Firstly, data were summed over all diameter classes, soil depths, and widths to calculate total root mass (TRM) and total root length (TRL) per tree. Secondly, data were summed over all diameter (D) classes only, providing attributes of TRMD and TRLD for all other factor combinations (width and depth). As an example of models used, TRM and TRL data were analysed using a model with terms block (4 df), year (2 df), PM (2 df), PM × year interaction (4 df), and residual (28 df). There was considerable data imbalance from the absence of roots, for example, in the larger diameter classes for trees from all PMs in Y1 and from many trees from cuttings in Y2 and Y3. The widest distribution of diameter classes (<2 to ≥20 mm) occurred for roots from trees from poles in Y3. For these data, root mass and root length in each diameter class were analysed separately to determine the effect of depth (0 < 0.5, ≥ 0.5 m) and width (0 < 0.5, 0.5 < 1.0, ≥1.0 m). The model comprised block (4 df), depth (1 df), width (2 df), depth × width interaction (2 df), and residual (17 df).

In trial 2, root presence/absence was analysed (step 1). Roots were absent or detected rarely in the larger diameter classes (5 < 10, ≥10 mm) and width zones (0.5 < 1.0, ≥1.0 m), and therefore, diameter was reduced to three classes for root mass (<2, 2 < 5, ≥5 mm) and root length (1 < 2, 2 < 5, ≥5 mm), and width from the trees was reduced to two classes (0 < 0.5, ≥0.5 m). Classification by depth was discarded because only 3 of 25 trees in Y1 and 4 of 23 trees in Y2 had root development exceeding 0.5-m soil depth. A ratio of TRL to TRM was calculated.

Results

Soil properties

Soil had a pH of 6.0 at all depths: 0 < 25, 25 < 50, and 50–75 cm and corresponding values for Olsen phosphate of 16, 11, and 4 μg mL^{-1}, respectively. Sulphate-sulphur levels were 1 ppm or less at the three soil depths.

Trial 1: planting material comparison

Above-ground attributes

There was a large variation in stem volume between PMs—approximately 8490 cm^3 for poles, 490 cm^3 for stakes, and 95 cm^3 for cuttings. Tree growth over the first 3 years of establishment varied markedly between PMs with the largest growth achieved from poles. Mean shoot length over 3 years was in the order poles (3.4 m) > stakes (2.9 m) > cuttings (1.7 m), and differences among PMs increased over time (PM × year interaction $P < 0.001$; Fig. 2a). In Y3, shoot length from cuttings averaged 2.3 m which was less than half that of the longest shoots from stakes (4.8 m) and poles (5.6 m).

Shoot diameter averaged over years was in the order poles (41 mm) > stakes (34 mm) > cuttings (20 mm)

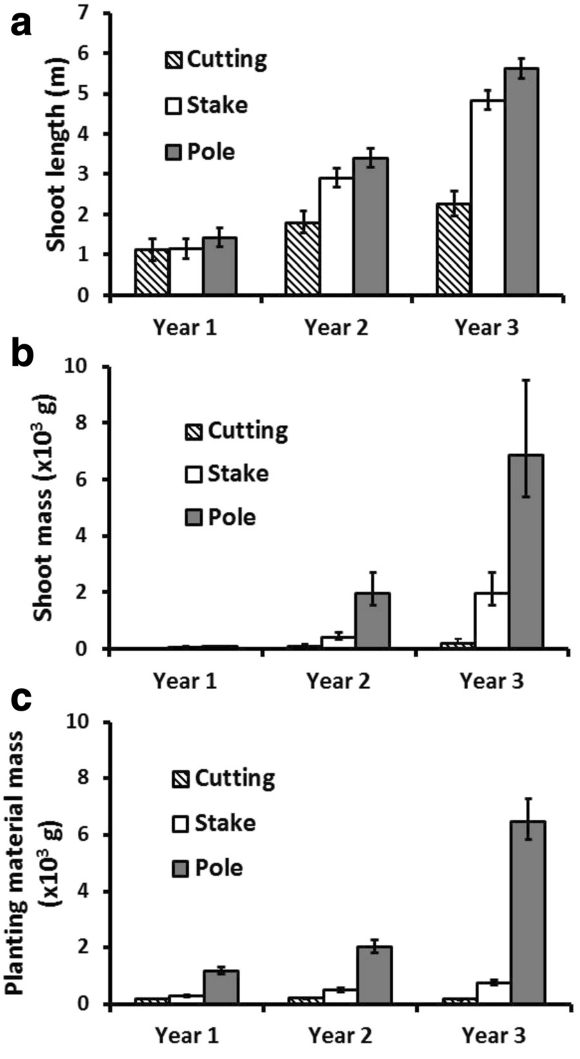

Fig. 2 Above-ground attributes of **a** shoot length, **b** shoot mass, and **c** planting material mass of Veronese poplar established from three planting materials. *Values* are means and *capped vertical lines* are standard errors

($P < 0.001$) and increased from an average across PMs of 15 mm in Y1 to 56 mm in Y3 ($P < 0.001$). Shoot diameter of PMs was similar in Y1 (range 13–18 mm) whereas, in Y3, the diameter of poles (66 mm) was 16 % greater than from stakes (57 mm) and 113 % greater than from cuttings (31 mm). The longest shoots from poles originated at an average height above the ground of 1.77 m which was significantly greater than those from cuttings (0.05 m above ground) and stakes (0.34 m). There were more and thicker shoots from PMs in the order poles > stakes > cuttings. In Y1, root collar diameter averaged 58 mm for poles, 43 mm for stakes, and 35 mm for cuttings, which all differed from each other ($P < 0.001$).

Shoot mass of trees from the three PMs in Y1 ranged from 30 to 70 g whereas, in Y2 and Y3, shoot mass was in the order poles > stakes > cuttings (PM × year interaction $P < 0.01$; Fig. 2b). Stakes and poles produced significant increases in shoot mass over the 3 years. Similar trends occurred over time for the total mass of pole PM, with a marked increase occurring between Y2 and Y3 (Fig. 2c). In contrast, between Y1 and Y3, there was only a small increase in mass of stakes and no significant change in cutting mass.

Root attributes

Root presence increments decreased with increasing width from stem and soil depth ($P < 0.001$). Roots were present within the top 0.5 m of soil in 72 % of cells for cuttings, 90 % for stakes, and all cells for poles whereas, at $0.5 < 1.0$ m depth, root presence was 33 % for cuttings, 47 % for stakes, and 60 % for poles (PM × depth interaction $P = 0.014$). A decrease in root presence at $0 < 0.5$ m depth with increasing width (100 % at $0 < 0.5$ m width, 78 % at $0.5 < 1.0$ m) was smaller than at $0.5 < 1.0$ m depth (66 vs. 29 %) (depth × width interaction $P = 0.024$). In the analysis of pole data, root presence decreased with increasing width ($P < 0.001$), being 87, 77, and 50 % for $0 < 0.5$, $0.5 < 1.0$, and ≥ 1.0 m, respectively, and this trend was not influenced by other factors. There were large increases in root presence over time at $0.5 < 1.0$ m depth compared with at $0 < 0.5$ m depth (depth × year interaction) in the analyses comprising data for all PMs ($P = 0.001$) and poles only ($P = 0.049$). For example, root presence of poles at $0.5 < 1.0$ m depth increased from 27 % in Y1 to 87 % in Y3, whereas, at $0 < 0.5$ m depth, roots were found in 73 % of cells in Y1 and all cells in Y2 and Y3.

Each year, roots from cuttings did not extend beyond 0.5-m width, except for one instance where a root extended between 0.5 and 1.0 m, in contrast to those from poles where extension was >1.0 m, but no intersection between roots from different trees was observed. An exception was the intersection of the roots of two trees from poles in Y3. Root extension from stakes was intermediate between that from cuttings and poles, with roots found at both $0 < 0.5$ m and $0.5 < 1.0$ m widths in Y1 and Y2 and at ≥ 1.0 m in Y3. Roots extended between 0.5- and 1.0-m soil depth at all widths from poles in Y2 and Y3, and Y3 roots were also found at ≥1.0-m depth within 0.5 m of poles. No roots were found at this depth for the other PMs. The greatest radial distance attained by the individual roots of PMs was about 0.8, 1.7, and 2.6 m for those from cuttings, stakes, and poles, respectively. A root 4.6 m long was found in Y3 from a pole, but it was not in a straight line. Roots <5 mm diameter were produced by all PMs each year whereas roots $5 < 10$ mm diameter were only found in Y2 and Y3. Roots ≥10 mm diameter were only excavated from poles in Y2 and Y3 and from stakes in Y3.

The value of TRM averaged over 3 years was in the order poles (364 g) > stakes (70 g) > cuttings (17 g) ($P < 0.001$). There was much greater variation between years for TRM of trees from poles than from cuttings and stakes (PM × year interaction $P < 0.05$; Fig. 3a). In Y3, the TRM of poles was 8-fold greater than stakes and 80-fold greater than cuttings.

The value of TRMD decreased dramatically with increasing width from trees and with increasing soil depth, and a greater increase in TRMD occurred at $0 < 0.5$ m depth over time than at ≥ 0.5 m (depth × year interaction $P = 0.033$; Fig. 4a). In Y1 and Y3, TRMD at the shallower

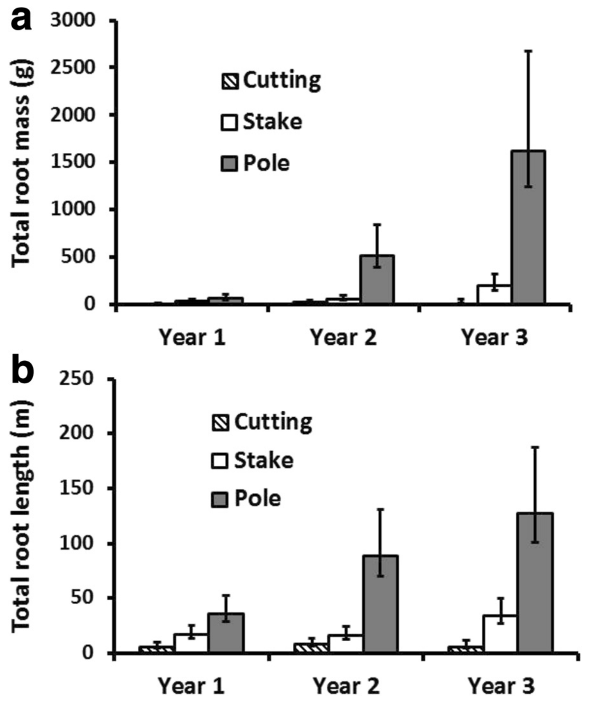

Fig. 3 Total root mass (**a**) and length (**b**) of Veronese poplar established from three planting materials. *Values* are means and *capped vertical lines* are standard errors

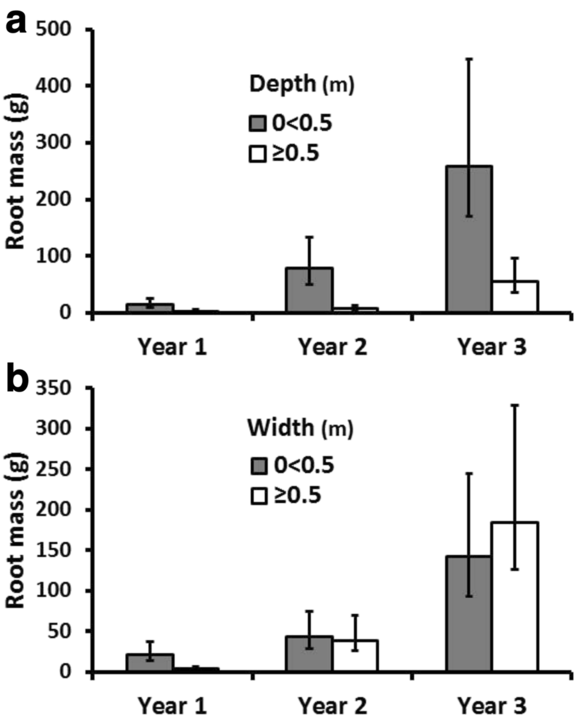

Fig. 4 Root mass of Veronese poplar with **a** soil depth and **b** width over time. *Values* are means and *capped vertical lines* are standard errors

depth was 5-fold greater than at ≥0.5-m depth, whereas, in Y2, it was 11-fold greater. TRMD in Y1 within 0.5 m of trees was significantly greater than beyond 0.5 m in contrast to other years, where no difference was found between widths (width × year interaction $P < 0.001$; Fig. 4b).

For trees established from poles, in Y3, mass of roots of <2, 2 < 5, and 5 < 10 mm diameter was 3–6-fold greater in 0 < 0.5 m soil depth than deeper in the profile (Table 2). Within 0.5 m of trees, mass of the thinnest roots was 3-fold greater than at 0.5 < 1.0 and ≥1.0 m widths, which were not significantly different from each other (Table 2). Trends for depth and width were inconsistent for these smaller-diameter classes (depth × width interaction $P < 0.05$).

The relative differences in TRL between trees established from the three PMs were less than those found for TRM but still followed a similar order of poles (73 m) > stakes (21 m) > cuttings (7 m) ($P < 0.001$), and there was also less variation between years (Fig. 3b). The values of TRLD decreased with increasing distance from trees and increasing soil depth (not presented), but responses varied with year. Over time, the difference between root lengths at 0 < 0.5 m and ≥0.5 m depths increased ($P = 0.017$; Fig. 5a). Root length at 0 < 0.5 m width exceeded that beyond 0.5 m from trees in Y1, whereas, in subsequent years, length did not vary significantly between widths (width × year interaction $P < 0.001$; Fig. 5b).

The length of roots of trees established from poles of <2, 2 < 5, and 5 < 10 mm diameter was 4–6-fold greater in 0 < 0.5 m soil depth than deeper in the profile ($P < 0.001$; Table 2). Within 0.5 m of trees, the length of 1 < 2 mm roots was over 2-fold greater than at 0.5 < 1.0 m and ≥1.0 m widths. For 5 < 10 mm roots, length did not vary significantly between widths at 0 < 0.5 m depth whereas, at ≥0.5-m depth, length beyond 1.0 m from trees (0.8 m) was significantly greater than at 0 < 0.5 m width (0.6 m) (depth × width interaction $P = 0.044$).

The partitioning of biomass between the root and shoot changed over time for the three sizes of PM, with the root as a proportion of total biomass (shoot + root, excluding PM mass) in trees from poles reducing from

Table 2 Mean root mass and length of Veronese poplar trees 3 years after establishment from poles

	Root mass (g)					Root length (m)				
	Root diameter (mm)					Root diameter (mm)				
Factor	<2	2 < 5	5 < 10	10 < 20	≥20	1 < 2	2 < 5	5 < 10	10 < 20	≥20
Soil depth (m)										
0 < 0.5	11.1^a (2.0)	29.8^a (6.4)	96.1^a (19.3)	114.1 (32.6)	120.4 (67.3)	7.3^a (1.6)	10.3^a (1.8)	6.7^a (1.4)	2.6 (0.6)	2.2^a (0.4)
≥0.5	2.0^b (0.4)	10.1^b (2.4)	28.4^b (6.4)	66.2 (25.4)	11.8 (9.1)	1.2^b (0.3)	2.6^b (0.5)	1.7^b (0.4)	1.0 (0.3)	1.1^b (0.2)
P value	*<0.001*	*0.004*	*<0.001*	0.556	0.087	*<0.001*	*<0.001*	*<0.001*	0.102	*0.040*
Width (m)										
0 < 0.5	10.7^a (2.4)	27.0 (7.1)	77.3 (19.1)	199.5 (74.7)	93.2 (54.7)	5.8^a (1.6)	8.8 (1.9)	4.2 (1.1)	3.3 (0.9)	2.6 (0.6)
0.5 < 1.0	3.5^b (0.8)	13.9 (3.9)	37.2 (9.7)	45.9 (18.1)	27.4 (21.5)	2.4^b (0.7)	4.2 (1.0)	3.4 (0.9)	1.2 (0.4)	1.4 (0.4)
≥1.0	3.7^b (0.9)	17.9 (5.3)	70.0 (19.3)	88.7 (40.0)	103.9 (180.1)	2.6^b (0.8)	5.2 (1.3)	4.0 (1.1)	2.1 (0.7)	1.1 (0.3)
P value	*0.002*	0.190	0.184	0.084	0.689	*0.047*	0.054	0.794	0.141	0.067
Depth × width										
P value	*0.029*	*0.049*	*0.010*	0.250	0.261	0.072	0.145	*0.044*	0.187	0.067

Within factors within columns, means with different letters differ significantly at $P = 0.05$. *P* values that were significant ($P < 0.05$) are shown in italics. Figures in brackets are standard errors

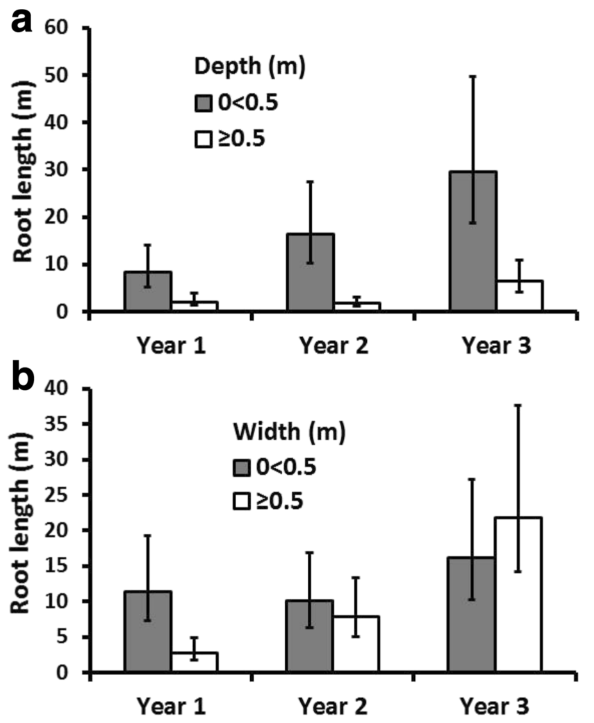

Fig. 5 Root length of Veronese poplar with **a** soil depth and **b** width over time. *Values* are means and *capped vertical lines* are standard errors

48 % in Y1 to 21 % in Y2 and 19 % in Y3. Corresponding values for stakes were 39, 13, and 9 % and for cuttings were 25, 19, and 9 %, respectively.

Trial 2: clonal variation comparison

Above-ground attributes

Clones varied in shoot length, shoot mass, and cutting mass (Table 3) but not in shoot diameter ($P = 0.078$). Mean shoot length of Kawa was greater than for San Rosa, Fraser, Veronese, and PN471, and it had greater shoot mass than all other clones, except for the mass of Geyles, which did not vary significantly from that of Kawa. The cutting mass of Veronese was twice that of San Rosa, and it was also significantly greater than for PN471 and Geyles (Table 3). Across clones, shoot length increased ($P < 0.001$) 77 % between Y1 (1.19 m) and Y2 (2.09 m), shoot mass increased 4.8-fold between Y1 (29.1 g) and Y2 (168.0 g), and cutting mass increased only slightly over the same period (133 to 144 g). Shoot diameter of clones averaged 13 (s.e. = 0.7) mm.

Root attributes

The presence of roots varied between clones, years, and widths from trees. The root presence of all clones was more than 80 % in both years except for San Rosa and PN471 in their first year (50 %) (clone × year interaction $P = 0.043$), where they only produced roots within 0.5 m of trees. In Y1, all roots of clones were <5 mm diameter except for those of San Rosa and Geyles where roots ≥5 mm were also found.

Mean TRM per tree varied between clones ($P = 0.001$) and ranged from 10.4 g for PN471 to 45.9 g for Geyles (Table 3). Clones Kawa and Geyles had similar TRM that was 2.5–4.5-fold greater than for the other clones, all of which did not vary significantly from each other. Across all clones, mean TRM in Y2 (43.5 g) was almost 5-fold greater than in Y1 (9.2 g) ($P < 0.001$).

Clones varied in mass of roots <2 and 2 < 5 mm diameter, but there were no significant differences between them for ≥5-mm roots (Table 4). The root mass of Kawa and Geyles exceeded that of most other clones. For all root diameters, mass of roots beyond 0.5 m was at least 75 % less than within 0.5 m of trees (Table 4). There was a trend of increasing root mass between Y1 and Y2, with mass of 2 < 5 mm roots increasing 5-fold ($P < 0.001$). The mass of this root class beyond 0.5-m width was 12 % of that at 0 < 0.5 m in Y1, increasing to 48 % in Y2 (width × year interaction $P < 0.001$).

The TRL of Kawa and Geyles was greater than for Fraser and PN471, and the mean for San Rosa was not significantly different from that for any other clone (Table 3). Clone Kawa had approximately 3-fold greater TRL than PN471. The length of 2 < 5 mm diameter roots of Geyles was greater than for Fraser and PN471 but was not significantly different from that for San Rosa, Veronese, and Kawa (Table 4). There was no

Table 3 Mean above-ground attributes and total root mass and length of clones of poplar established from cuttings

Clone	Shoot length(m)	Shoot mass(g)	Cutting mass(g)	Total root mass(g)	Total root length(m)
P. deltoides × *P. ciliata* San Rosa	1.52^{bc} (0.34)	48.8^{b} (23.6)	93.6^{c} (26.9)	15.2^{b} (5.0)	6.4^{abc} (1.7)
P. deltoides × *P. nigra* Fraser	1.47^{bc} (0.24)	58.7^{b} (19.5)	141.4^{abc} (19.5)	13.7^{b} (4.4)	4.1^{bc} (1.1)
P. deltoides × *P. nigra* Veronese	1.51^{bc} (0.21)	60.1^{b} (16.6)	190.0^{a} (16.5)	16.4^{b} (5.3)	7.3^{ab} (2.0)
P. deltoides × *P. yunnanensis* Kawa	2.30^{a} (0.17)	156.2^{a} (27.1)	164.7^{ab} (13.3)	39.1^{a} (12.7)	11.8^{a} (3.2)
P. maximowiczii × *P. nigra* Geyles	1.84^{ab} (0.20)	85.9^{ab} (22.4)	108.6^{c} (15.6)	45.9^{a} (14.9)	10.3^{a} (2.8)
P. trichocarpa PN471	1.20^{c} (0.22)	51.0^{b} (15.3)	132.1^{bc} (17.8)	10.4^{b} (3.4)	3.5^{c} (0.9)
P value	*0.004*	*0.021*	*0.009*	*0.001*	*0.006*

Means are averaged over 2 years. Means for shoot mass and root attributes are back-transformed from logarithms. Within columns, means with different letters differ significantly at $P = 0.05$. P values that were significant ($P < 0.05$) are shown in italics. Figures in brackets are standard errors

Table 4 Mean root mass and length of six clones of poplar established from cuttings

	Root mass (g)			Root length (m)		
	Root diameter (mm)			Root diameter (mm)		
Factor	<2	2 < 5	≥5	1 < 2	2 < 5	≥5
Clone						
P. deltoides × *P. ciliata* San Rosa	1.7^{ab} (0.5)	2.6^{bc} (0.9)	2.0 (1.3)	1.5 (0.4)	1.2^{abc} (0.3)	0.2 (0.1)
P. deltoides × *P. nigra* Fraser	1.0^{b} (0.3)	2.8^{bc} (0.9)	4.5 (3.0)	1.2 (0.3)	1.1^{bc} (0.3)	0.3 (0.2)
P. deltoides × *P. nigra* Veronese	1.1^{b} (0.3)	3.8^{b} (1.2)	2.0 (1.3)	1.3 (0.4)	1.5^{abc} (0.4)	0.2 (0.1)
P. deltoides × *P. yunnanensis* Kawa	2.7^{a} (0.8)	5.9^{ab} (1.9)	12.9 (8.6)	2.1 (0.6)	2.1^{ab} (0.6)	0.8 (0.6)
P. maximowiczii × *P. nigra* Geyles	2.5^{a} (0.8)	9.4^{a} (3.0)	8.6 (5.7)	1.6 (0.4)	2.8^{a} (0.8)	0.6 (0.4)
P. trichocarpa PN471	0.8^{b} (0.2)	1.5^{c} (0.5)	6.7 (4.5)	1.1 (0.3)	0.7^{c} (0.2)	0.5 (0.4)
P value	*0.027*	*0.005*	0.118	0.333	*0.013*	0.322
Width (m)						
0 < 0.5	4.2^{a} (0.7)	7.2^{a} (1.2)	9.8^{a} (3.6)	3.2^{a} (0.5)	2.1^{a} (0.3)	0.7^{a} (0.3)
≥0.5	0.5^{b} (0.1)	1.8^{b} (0.3)	2.4^{b} (0.9)	0.7^{b} (0.1)	1.0^{b} (0.1)	0.2^{b} (0.1)
P value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.002*	*0.006*
Year after planting						
1	1.2 (0.2)	1.5^{b} (0.3)	2.9 (1.3)	1.2 (0.2)	0.9^{b} (0.1)	0.3 (0.1)
2	1.9 (0.4)	8.9^{a} (1.7)	8.2 (3.7)	1.7 (0.3)	2.2^{a} (0.4)	0.7 (0.3)
P value	0.085	*<0.001*	0.137	0.081	*<0.001*	0.158

Within factors within columns, means with different letters differ significantly at $P = 0.05$. P values that were significant ($P < 0.05$) are shown in italics. Figures in brackets are standard errors

significant variation between clones for the length of the other root diameter classes. For each diameter, the length decreased 52–78 % with increasing width from trees. For all clones and in both years, roots ≥5 mm diameter made negligible contribution to mean root length. The ratio of TRL to TRM was 0.22 for Geyles, 0.30 for Kawa and Fraser, 0.34 for PN471, 0.42 for San Rosa, and 0.45 for Veronese.

Discussion

The ability to establish trees of *Populus* spp. rapidly and easily using unrooted stems is a major reason for their widespread use for stabilising erodible pastoral hill country (Wilkinson 1999). This study showed the significant benefits in early establishment from planting poles compared with shorter and thinner material in terms of above-ground (shoot length, shoot diameter, shoot mass) and below-ground (root length, root mass, lateral and vertical root distribution) attributes. The different responses were predominantly due to the large variation in stem volume between PMs, ranging from 95 cm^3 for cuttings to 8490 cm^3 for poles, which suggested significant differences in stored energy reserves available to initiate growth under suitable conditions. The differences in surface area between the PMs would have influenced the number of root initials and potential root production. Variation in planting depth of the PMs would have ensured root initiation to varying depths and subsequent access to water. These factors favour larger PM over smaller such as cuttings and aid survival. Poles would have also been able to hold more water than the two other PMs, and proportionally less of their surface area was cut and exposed to air (DesRochers and Thomas 2003), which would have slowed water loss and facilitated growth. However, larger PMs will also be at greater risk of desiccation because they produce more foliage rapidly after planting, when roots are limited (DesRochers and Tremblay 2009).

In a range of species, the carbohydrate content used for initiating and supporting adventitious root growth and shoot meristem development is related directly to the dimensions of the PM (diameter and length), although it is affected by many other factors including environment (e.g. temperature, soil moisture, soil texture), physiology (e.g. phytohormonal balances, particularly of auxin and cytokinins), condition of the parent trees from which the PM was obtained, and sampling position within parent trees (Zalesny Jr et al. 2003; Leakey 2004; da Costa et al. 2013; Zhao et al. 2014). In this study, the sampling of specific parts of parent trees to obtain the different PMs suggests that stem units of each PM had similar physiological states and propensities for root initiation and development.

Comparisons between the PMs were confounded because of factors including different depths of burial and variation in the ratio of above- to below-ground stem length. These were considered minor issues because the study aimed to compare PMs established using best practice techniques. For example, depth of pole planting in this study aligned with recommendations of planting at depths of 0.6–0.8 m or even up to one third of their length depending on site conditions such as dryness and exposure to wind (Hathaway 1986; National Poplar and Willow Users Group 2007).

The development of fewer and thinner shoots from the smaller PMs was probably because of relatively low stored energy reserves and fewer epicormic buds (Meier et al. 2012) along the shorter stem sections. Greater shoot initiation and growth from the upper compared with lower parts of all PMs may have been in response to slightly elevated irradiation higher up the stems; variation in bark thickness along the above-ground stem sections, particularly for the longer poles; and differential distribution of soluble sugars and carbohydrate reserves (Morisset et al. 2012). Field observations in Y3 indicated that the significantly greater shoot mass produced by trees from poles than from cuttings and stakes was likely because of more and larger shoots and the greater total photosynthetic leaf area. No carbohydrates were assayed, but the contribution to growth of reserves and current photosynthate (Tromp 1983; Magel et al. 2000) in trees from poles was likely considerably greater than in those from the other PMs.

The lower variation among PMs and among years within each PM for root length compared with root mass was considered due to the predominance of roots <5 mm contributing to the length in all treatments and the investment in root diameter of trees established from poles in Y3. The ≥10-mm roots contributed 55 % to root mass but only 10 % to root length. Proliferation of fine roots is essential for enhancing water and nutrient uptake, but there is variation within and among seasons in their longevity and mass depending on soil factors (e.g. water content), tree species, age, and root diameter (Block et al. 2006). Conducting root excavations at the end of the growing season each year, as was done in this study, would have minimised any confounding effects when comparing responses between years. The increased partitioning of biomass to shoots and reduced allocation to roots with increasing age, found in trial 1, has been reported for young hybrid poplars grown from cuttings from plantation stock in North America (Wullschleger et al. 2005). Such results have implications for growth and survival of young trees in dry environments.

Root extension is important in aiding tree survival and growth. The larger PM produced greater root extension and accessed a greater soil volume for water and nutrients than smaller PMs over the same time period. The results reflected the greater resources available in the larger PM. Greater abundance of roots in shallow soil layers than deeper in the soil profile is a common occurrence because of factors such as enhanced soil organic matter content and higher soil nutrient status (e.g. trends for Olsen phosphate in this study) (Block et al. 2006; Johnston et al. 2009; McIvor et al. 2009). The spacings used were appropriate to allow development of young root systems unaffected by those of neighbouring trees because, for all trees except for two from poles in Y3, no intersection between roots from different trees was observed.

The variation among clones grown from cuttings in trial 2 supported findings for field-grown hybrid poplar clones evaluated elsewhere (Pregitzer et al. 1990; Dickmann et al. 1996; Wullschleger et al. 2005; Phillips et al. 2014). Clones Kawa and Geyles had relatively high above- and below-ground growth. Kawa is one of the main poplar clones grown in New Zealand for soil stabilisation and other purposes (National Poplar and Willow Users Group 2007), and this study demonstrated its ability to rapidly establish an extensive root system. Clone Geyles would also seem worthy of further appraisal for root proliferation in soil and was released for commercialisation in 2011 (McIvor et al. 2011). The role of cutting mass in contributing to the shoot and root growth of Kawa and Geyles was uncertain because Geyles had 30 % lower cutting mass than Kawa whereas the two clones did not differ significantly with respect to shoot length, shoot mass, and root attributes. Veronese is grown for a range of applications (National Poplar and Willow Users Group 2007), but this study found that its early growth from cuttings was less than Kawa for shoot length and shoot mass and less than Kawa and Geyles for total root mass. The results suggest that where cuttings are used in applications, clones such as Kawa and Geyles could be used as alternatives to plantings of Veronese or be included in mixtures with Veronese. Phillips et al. (2014) found that 9-month-old Veronese and Kawa trees established from 0.5-m-long stem sections were similar for above- and below-ground attributes, except for maximum root depth where Veronese was about 40 % greater than Kawa (1.0 vs. 0.7 m). They did not recommend a particular clone for planting. Based on its overall low above- and below-ground growth, PN471 could not be recommended for providing rapid and extensive early root development when grown from cuttings and could be difficult to establish from cuttings in regions where summer rainfall is low and irrigation is not available.

The development of relatively thick roots (≥5 mm diameter) in Y1, as shown by trees of San Rosa and Geyles, could be advantageous for storing reserves for maintenance and growth, enhancing anchorage of the developing tree to the soil, and providing a foundation for further development and position within the soil of thinner roots essential for water and nutrient uptake

(Stokes et al. 2009). The differences between all clones in TRL:TRM ratio indicated clonal variation in root development and morphology. Higher TRL:TRM ratio for clones such as Veronese and San Rosa suggested that they had more numerous roots, particularly fine roots, than clones such as Geyles and Kawa. It is possible that the focus of some clones is root extension into new nutrient sources, whereas other clones tend to exploit smaller nutrient sources but to a greater degree. This has possible implications for risk from drought in the first few establishment years.

The death of trees established from cuttings could have been due to several factors. Cuttings had potentially fewer reserves to initiate growth above and below ground. They also had shorter stem lengths buried than stakes and poles, presenting lower surface areas for potential root development and extraction of soil water and nutrients. Inspection of cuttings and the other PMs within 3 months of planting found that all were alive and therefore that post-planting factors were responsible for any tree mortality. There was no evidence of pest or disease attack, the area of the trials was not grazed by livestock, and browsing damage by small mammals was not observed.

Although soil pH at the trial sites was within the range of 5.5 to 7.0 recommended for poplar-nursery production (van Kraayenoord et al. 1986), levels of Olsen phosphate were low, particularly at 50–75-cm soil depth, and levels of sulphate-sulphur were very low. Raising the levels of phosphate and sulphur through strategic fertiliser application may have accentuated the differences found between the PMs in root and shoot responses (van den Driessche 1999; Guillemette and DesRochers 2008), particularly by favouring trees from poles with their larger and more extensive root systems and consequent exploration of greater soil volumes.

Poles are more costly to produce than cuttings and stakes and are heavier and bulkier to transport. However, these disadvantages are more than compensated for in field applications with their potentially higher survival and lower maintenance requirements. Also, the planting of poles (with sleeve protection) is the only practicable option for establishment in pastoral areas continuing to be grazed by livestock (Wilkinson 1999).

In a comparison of poplar PMs at Gisborne on the east coast of the North Island, Phillips et al. (2014) found that 9 months after planting, the above- and below-ground growth of trees from poles exceeded that from stakes and cuttings, as found presently. Both studies also found no significant differences in root length between clones Veronese and Kawa. However, growth at Gisborne was considerably greater than found in this study with, for example, root collar diameter of Veronese PMs at Gisborne (77–104 mm) being almost 2-fold greater than in Y1 (35–58 mm). At Gisborne, TRL ranged from 155 m for trees established from stakes to 255 m for trees established from poles, compared with less than 40 m for trees from any PM after one growing season in this study. At Gisborne, roots extended 3 to 5 m from the stem after 9 months, whereas, currently, maximum radial extension was 2.6 m. Finally, the lowest estimates of TRM of Veronese at Gisborne ranged from 1.50 to 3.05×10^3 g, which were considerably greater than those found in Y1. By Y3, pole TRM was at the lower end of the earlier estimates (Phillips et al. 2014). The much greater tree growth at Gisborne than Palmerston North may have been because of higher soil nutrient status, higher average air temperatures (long-term values of 12 to 23 °C at Gisborne; 8.6 to 18.3 °C at Palmerston North), irrigation during summer (Gisborne only), and loose structured soil at Gisborne compared with more compacted upper soil layers at Palmerston North, which would have facilitated root extension.

The rapid interlocking of roots of neighbouring trees on man-made or natural slopes is an important attribute to minimise the risk of mass movement erosion of the ground between adjacent trees (Reubens et al. 2007; Stokes et al. 2009). The lower lateral root extension from stakes and particularly from cuttings, compared with that from poles, indicated that these smaller PMs need to be planted at much closer spacings than poles to achieve, within a given time period, a similar amount of root interlocking in a defined volume of shallow soil. The results indicated that for roots of trees established from each PM to touch those of neighbours by Y3, spacings would need to be about 5.2 m for poles (370 sph), 3.4 m for stakes (865 sph), and 1.6 m for cuttings (3900 sph). Spacings of established poplar trees on erodible pastoral hill country are often 10–15 m (100–45 sph), which are effective in reducing erosion processes such as shallow landslides (Cairns et al. 2001; Douglas et al. 2013). These spacings are achieved by planting at closer spacings with thinning later or the more common (but higher risk) approach of planting at final spacings and relying on near 100 % survival to achieve desired root coverage of the slope. There would also need to be negligible mass movement erosion in the meantime. Another important element in slope stabilisation by woody vegetation is vertical root development and its potential penetration and anchoring into underlying bedrock (Reubens et al. 2007; Stokes et al. 2009). In trial 1, the early soil conservation advantage of poles was shown further by the development in Y3 of vertical roots from the bottom or near bottom of poles that extended deeper than 1 m within 0.5-m radius of poles. The ability of these roots to penetrate stable strata would depend on factors such as their depth, pedological structure, and the presence of cracks in the strata.

Conclusions

Poles of Veronese hybrid poplar produced trees that had considerably greater above- and below-ground growth and development than those from cuttings within the first 3 years after planting. Trees from stakes were intermediate between poles and cuttings in their growth and development. After 3 years, maximum lateral root extension was about 0.8, 1.7, and 2.6 m for trees grown from cuttings, stakes, and poles, respectively. This indicated that large differences in spacing would be required to achieve similar levels of contact between roots of neighbouring trees established from the different PMs over the same period of time. Survival of trees from cuttings was <100 % whereas all trees from stakes and poles survived. The proportion of biomass allocated to roots decreased with age for trees from the three PMs. Among six different clones from cuttings, there was a 4.4-fold variation in TRM and a 3.4-fold variation in TRL. Hybrid poplar clones Kawa and Geyles produced the greatest amount of above- and below-ground biomass. This study indicates that there are poplar clones that root more readily and produce greater root mass in the first year than Veronese; they should be considered for greater commercial production than occurs presently.

The findings on early root development of poplar add to the very limited information available. Different-sized stem sections are used in a range of applications, and it is important to know how they influence root development spatially and temporally. This impacts directly on decisions regarding initial spacing of stem sections to achieve interlock of roots within a specific time frame. Practitioners will have to accommodate the delay in time of root interlock of trees established from stakes, and particularly cuttings, in their applications. The data for Veronese complement those for trees aged 5+ years collected for trees established from poles on slopes and will enable an improved understanding of root development over time. Results are for clones used widely in New Zealand, such as Veronese and Kawa, and therefore have immediate applicability.

Abbreviations

LSD: least significant difference; PM: planting material; REML: restricted maximum likelihood approach; sph: stems per hectare; TRL: total root length; TRLD: total root length diameter; TRM: total root mass; TRMD: Total root mass diameter; Y1: year 1; Y2: year 2; Y3: year 3.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

GD participated in the design of the study, data acquisition, and drafted the manuscript. IM conceived of the study, participated in its design, coordination and data acquisition, and helped to draft the manuscript. CL-W conducted the statistical analyses and helped draft the section on analyses. All authors read and approved the final manuscript.

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