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Below-ground morphology of *Cordyline australis* (New Zealand cabbage tree) and its suitability for river bank stabilisation

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Abstract Observations and measurements on the below-ground characteristics of the New Zealand cabbage tree, *Cordyline australis*, from river bank environments near Christchurch, New Zealand, revealed a unique structure of peg-like rhizomes and fine spaghetti-like roots. By age 25 years, root depths reached 1.75–2.00 m, root spread reached 3.00 m, and below-ground root biomass, including the rhizome, exceeded 50 kg or 38% of the total tree biomass. Fine *C. australis* roots of diameters 0.6–3.8 mm had mean tensile strengths in the range of 26.7–17.5 MPa, 30% less than those of most willow (*Salix*) species. The pullout resistance of five c. 8-year-old self-seeded *Cordyline australis* trees ranged between 5.57 and 14.2 kN. In terms of the parameters assessed against published information for willows, it appears that *C. australis* falls short on both growth rate and tree anchoring parameters (tensile strength and resistance to pullout) for use as a river bank protection plant in all rivers. However, when grown with other native riparian colonising plants such as flax (*Phormium* spp.), river bank protection may be comparable, especially in low-order streams with silty soils and lower hydrodynamic forces.

Keywords *Cordyline australis*; cabbage tree; biomass; rhizome; root tensile strength; erosion control; biodiversity

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INTRODUCTION

The below-ground characteristics of New Zealand's native plants have generally received little attention. Published studies have mostly involved one or a few specimens usually of a limited age range (e.g., Cameron 1963; Phillips & Watson 1994; Watson et al. 1995, 1999; Wardle 2002; Marden et al. in press). This paucity of data is a reflection of the time-consuming nature of root system extraction, particularly for large shrubs and trees, as well as the fact that root systems are often influenced by soil conditions, making statistical comparisons difficult. This study reports observations made on the below-ground morphology of *Cordyline australis* (G.Forst.) Endl. (cabbage tree, ti kouka), a distinctive monocotyledon tree endemic to New Zealand. While there has been significant research on its above-ground characteristics (e.g., Harris et al. 1998, 2003; Harris & Beever 2000), research specifically on the below-ground attributes of *C. australis* has largely been limited to young plants (Tomlinson & Fisher 1971) and accounts of its use for food (Harris & Mann 1994; Simpson 2000). This study focussed on what has been described as "structural roots" (Phillips & Watson 1994), in this case those greater than about 1 mm in diameter.

Cordyline australis is widely distributed in New Zealand, and Simpson (2000) detailed its classification, ecology, use, and place in New Zealand culture. Except in the far south, it grows throughout New Zealand under both moist and dry conditions between sea level and 1000 m a.s.l. A range of environments from swamps, rivers, and lake margins to rocky places and forests may be regarded as the main natural habitats. Associated with the New Zealand flax (harakeke, *Phormium tenax* J.R.Forst. & G.Forst.) and the native grass toetoe (*Cortaderia richardii* (Endl.) Zotov), cabbage trees usually form a band between water and dense swamp forest. *C. australis* is a light-demanding pioneer species that requires open space in order to establish. Phenomena like flood events that create bare river banks, windthrow that induces gaps in vegetation, drought, fire, and frost are required for this species to propagate and persist. Riparian environments have always been favoured habitats. Bare river banks and open, fluvial deposits of sand, silt, and gravel offer perfect sites for seedling establishment.

Species of the genus *Cordyline* not only differ from normal monocotyledonous growth in their above-ground, arborescent habit, but they also establish a conspicuous and uncommon rhizome and root system (Tomlinson & Fisher 1971). *C. australis* shows a normal hypogean growth pattern for large woody monocotyledons during the plant's seedling phase. However, a sudden change in growth pattern may be observed during the plant's juvenile phase. One of the earliest axillary buds develops an obliquely outward and later vertically downward growing shoot, which possesses a distinct rhizome morphology. The age of the plant on which the rhizome is initiated may vary appreciably (Tomlinson & Fisher 1971). In early stages of sapling development, growth of the young rhizome is so rapid that the existing seedling axis is displaced laterally. It may persist as a more or less distinct appendage. Such rapid growth is indicated by the rhizome's white, smooth surface and fleshy scale leaves. In subsequent development, the sapling retains a single axis without obvious indication that the lower (hypogean) part is a branch of the upper (epigean) part (Tomlinson & Fisher 1971). This below-ground stem or rhizome greatly increases the opportunity for new roots to form, helps anchor the young plant, and also stores food and water. This ability of the stem to grow in opposite directions at the same time is one reason why juvenile cabbage trees grow quickly. In older trees, multiple rhizomes are common and large, and may be described as an "elongated carrot" (Best 1976), "conic shaped" (Brunner 1952), or club-like acting as a series of massive pegs in the ground (Simpson 2000) (Fig. 1).

A young adult tree may have about a thousand roots, each several millimetres in diameter and growing horizontally or obliquely away from the rhizome(s). These "spaghetti-like" roots may branch into complex "brushes" of rootlets (Tomlinson & Fisher 1971; Simpson 2000). The many and long roots of a cabbage tree mean that a large patch of soil around a tree is dominated by them, helping anchor the tree. Growth of the fine roots, however, is not restricted to the rhizome. As the cambium (where root traces are initiated) is present along the entire trunk, adventitious roots may develop from any position of the tree or even a piece of fallen branch (Tomlinson & Fisher 1971; Simpson 2000).

Since 1997, the introduced willow sawfly (*Nematus oligospilus*) has caused widespread defoliation among New Zealand's willow trees, posing a threat to river bank protection programmes (Charles et al. 1999). River engineers are seeking alternative plant species that provide this river bank protection function. In addition, there is now an increasing movement to bring more indigenous plants back into New Zealand's managed landscapes, largely to improve water quality in streams and rivers but also to increase biodiversity (Ministry for the Environment 2000; Parliamentary Commissioner for the Environment 2002; New Zealand Ecological Restoration Network (NZERN) 2005). Because of its naturally occurring association with rivers, *C. australis* has been suggested as one of a number of indigenous species to provide both these roles. As waterway restoration and enhancement projects increase in popularity, there is a need to quantify the effectiveness of these vegetation strategies (Phillips et al. 2001).

The architecture or morphology of a plant's root system and the density (or number) of plants are factors that influence the degree to which soil is reinforced. This influence is reflected in variables such as the root area ratio (Wu et al. 1979) and its distribution in the soil. The mechanical contribution of plant roots to soils is normally assessed by determining the live root-wood tensile strength (tensile breaking stress) or the anchorage of entire root systems (pullout resistance).

In this study we excavated 13 riverside *C. australis* trees to examine their below-ground structures of rhizomes and roots. We determined the tensile strength of roots, and conducted in situ pullout tests of five other trees. The results are compared with similar studies of willow (*Salix* spp.) to consider whether *C. australis* may be an effective species for river bank protection.

METHODS AND MATERIALS

Site

The study area was in the lower floodplain of the Waimakariri River on the south berm between a rock rip-rap bank protection and the flood stopbank, 15 km north of Christchurch, New Zealand (43°25′S, 172°37′E). Soils are Recent Soils developed from alluvial deposits comprised mostly of silt and fine sand (c. 50% silt and around 10% clay) (Griffiths 1979), though one tree (Tree 7) grew in silty soils

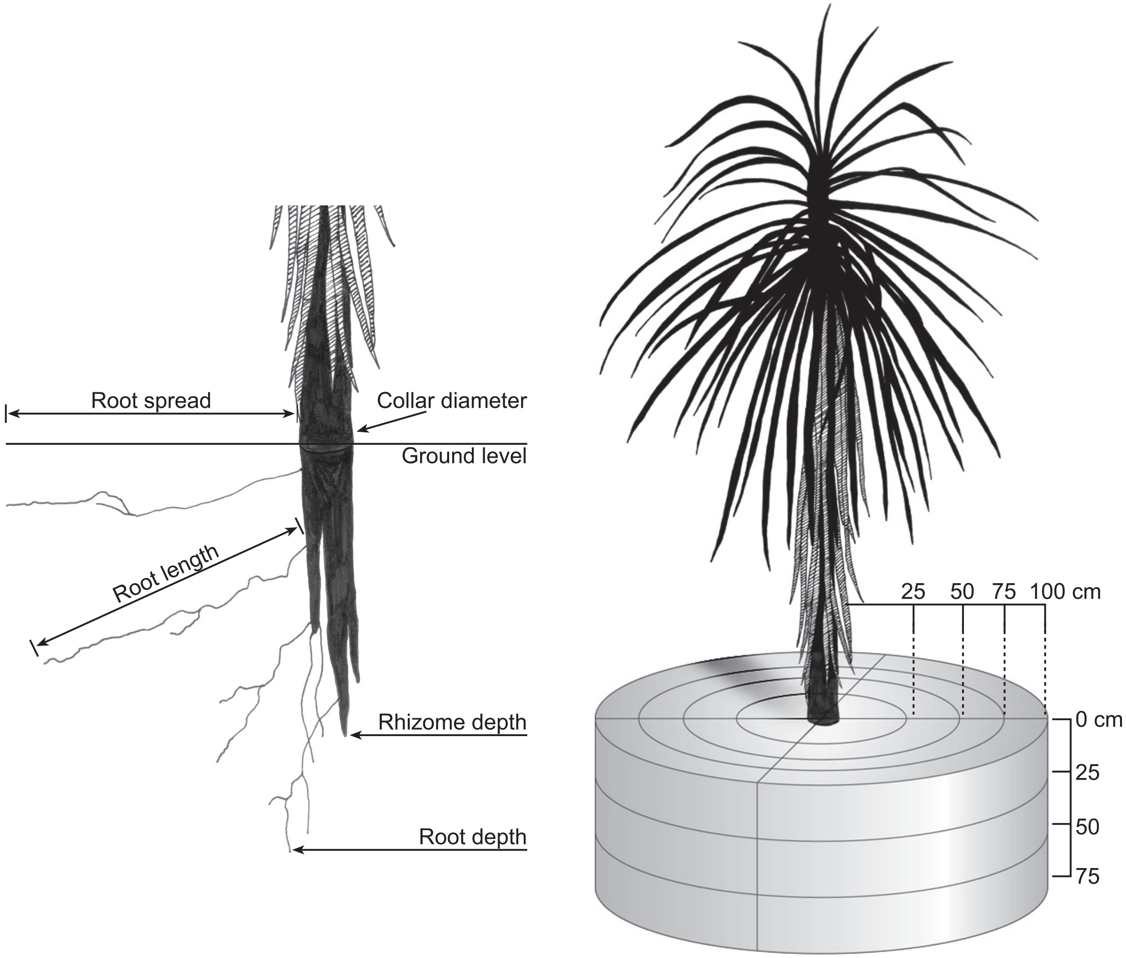


Fig. 1 Nomenclature and partitioning of below-ground morphological structure.

that contained a thin gravel layer at 15 cm below the ground surface. Soils show minimal profile development. Mean annual rainfall is 624 mm (Tomlinson & Sansom 1994). Below-ground morphology and biomass were assessed on 13 self-sown *C. australis* (1–25 years old) growing within willow protection plantings 20–30 years old. Five pullout tests were also conducted on trees growing within an area of willow and poplar protection plantings that had been removed about 6 months before the beginning of the study. The specimens were growing on areas undisturbed by the clearfelling operations, where the soil had not been compacted and root systems remained undamaged. Further site details are presented in Czernin (2002).

Morphology and biomass

The below-ground morphological structures of cabbage trees were exposed by hydraulic sluicing. Sluicing started far enough downslope from the tree stump to ensure that, as the excavation proceded upslope, it was of sufficient depth to expose the vertical rhizomes and deeper roots. After approximately a third of the rhizome(s) had been exposed, they were secured with rope to maintain their original position relative to the ground surface. The remaining parts of the structures were then excavated. The exposed structures were photographed, drawn to scale, and measured (Fig. 1). The excavated systems were partitioned into concentric rings (similar to growth rings) based on the rhizome surface (after Watson & Tombleson 2002). Each ring was 25 cm deep and 25 cm wide (Fig. 1). Root diameter (Tree 13 only), root spread (horizontal distance from the rhizome/trunk) (except Tree 8), maximum root length, rhizome depth, root depth, root growth angle (not reported here), collar diameter (diameter of junction of trunk and rhizome at ground surface), and dry weight were measured (Böhm 1979; Atkinson 2000). Individual root lengths were not measured due to time constraints, and all fine roots were grouped into 20-cm-length classes. Maximum root depth was taken as the maximum depth that a root was found or the depth of the rhizome, which for the younger plants tended to be the maximum depth. Root branching details (other than for rhizomes) were not recorded.

Adverse weather caused delays between excavation and detailed study of the root systems in all but Tree 13. Desiccation leading to possible shrinkage of exposed roots meant that diameters were assessed only for the oldest tree (13). Full hydraulic excavation of Tree 13 was not possible because of the unavailability of the sluicing pump, the size of the hole that needed to be excavated, and drainage from the site. For this tree, root depth including length of rhizome and biomass were estimated based on what was visible (about 40% of the structure). Its roots were manually dug up from the remaining, undisturbed part of the structure.

Plant age was determined by counting annual rings from oven-dried rhizome samples that had been cut at ground level (Simpson 2000, p. 101). Above-ground morphology and biomass assessed in the study are generally not reported in this paper (see Czernin 2002).

Root tensile strength testing and pullout testing

Tensile strength tests were conducted in the laboratory to measure the strength of individual cabbage tree roots, and in situ pullout tests were carried out to measure the anchorage of entire trees.

Tensile breaking tests on fine roots are commonly conducted using a Universal Testing Machine (e.g., Instron Floor Model 1195) (O'Loughlin & Watson 1979; Watson et al. 1997; Watson & Marden 2005). Issues with load cell resolution and compatibility with the available testing machine (Instron Floor Model 1195) required the construction of a special-purpose testing device, details of which can be found in Czernin (2002).

Generally, if root diameter (*x*-axis) is plotted against tensile strength (*y*-axis), root tensile strength decreases with increasing root diameter, i.e., a negative power function (Wu 1976; Stokes 2002). To enable comparison with other species, all roots tested must fall within a predetermined diameter range (Watson & Marden 2005). In this study, roots with an under-bark (cortex) diameter between 1 and 4 mm were selected for testing and comparison.

One hundred and fifty-five root samples approximately 200 mm long were randomly taken between 10 and 60 cm below the ground surface from Tree 13 for tensile strength testing, once the structure had been measured and drawn. Root samples were sealed in plastic wrap, transported to the laboratory, stored overnight at room temperature and constant humidity, and their diameters measured the following day before tensile strength tests were conducted. After the root cortex had been carefully removed, root diameters were measured with callipers to the nearest 0.1 mm at the mid-point of the 200-mm-long root sample before tensile tests were conducted. The root samples were then wiped dry and clamped at both ends in the testing device. The roots were tested at an approximate strain rate of 12°/s and the voltmeter-output at which breakage occurred (tensile breaking stress) was recorded. The applied force required to break the roots was taken as the measure of root strength. Tensile strength was calculated by dividing the applied force required to break the root by the cross-sectional area of the root at its rupture point. As the root samples were roughly circular in diameter, the tensile strength, σ_{max} (MPa), was calculated using the expression

$$\sigma_{\mathrm{max}} = 4F_{\mathrm{max}} / \pi D^2$$

where $Fmax$ = force required to break the root (kN/10^3) and D = diameter of the root (m).

Tests subject to slippage or those roots that broke because of problems with clamping were discarded.

Roots from willow trees (*Salix fragilis* L.) growing at the study site were also extracted using similar extraction and handling/storage methods to those of cabbage trees and tested to determine their tensile strength. A total of 77 tests were conducted. In addition, these data were compared with published tensile strength data for willow trees. However, as limited published data exist for self-sown willow trees, comparisons also include those propagated from poles (Hathaway 1973; Schiechtl 1973; Gräßer 1994; Oplatka 1995, 1998; Weitzer et al. 1998). Willow species used in the comparisons are those most commonly used for riverbank protection measures throughout New Zealand: *Salix elaeagnos* Scop., *S. purpurea* L., and *S. matsudana* Koidz. × *alba* L. Where it was possible, tensile tests on fine roots from silty soils generally comparable to the study site were compared. However, some studies gave no information on the soil conditions in which the roots were growing.

In studies on anchorage components, the root system's strength is calculated from the sum of the basal strengths of individual roots and their growing media. In situ, however, entire underground systems may resist much greater forces since the system is still embedded in the soil. Contrary to tensile strength tests where roots are clamped in the testing device only at their ends, the entire underground system (including rootlets and root hairs) contributes to anchorage when tested under natural conditions.

Pullout tests are performed by applying a tensile force to the plant while the peak force required to pull the tree from the soil (pullout or uprooting resistance) is measured. The uprooting resistance of plants depends upon numerous factors including the soil shear strength, τ, the soil moisture content, and the plant's underground morphology (Ennos & Pellerin 2000).

Soil shear strength was measured with a hand shear vane tester (Pilcon brand) at 20, 40, and 60 cm depth under saturated and unsaturated conditions for each of the studied trees. Five measurements were made at each depth at a distance approximately 1.5 m from the tree stump. Soil water content of field soils was measured using a Campbell Scientific CS615 Water Content Reflectometer. However, after initial measurements produced unreproducible and erroneous results, water content measurements were abandoned.

The in situ pullout tests followed the general methodology of Oplatka (1998). The five trees were felled approximately 50 cm above ground level. A sash cord, placed around the tree stem (trunk) approximately 20 cm above ground, was used to attach the plant to a hand-powered chain hoist (max. load 6 t) that had been fastened to a strong anchor tree by a steel chain. To avoid slippage of the cord, the tree's bark was removed where the cord was attached to the tree stump. The tension force, applied horizontally (i.e., parallel to the ground surface) in the direction of water flow, was measured using a PT-ST 500 load cell (Precision Transducers Instrument, max. load 500 kg) and a CR21X datalogger (Campbell Scientific). A measuring tape, fixed to the stump and to a wooden pole, measured the tree stump's horizontal displacement. Measured logger-output was recorded for every centimetre of stump displacement. Recording started as soon as the chains were tightened and ended with the total failure of the underground system, i.e., the trunk and attached roots or rhizomes that were broken during the test. Following the pullout tests, the removed underground systems were photographed and measured and the (largely broken) rhizomes were cleaned and measured in detail. Additionally, the depth at which the rhizomes broke and the type of breakage were recorded. It should be noted that such horizontal pullout tests simulate the resistance of plants to windthrow (e.g., Coutts 1983, 1986) rather than their ability to resist fluvial erosion. However, as the aim of this research was to compare the results with existing pullout-data on willow trees, the methods needed to be comparable to those of previous studies (e.g., Oplatka 1995, 1998). While exact measurements of water content were not made, field soils were either manually saturated prior to pullout testing or the tests carried out immediately after heavy rainfall.

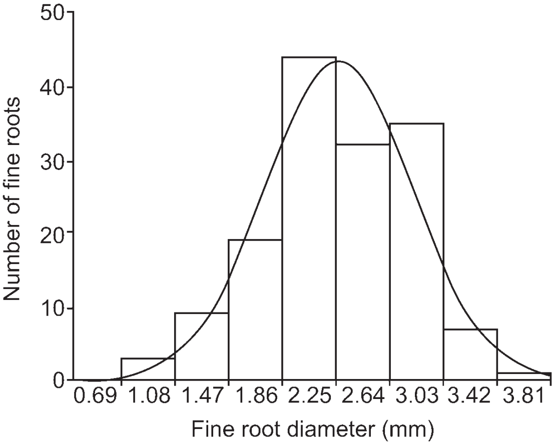


Fig. 2 Normal distribution of fine root diameters from Tree 13.

RESULTS

Below-ground characteristics and biomass

A Kolmogorov-Smirnov test showed that root diameters were normally distributed and the mean root diameter from Tree 13 was 2.45 mm (Fig. 2). Most of the roots (58–100%) of younger trees (1–5 years old) were 0–40 cm long (Table 1). Root spread among these plants varied between 75 and 125 cm, with roots reaching depths of 50–100 cm below ground level. Root spread of the oldest tree (Tree

13) was 360–380 cm and the maximum depth was estimated to be 175–200 cm below ground level (further details can be found in Czernin 2002).

At the age of 4–5 years, most of the trees studied possessed a single vertical rhizome with collar diameters of 1.4–3.4 cm and reaching depths of 16–22 cm. The vertical growing rhizome starts to fork between the ages of 4 and 5 years and appearance of additional rhizomes generally occurred within the uppermost 30 cm of soil depth. Older plants (8–25 years) developed varying numbers of rhizomes (8–21 per tree). Most trees at ages 8–13 years had multiple-forked rhizomes (7.5–23.6 cm diam.) that reached depths of 60–109 cm. The oldest tree (25 years) had a multiple-forked rhizome that reached a depth of 178 cm. In all the trees studied, the depth of the rhizome was strongly correlated with the collar diameter of the plant at ground level (rhizome depth = diameter × 4.9, $t_{12} = 16$, $P < 0.001$, $r = 0.98$) (Fig. 3). The oldest tree had three stems/rhizomes and a compound collar diameter of 59.2 cm.

In younger trees (2–8 years), nearly 70–90% of the total root biomass was concentrated in the top 25 cm of soil (Table 2). More than 90% of the root dry weight was found within 50 cm of the soil surface. Distribution of root biomass in the oldest plants showed that 30–40% of the root dry weight occurred within the top 25 cm of soil.

The smaller trees had 60–90% of their root biomass within 25 cm of the rhizome and 83–100% within less than 50 cm. For the larger trees (11–25 years old) 44–59% of the root biomass was found less than 25 cm from the rhizome while 67–84% was located within 50 cm of the rhizome surface.

Table 1 Summary of below-ground characteristics of *Cordyline australis* trees of increasing collar diameter. *Tree 8 was not fully assessed. Tree 13 includes the mean diameter of the three rhizomes (37.4 cm) and the compound collar diameter (59.2 cm).

Diam. (cm)	0.7	1.4	1.8	2.1	2.1	2.7	3.2	3.4	7.5	8.7	15.9	23.6	37.4/59.2
Age (yrs)	1	2	4	2	4	5	4	4	8	8	11	13	25
Tree no.	12	4	3	5	9	11	2	10	8	1	6	7	13
Maximum root length class (cm)	20–40	20–40	60–80	40–60	20–40	80–100	100–120	100–120	280–300	200–220	160–180	200–220	360–380
Root spread class (cm)	25–50	25–50	50–75	25–50	25–50	50–75	100–125	75–100	*	200–225	125–150	225–250	275–300
Root depth class (cm)	25–50	25–50	25–50	25–50	25–50	25–50	25–50	75–100	150–175	75–100	75–100	125–150	175–200
Number of rhizomes	1	1	1	1	2	2	1	1	8	1	3	7	21
Rhizome depth (cm)	1.3	10.0	13.7	8.5	10.8	16.7	18.7	22.0	66.0	30.5	79.0	109.0	178.0

Table 2 Summary of root and total rhizome dry weight (g) of *Cordyline australis* trees of increasing collar diameter. Figures in parentheses are the percentage of the total. Tree 13 includes the mean diameter of the three rhizomes (37.4 cm) and the compound collar diameter (59.2 cm). For Tree 13, approximately 40% of the total root dry weight could not be determined.

d_o (cm)	0.7	1.4	1.8	2.1	2.1	2.7	3.2	3.4	7.5	8.7	15.9	23.6	37.4/59.2
Age (yrs)	1	2	4	2	4	5	4	4	8	8	11	13	25
Tree no.	12	4	3	5	9	11	2	10	8	1	6	7	13
Roots	0.1 (50)	1.1 (28)	1.8 (19)	0.6 (22)	2.4 (21)	7.9 (26)	55.5 (58)	14.8 (21)	107.9 (7)	45.1 (16)	145.3 (6)	137.3 (1)	800.3 (2)
Rhizome	0.1 (50)	2.8 (72)	7.5 (81)	2.1 (78)	8.8 (79)	22.2 (74)	40.3 (42)	56.0 (79)	1473.2 (93)	233.6 (84)	2270.8 (94)	10994.1 (99)	51306.4 (98)
Total (g)	0.2	3.9	9.3	2.7	11.2	30.1	95.8	70.8	1581.1	278.7	2416.1	11131.1	52106.7

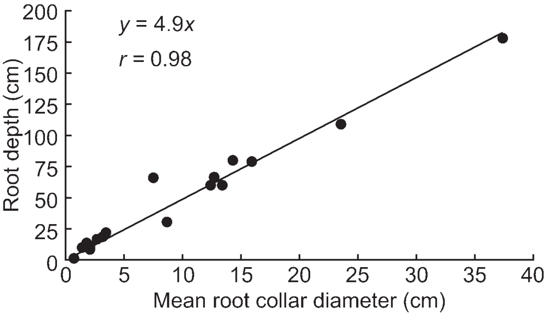


Fig. 3 Regression of mean collar diameter (cm) against root depth (cm). This regression was calculated using the mean collar diameter of 37.4 cm for the oldest studied cabbage tree.

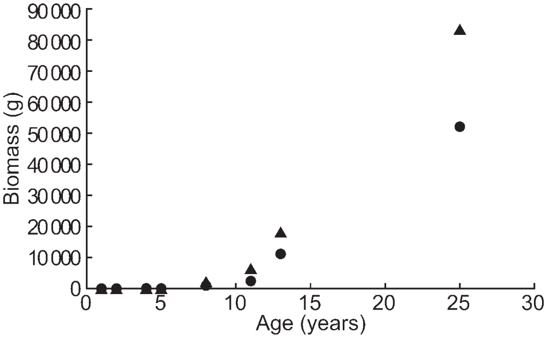


Fig. 4 Relationship of age (years) and biomass (g), showing above- (▲) and below- (●) ground biomass. The mean diameter of the three rhizomes (37.4 cm) is used.

About 90–100% of the root dry weight was located within 150 cm of the rhizome.

The total rhizome dry weight was also strongly correlated to the mean collar diameter ($r^2 = 0.99$). Most of the rhizome biomass of older trees was distributed within the uppermost soil layers (>60% in top 50 cm of soil). For the oldest tree, nearly 90% of the rhizome dry weight was found in the top 75 cm.

As development of the rhizome commences after development of fine roots, juvenile trees may have a relatively balanced ratio of fine-root and rhizome dry weight. While below-ground systems of young trees showed that 21–58% of the total dry weight consisted of the fine roots, they only contributed 1–6% to the total below-ground dry weight in older trees (11–25 years) (Table 2).

In terms of total biomass, the above-ground parts (trunks, branches, and tufts) as well as the rhizome formed an increasing proportion of the total plant biomass as the plants got older (Fig. 4, 5). While in younger cabbage trees 36–87% of the total dry weight was contained in the foliage and the roots, these parts contributed only 11–12% to the total plant biomass in later stages of development.

For the two oldest cabbage trees, 83–89% of the biomass was in the above-ground parts and the rhizome, of which the rhizome had 26–38%.

Root strength

Roots of *C. australis* trees with diameters 1.0–3.8 mm showed a decrease in tensile strength with increasing diameter, though the relationship has a wide scatter (Fig. 6). Roots of diameters 0.6–2.0 mm had a mean tensile strength of 26.7 MPa, roots of 2–3 mm had a mean tensile strength of 24.4 MPa, and roots of diameters 3.0–3.8 mm showed a mean tensile strength of 17.5 MPa. Differences between the three groups were not significantly different.

Roots of *S. fragilis* with diameters 1.0–3.8 mm also showed a decrease in tensile strength with increasing diameter and a wide scatter in the data (Fig. 7). The tensile strength of willow roots were on average 30% greater than those of an equivalent diameter from cabbage trees.

Soil shear strength at the pullout test sites was markedly influenced by a high groundwater table (approximately 60 cm below ground) and values decreased by 22–50% between 20 and 60 cm depth below the ground surface. Unsaturated shear strength ranged between 24 and 39.9 kN mm^{-2} at 20 cm depth, between 19.9 and 28.7 kN mm^{-2} at 40 cm depth, and between 14.3 and 20.3 kN mm^{-2} at 60 cm depth. Once soils were wetted, the saturated shear strength was reduced at all depths, 7–25% lower at 20 cm, 12–31% lower at 40 cm, and 6–25% lower at 60 cm depth.

The pullout resistance of five 7–8-year-old self-sown *C. australis* trees ranged between 5.57 and 14.2 kN. Failure of the underground system in all pullout tests occurred by breakage (shear break) of the rhizome. After the peak tension force had been reached, no significant second peaks were observed as the root system continued to be pulled from the ground. On the "upstream" side of the root system (i.e., away from the direction of pull), the majority of near-surface roots showed a typical tensile break, while most of the roots in deeper soil layers slipped out of the ground (thereby losing the cortex). Most roots on the "downstream" side also slipped out of

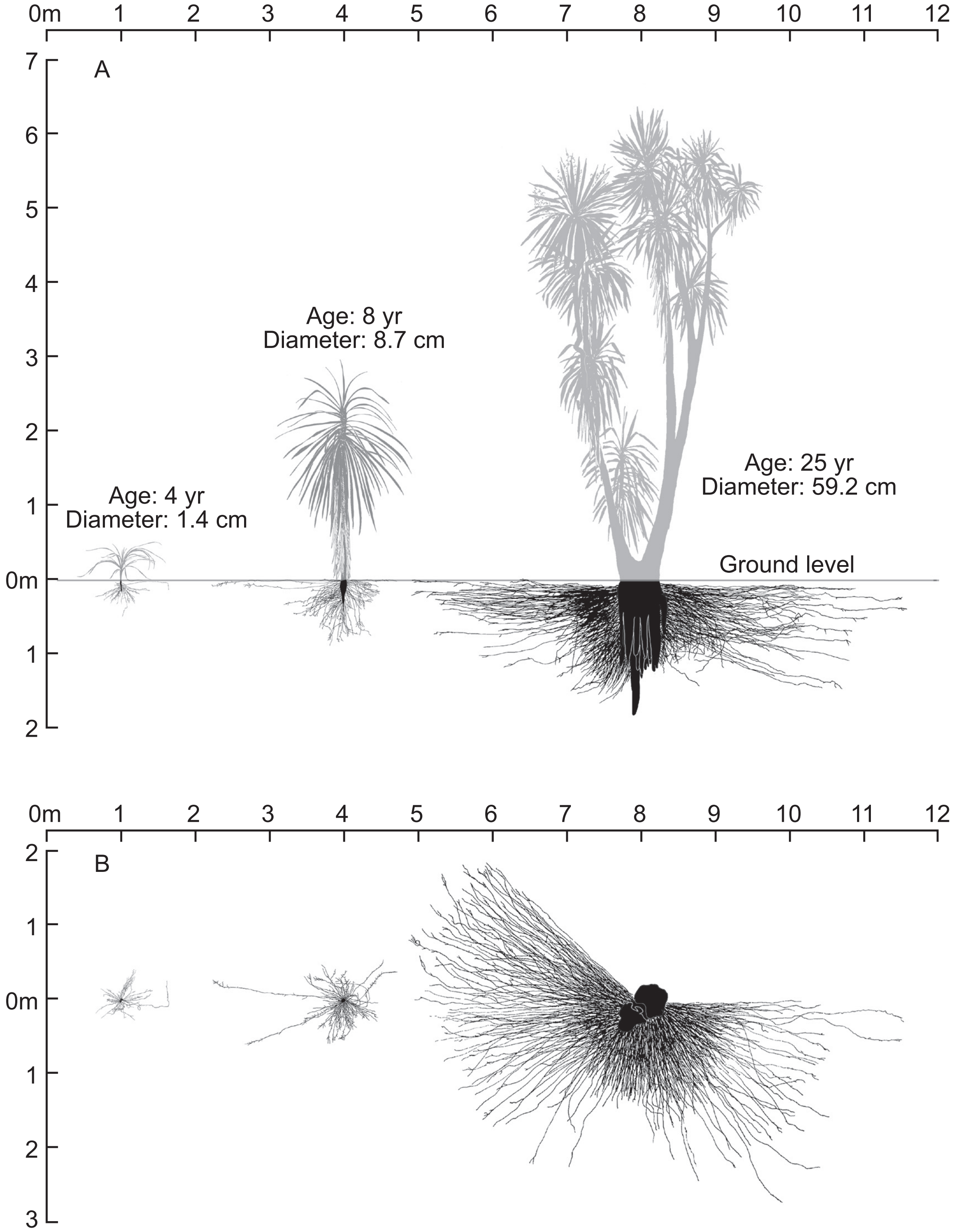


Fig. 5 Three age classes of *C. australis* showing above- and below-ground morphology in **A**, side view and **B**, plan view.

Fig. 6 Tensile strength (MPa) of fine cabbage tree roots from this study.

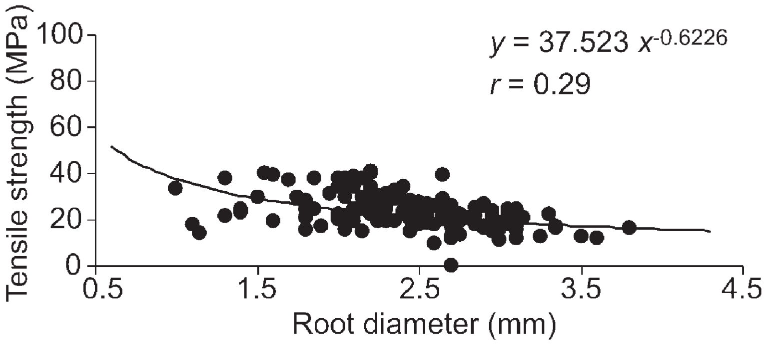
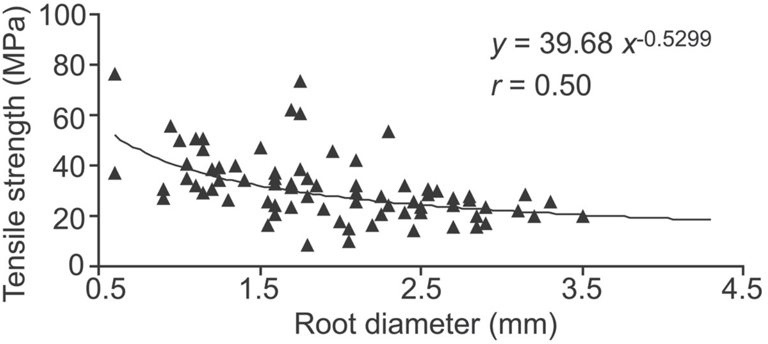


Fig. 7 Tensile strength (MPa) of fine willow tree roots from this study.



the ground. During testing, trees with larger collar diameters appeared to resist higher tension forces, though no significant correlation was found ($r^2 = 0.35$, $P = 0.297$). The pullout resistance and the point at which breakage occurred were also not significantly correlated to soil shear strength. Regression analysis showed that the pullout resistance was more correlated to rhizome length ($r^2 = 0.88$, $P = 0.062$).

Comparisons with willows

An attempt was made to compare cabbage tree and willow tree data obtained from similar field conditions and sites. However, in comparing results, several factors may contribute to the observed differences. The most significant is that site conditions are not usually identical between studies. Additionally, edaphic factors and light conditions can influence plant growth and development even within the same species and on the same general site.

Most published data on the above- and below-ground development of willow trees are from tests conducted on willows used in soil-bioengineering measures (e.g., brush layers or pole plantings). Most data are for parameters such as tensile root strength or pullout resistance rather than biomass development at different ages from planting. Development of root systems propagated from poles also differs greatly from that of self-sown plants. While juvenile self-sown plants generally exhibit a vertically oriented primary root, adventitious roots dominate root development among plants propagated from poles.

Willow roots tend to resist higher tension forces than fine *C. australis* tree roots. At diameters of 1.0–3.8 mm (range of the studied *C. australis* tree roots), mean tensile strength of *Salix fragilis* roots exceeded that of *C. australis* tree roots by 30%, *Salix matsudana* × *alba* (Oplatka 1995) by 38%, *S. matsudana* (Hathaway 1973) by 64%, *S. purpurea* by 58%, and *S. elaeagnos* by 123% (Fig. 8).

In the early years of development, growth of willow trees exceeds that of *C. australis* trees until about age 10 years when *C. australis* trees reach heights comparable to that of willows. In addition, the above-ground parts of shrub willows generally develop a multiple-stemmed form, while cabbage trees generally develop an arborescent form.

Young willows grown from seeds and poles possess a heart root system with horizontal roots in

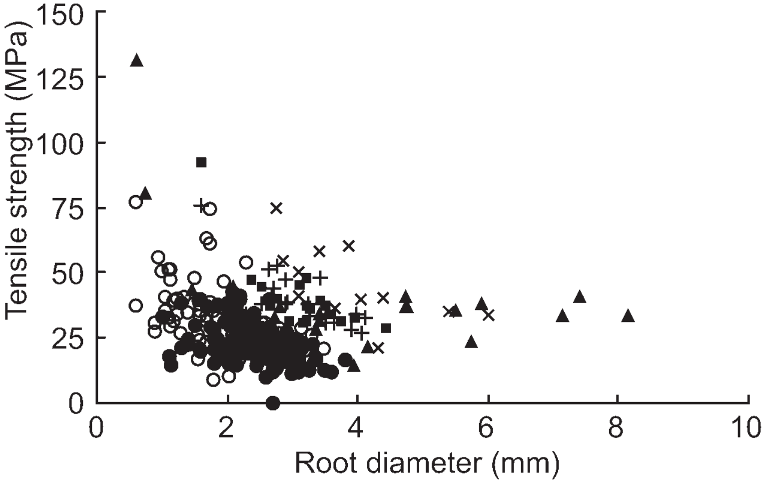


Fig. 8 Tensile strength (MPa) of fine cabbage tree and willow tree roots from this study and other willow roots from available literature. ●, *Cordyline australis* (this study); ▲, *Salix matsudana* × *alba* (Oplatka 1995); ×, *Salix elaeagnos* (Oplatka 1995); ■, *Salix purpurea* (Hathaway 1973); +, *Salix matsudana* (Hathaway 1973).

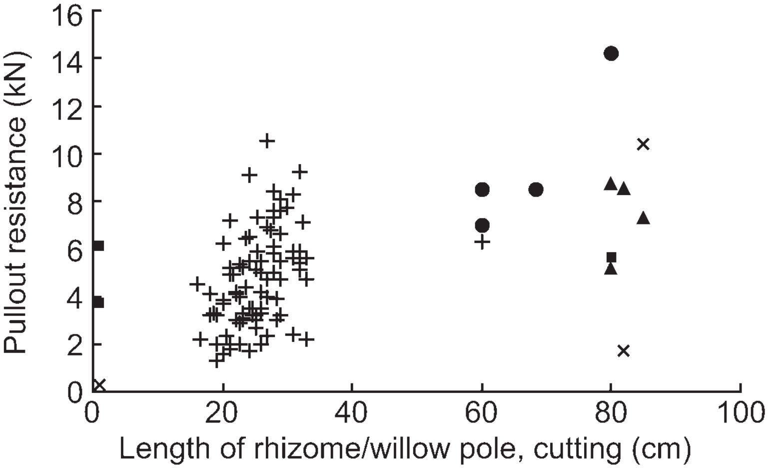


Fig. 9 Pullout resistance of self-sown cabbage trees and willow poles. ●, *Cordyline australis* (this study); ■, *Salix purpurea* (Oplatka 1998); ×, *Salix elaeagnos* (Oplatka 1998); ▲, *Salix matsudana* × *alba* (Oplatka 1998); +, *Salix purpurea* (Volsinger et al. 2000).

the well-aerated superficial soil layers, as well as deeper penetrating and supporting roots (Ortner in Hathaway 1973, p. 8). Hathaway (1973) described root systems (from cuttings) of *Salix matsudana* and *S. purpurea* that developed most of their roots at the end of the cutting. These (adventitious) roots were oriented downwards at an angle of approximately 45°. Root systems of *S. matsudana* reached 2–2.5 m below ground level.

Cordyline australis trees, in contrast to willows, develop a distinct rhizome from which lateral fine roots with diameters of 2–5 mm arise from the entire length of the rhizome. This is the main difference between cabbage tree and willow tree root systems. In addition, unlike willows and many other trees that show thickening of lateral roots close to the root bole, thickening of *C. australis* tree roots spreading from the central root bole (rhizome) does not occur.

Comparing pullout resistance of *C. australis* trees with that of willows proved to be difficult, as willow pullout studies have been conducted mainly on poles. The data on willow poles selected for this comparison either developed in 40-cm-deep sand/silt overlying coarse gravel in the same river system as the current study (Oplatka 1998) or in fluvial soils with little or no stone content (S. Vollsinger pers. comm.). As the diameter of the willow poles had not been measured at ground level (M. Oplatka pers. comm.), the comparison was plotted as a function of the pullout resistance against the pole/rhizome length (Fig. 9).

At first glance, the pullout resistance of 7–8-year-old *C. australis* trees (5.57 and 14.2 kN (Fig. 9)) appears to lie within the range of tested willow poles (cuttings). However, it should be noted that diameters of the willow poles were only 30% of those of *C. australis* trees, although both had similar root depths. The only data set of willows comparable with the *C. australis* trees was conducted in gravel soils (aged 6.5 years; Oplatka 1998).

Data on the ratio of roots to shoots (or below-ground to above-ground biomass) of willow trees is limited. Schiechtl (1973) determined the root: shoot ratio among self-seeded *Salix purpurea* to be 1.5 while Gräßer (1994) found a mean root:shoot ratio of 0.25 among 1-year-old plants increasing to 0.47 in 4-year-old plants. In this study, considerable variation existed in the 1–5-year-old plants, with values ranging between 0.22 and 1.50. The ratio in the older trees ranged between 0.37 and 0.62. Thus, cabbage trees have between 27 and 38% of the total plant dry weight in their below-ground parts while Schiechtl's (1973) data for *S. purpurea* indicated that 60% of the total plant biomass was contained in the root system.

DISCUSSION

Most methods of studying the morphological characteristics, architecture, or biomass of underground plant systems are time and labour intensive and usually involve partial or complete removal of the growing media (e.g., Polomski & Kuhn 2002), although non-invasive methods have been tried with some success (e.g., ground penetrating radar; Stokes et al. 2002). Because of these constraints it is often difficult to obtain enough sample trees to satisfy statistical analyses or to deal with variability of site factors. Nevertheless, there is value in making relatively simple, but repeatable, observations of the below-ground characteristics of plants. Such information is useful not only for completing our knowledge of the plant in question but also to assist in understanding of the functions a plant might be suited for, such as soil stabilisation or wind firmness.

There have been few data published on the below-ground parameters of *C. australis*. Harris & Mann (1994) reported the excavation of a tree 6 m high from a home garden. This tree had several rhizomes that extended vertically to a depth of 90 cm. The fine roots extended even deeper and also laterally from the longest rhizome. A 6-year-old *C. australis* plant extracted and examined from a mine restoration plant trial site had fine roots between 1 and 2 mm in diameter that spread radially up to 2.10 m from the 86-cm-deep rhizome and did not change in diameter for 95% of their length (A. Watson unpubl. data). Simpson (2000) reported a maximum rhizome length of 1 m for a 16-year-old plant and 3 m for an old plant of unknown age, as well as fine roots that can grow 5–10 m away from the tree. More recently a trial of indigenous riparian colonisers looked at the above- and below-ground characteristics of 10 *C. australis* trees 1–5 years old (Marden et al. in press). At age 5 years, *C. australis* had greatest root depth (including rhizome depth) (mean 0.4 m) but had the lowest percentage of root biomass to total biomass of the 12 species studied (19%).

Our study has provided quantitative data over a range of ages relating to the below-ground structures of these trees. It complements studies on the above-ground aspects of this plant (Tomlinson & Fisher 1971; Harris & Mann 1994; Harris et al. 1998, 2003; Harris & Beever 2000; Simpson 2000) as well as the limited studies on the below-ground aspects (Tomlinson & Fisher 1971; Harris & Mann 1994; Marden et al. in press). This study has supported what was largely anecdotal and observational evidence of the below-ground structures of *C. australis* (e.g., Simpson 2000).

In summary, the below-ground morphology of the cabbage tree shows the development of a distinct rhizome, from which numerous roots arise and radiate from the rhizome like strands of spaghetti or the spokes of a wheel. In a 25-year-old tree these roots have a mean diameter of 2.45 mm. The outer margins of these roots form complex "brushes" of rootlets (Simpson 2000, p. 97). In the younger trees (1–5 years), roots were concentrated in the top 50 cm of soil and did not spread more than 1.25 m from the trunk. At 25 years, roots reached depths of 1.75–2.0 m and spread 3.0–3.25 m. Our findings are similar to those of Marden et al. (in press) who reported 5-year-old cabbage trees having root depths of 0.43 m and root spread from the trunk of 1.11 m.

It is likely that that there will be genetic and/or environmental effects on the growth of the below-ground structures of cabbage trees such as those reported for above-ground attributes between different provenances (populations) (Harris et al. 2003). Harris et al. (2003) suggested that *C. australis* provenances would be good subjects for study in controlled-environment facilities where the effects of temperature and photoperiod control of seasonal growth patterns could be separated. Such studies would add to the relatively small body of information about these controls on the growth and phenology of native plants, and we suggest that the below-ground structures should also be examined. Our knowledge of the variation of the below-ground structure of these trees across the country is limited, and, while it would be time-consuming, it would be beneficial to repeat the simple measurements we have made on a range of plants, particularly those older than about 5 years.

Application to river bank protection

There is growing interest in using more indigenous plants in New Zealand's managed landscapes. This, coupled with an emerging threat of willow sawfly damage to river protection works, has provided the general context for the studies carried out and reported in this paper.

Live root wood tensile strength and whole-tree pullout resistance coupled with the below-ground architecture or arrangement of roots and their distribution within the soil are important in terms of tree anchorage. Tensile strength of cabbage tree roots ranged between 17.5 and 26.7 MPa at diameters between 1 and 3.8 mm. For a similar diameter range, Watson & Marden (2005) reported a mean tensile strength of 26.42 MPa. These data are in the mid–lower end of tensile strengths for tested New Zealand native plants (Watson & Marden 2005) and at least 30% less than those of willows.

While the cabbage tree pullout resistance data are of the same order of magnitude as those from previous tests on willows, it is difficult to compare them because all the test plants were growing in different substrates, the willows tended to have grown from poles, and the ages of the plants were not the same. In terms of assessing pullout resistance as but one index of riverbank protection, we believe the comparison is justified at this stage in the absence of directly comparable data.

During flood events, flexible plants may form streamlined bodies in order to minimise the area subjected to the current. As the plant is bent down, it covers the soil surface thereby contributing to the protection of the river bank (Oplatka 1998). Rigid, solitary plants, like cabbage trees and some species of willow, develop an upright form that may lead to localised increases in flow velocity and erosion as flow becomes concentrated between the trees (Florineth & Gerstgraser 1995).

Based only on the parameters assessed, it appears that *C. australis* cannot serve as a primary substitute to presently used willow species for river protection across a range of river sizes. Young cabbage trees should generally not be planted directly on the lower banks of larger rivers where large hydrodynamic stresses can be expected. However, the cabbage tree may still play an important role in the protection of river banks, particularly on smaller streams with finer grained bank substrates and, perhaps, where hydrodynamic stresses may be less of an issue.

Above the age of 10 years, however, cabbage trees may well afford a high level of protection for river banks, though two issues are worthy of note. Firstly, the rhizome, while significantly increasing its volume as the tree grows, still represents only a local level of protection. In many ways it acts like a localised slope nail. To enhance the protection value, trees may have to be planted at spacings of around 2 m to ensure that a dense network of fine roots develops between neighbouring trees. Alternatively, if planting is required closer to the river bank, sufficient surface coverage has to be ensured in order to protect the ground surface from erosion. New Zealand flax (*Phormium tenax*), which naturally occurs in wet and periodically flooded soils as well as under dry conditions, may be a suitable candidate to fulfil these requirements (Harris 2005). This plant is now commonly used in many stream restoration projects throughout the country as it is easy to propagate and will establish relatively easily. *Phormium* commonly forms thickets up to 3 m tall, with very strong, broad leaves which will bend down to provide a dense ground cover during floods. While flax does not develop a deep or wide-spreading root system, it is reported to grow and maintain roots below the groundwater table (Pollock 1986).

The above-ground form of the cabbage tree may also lead to localised increases in flow velocity of river water around trees during floods. One solution to this might be to coppice trees at regular intervals (approximately every 10 years) to avoid solitary growth (and large trunks) and to encourage multiple-stemmed development. Before European settlement, Maori carried out coppicing of cabbage tree stems on a 4-year rotation as a food crop (Harris & Mann 1994). The ability of cabbage trees to initiate new shoot growth following stem removal coupled with its below-ground structure that allows it to exploit a considerable volume of soil for nutrients and water make it suitable for use in stream-side rehabilitation and restoration projects.

In general terms, while the use of cabbage trees and other native species may be more costly both in terms of establishment and maintenance than for willows, such protection plantings are worth considering, especially where biodiversity enhancement is a top priority. In areas where river bank stability is a major issue, perhaps the way forward is a combination of cabbage trees, other natives such as flax and toetoe, and willows. This approach would maximise the stabilising functions of these plants but also limit any possible future effects of pest outbreaks that might occur in single species plantings.

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REFERENCES

Atkinson D 2000. Root characteristics: Why and what to measure. In: Smit AL, Bengough AG, Engels C, van Norrdwijk M, Pellerin S, van de Geijn SC ed. Root methods, a handbook. Berlin, Springer. Pp. 1–32.

Best E 1976. Maori agriculture, the cultivated food plants of the natives of New Zealand, with some account of the native methods of agriculture, its ritual and origin myths. Dominion Museum Bulletin 9. Wellington, Government Printer. Reprint of 1925 edition. 315 p.

Böhm W 1979. Methods of studying root systems. Ecological Studies 33. Berlin, Springer-Verlag.

Brunner T 1952. The great journey: an expedition to explore the interior of the middle island, New Zealand 1846–8. Christchurch, The Pegasus Press. 111 p.

Cameron RJ 1963. A study of the rooting habits of rimu and tawa in pumice soils. New Zealand Journal of Forestry 8: 771–785.

Charles JG, Allen DJ, Froud KJ, Fung LE 1999. A guide to Willow Sawfly (*Nematus oligospilus*) in New Zealand. http://www.hortnet.co.nz/publications/guides/willow_sawfly/wsawfly.htm [Accessed on 8 September 2005].

Coutts MP 1983. Root architecture and tree stability. Plant and Soil 71: 171–188.

Coutts MP 1986. Components of tree stability in Sitka spruce on peaty gley soil. Forestry 59: 173–197.

Czernin A 2002. Above-ground and below-ground characteristics of the New Zealand cabbage tree (*Cordyline australis*) with particular reference to the root system morphology and root strength. Unpublished MSc thesis, University of Agricultural Sciences, Vienna, Austria. 183 p.

Ennos AR, Pellerin S 2000. Plant anchorage. In: Smit AL, Bengough AG, Engels C, van Norrdwijk M, Pellerin S, van de Geijn SC ed. Root methods, a handbook. Berlin, Springer. Pp. 545–565.

Florineth F, Gerstgraser C 1995. Studienblätter zur Vorlesung Ingenieurbiologie. Institut für Landschaftsplanung und Ingenieurbiologie, Universität für Bodenkultur, Wien.

Gräßer M 1994. Heckenbuschlagen. Ingenieurbiologische Methode zur Hangsicherung. Universität Karlsruhe, Karlsruhe, Germany.

Griffiths G 1979. Recent sedimentation history of the Waimakariri River, New Zealand. Journal of Hydrology (NZ) 18(1): 6–28.

Harris W 2005. Ethnobotanical study of growth of *Phormium* varieties used for traditional Maori weaving. New Zealand Journal of Botany 43: 83–118.

Harris W, Beever RE 2000. Genotypic variation of seedlings of wild populations of *Cordyline australis* (Lomandraceae) in New Zealand. New Zealand Journal of Botany 38: 597–606.

Harris W, Mann JD 1994. Preliminary investigation of the suitability of *Cordyline australis* as a crop for fructose production. New Zealand Journal of Crop and Horticultural Science 22: 439–451.

Harris W, Beever RE, Heenan PB 1998. Phenotypic variation of leaves and stems of wild stands of *Cordyline australis* (Lomandraceae). New Zealand Journal of Botany 36: 593–604.

Harris W, Beever RE, Parkes S, Webster R, Scheele S 2003. Genotypic variation of height growth and trunk diameter of *Cordyline australis* (Lomandraceae) grown at three locations in New Zealand. New Zealand Journal of Botany 41: 637–653.

Hathaway RL 1973. Factors affecting the soil binding capacity of the root systems of some *Populus* and *Salix* clones. Unpublished MSc thesis, Massey University, Palmerston North, New Zealand.

Marden M, Rowan D, Phillips CJ In press. Stabilising characteristics of New Zealand indigenous riparian colonising plants. Plant and Soil.

Ministry for the Environment 2000. Managing waterways on farms: A guide to sustainable water and riparian management in rural New Zealand. Wellington, Ministry for the Environment.

New Zealand Ecological Restoration Network 2005. http://www.bush.org.nz [Accessed on 8 September 2005].

O'Loughlin CL, Watson AJ 1979. Root-wood strength deterioration in *Pinus radiata* after clearfelling. New Zealand Journal of Forestry Science 9: 284–293.

Oplatka M 1995. Beanspruchung von Weiden durch die Strömung, Bericht über den Ausreißwiderstand von Weiden, Versuche in Neuseeland. Eidgenössische Technische Hochschule, Zürich.

Oplatka M 1998. Stabilität von Weidenverbauungen an Flussufern. Unpublished PhD thesis, Eidgenössische Technische Hochschule, Zürich, Switzerland.

Parliamentary Commissioner for the Environment 2002. Weaving resilience into our working lands: Recommendations for the future roles of native plants. Wellington, Office of the Parliamentary Commissioner for the Environment.

Phillips CJ, Watson AJ 1994. Structural tree root research in New Zealand, a review. Landcare Research Science Series 7. Lincoln, Manaaki Whenua Press.

Phillips CJ, Marden M, Rowan D, Ekanayake JC 2001. Stabilising characteristics of native riparian vegetation in New Zealand. Proceedings of 3rd Australian Stream Management Conference, Brisbane, August 2001. Pp. 507–512.

Pollock KM 1986. Plant materials handbook for soil conservation 3: Native plants. Water & Soil Miscellaneous Publication 95. Wellington, Ministry of Works and Development.

Polomski J, Kuhn N 2002. Root research methods. In: Waisel Y, Eshel A, Kafkafi U ed. Plant roots, the hidden half. 3rd ed. New York, Marcel Dekker. Pp. 295–321.

Schiechtl HM 1973. Sicherungsarbeiten im Landschaftsbau. München, Callwey Verlag.

Simpson P 2000. Dancing leaves, the story of New Zealand's cabbage tree, tī kouka. Christchurch, Canterbury University Press.

Stokes A 2002. The biomechanics of tree root anchorage. In: Waisel Y, Eshel A, Kafkaki U ed. Plant roots, the hidden half. New York, Plenum. Pp. 175–186.

Stokes A, Fourcaud T, Hruska J, Cermak J, Nadyezhina N, Nadyezhdin V, Praus L 2002. An evaluation of different methods to investigate root system architecture of urban trees *in situ*. 1. Ground penetrating radar. Journal of Arboriculture 28(1): 2–10.

Tomlinson PB, Fisher JB 1971. Morphological studies in Cordyline (Agavaceae). I. Introduction and general morphology. Journal of the Arnold Arboretum 52: 459–478.

Tomlinson AI, Sansom J 1994. Rainfall normals for New Zealand for the period 1961 to 1990. National Institute of Water & Atmospheric Research Science and Technology Services 4: 9–10.

Vollsinger S, Doppler F, Florineth F 2000. Ermittlung des Stabilitätsverhaltens von Ufergehölzen im Zusammenhang mit Erosionsprozessen an Wildbächen. Wien, Endbericht vom Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Institut für Landschaftsplanung und Ingenieurbiologie.

Wardle P 2002. Vegetation of New Zealand. Caldwell, USA, The Blackburn Press. 672 p.

Watson AJ, Marden M 2005. Live root-wood strengths of some common New Zealand indigenous and plantation trees. New Zealand Journal of Forestry Science 34: 344–353.

Watson AJ, Tombleson JD 2002. Toppling in juvenile pines: a comparison of the root system characteristics of direct-sown seedlings, and bare-root seedlings and cuttings. Plant and Soil 239: 187–196.

Watson AJ, Marden M, Rowan D 1995. Tree species performance and slope stability. In: Barker DH ed. Vegetation and slopes. London, Thomas Telford. Pp. 161–171.

Watson AJ, Marden M, Rowan D 1997. Root-wood strength deterioration in kanuka after clearfelling. New Zealand Journal of Forestry Science 27: 205–215.

Watson AJ, Phillips CJ, Marden M 1999. Root strength, growth, and rates of decay: root reinforcement changes of two tree species and their contribution to slope stability. Plant and Soil 217: 39–47.

Weitzer C, Doppler F, Florineth F 1998. Untersuchungen über die Wirksamkeit von Pflanzen in Einzugsgebieten des Forsttechnischen Dienstes der Wildbach- und Lawinenverbauung. Wien, Institut für Landschaftsplanung und Ingenieurbiologie, Universität für Bodenkultur.

Wu TH 1976. Investigation of landslides on Prince of Wales Island. Civil Engineering Department, Ohio State University, Geotechnical Engineering Report 5. 94 p.

Wu TH, McKinnel WP, Swanston DN 1979 Strength of tree roots and landslides on Prince of Wales Island, Alaska. Canadian Geotechnical Journal 16: 19–33.