academicJournals

Vol. 12(45), pp. 3214-3220, 9 November, 2017
DOI: 10.5897/AJAR2017.12715
Article Number: DC892C566604
ISSN 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Uprooting resistance of two tropical tree species for sand dune stabilization

Jung-Tai Lee*, Sung-Ming Tsai and Ming-Jen Lee

Department of Forestry and Natural Resources, National Chiayi University, Chiayi 60004, R.O.C. Taiwan.

Received 6 September, 2017; Accepted 10 October, 2017

Coastal windbreak restoration is important in Taiwan for agroforestry and sand dune stabilization. Australian pine (*Casuarina equisetifolia* Forst.) is the main species in windbreaks. It often suffers from serious uprooting and waterlogging damages, whereas sea hibiscus (*Hibiscus tiliaceus* L.) is more resistant to wind and tolerant to waterlogging. It is suggested that sea hibiscus can be substituted for Australian pine in coastal windbreak restoration. However, the adaptive mechanism of its root system to wind is not well understood. In this study, a field experiment was conducted to investigate the anchorage capabilities and root morphology of 10-year-old Australian pine and sea hibiscus plants. The results showed that root system morphologies of Australian pine and sea hibiscus plants belonged to taproot system and heart system, respectively. Root systems of both species were distributed towards northeast and southwest, which coincided with the monsoon directions. Sea hibiscus plants had significantly larger root collar diameter, longer taproot length, larger root biomass and shoot biomass than that of Australian pine plants. Additionally, sea hibiscus plants had significantly larger root volume than Australian pine plants. Moreover, sea hibiscus developed significantly stronger root functional traits, that is, root density (245%), root tissue density (300%) and the root to shoot ratio (138%) than Australian pine plants. Consistently, the root maximum uprooting resistance of sea hibiscus plants was significantly higher than that of Australian pine plants. These results demonstrate that sea hibiscus plants have stronger anchorage capability and they are more suitable for windbreak restoration and sand dune stabilization.

Key words: Anchorage, pullout, root system morphology, uprooting resistance.

INTRODUCTION

Australian pine (*Casuarina equisetifolia* Forst.), belonging to the Casuarinaceae family, is a nitrogen-fixing tree species (Diem and Dommergues, 1983; Mailly et al., 1994; Subbarao and Rodríguez-Barrueco, 1995; Tani et al., 2003) introduced to Taiwan in 1910 for windbreak reforestation (Liu and Liao, 1980). Sea hibiscus (*Hibiscus tiliaceus* L.), affiliated with the family Malvaceae, is also an introduced tropical tree species for windbreak and

*Corresponding author. E-mail: jtlee@mail.ncyu.edu.tw. Tel: 886-5-271-7482; 886-921-630-624.

sand dune stabilization in coastal agricultural lands of Taiwan (Chang, 1993; Liu and Liao, 1980). Both species have high potential for agroforestry, lumber production and coastal dune stabilization. There are 10,000 ha of windbreak forests along the coast of Taiwan. Australian pine is the main planting species used for reforestation. However, Australian pine has suffered from short life span of 20 years, serious insect pest of *Lymantria xylina* and brown root rot disease caused by *Phellinus noxius* (Chang, 1995; Ann et al., 2002). In the southwestern coast of Taiwan, Australian pine often suffers from serious uprooting and waterlogging caused by typhoons in summer and autumn (Chen et al., 2008). However, sea hibiscus, with a shorter trunk and many crooked, sprawling, intertwined branches, exhibits higher wind resistance. It is suggested that sea hibiscus can be substituted for Australian pine in coastal windbreak restoration. However, its ability to withstand uprooting by wind has not been investigated. Therefore, a comparison of anchorage capability between Australian pine and sea hibiscus plants is important for the implementation of windbreak restoration projects.

Typhoon, that is, tropical cyclone, comes with windstorm and torrential rain in summer and autumn, is one of the major causes of destruction of windbreak forests in Taiwan. Wind plays an important role in the growth and development of coastal tree species. Several studies have demonstrated that wind affects root morphology and mechanical properties of trees (Telewski and Jaffe, 1986; Stokes et al., 1995; Wu et al., 2016). Stokes and Mattheck (1996) classified tree root systems into heart system, plate system and taproot system. Lee et al. (2016) indicated that root distribution pattern of edge trees of 8-year-old Australian pine windbreak forest coincides with the monsoon direction, and its average maximum uprooting force amounts to 1.04 ± 0.29 kN. However, the effect of wind on root system morphology and mechanical properties of sea hibiscus have not been investigated. This study was conducted to (1) investigate the effect of wind on root system morphology and anchorage capability of 10-year-old Australian pine and sea hibiscus plants grown in windbreak plantation and (2) compare the differences in root morphology and anchorage capability between these two species in order to apply in ecotechnological projects for sand dune stabilization.

MATERIALS AND METHODS

Sample selection and site characteristics

In July 2016, fourteen plants each of 10-year-old Australian pine and sea hibiscus were randomly selected from the windward side of a windbreak plantation located at the coastal area of Taisi Township, Yunlin County, Taiwan (120°10'22.3" E, 23°43'19.7" N). The climate conditions of the experimental site are as follows: average temperature 22.7°C, relative humidity 85%, annual precipitation 1043.9 mm, northeast monsoon from October to March with average wind speed of 8.6 to 10.8 m/s, and southwest monsoon from April to September with average wind speed of 4.9 to 7.3 m/s. Seven plants each of the Australian pine and sea hibiscus were randomly sampled for growth and root system morphology investigation. Another 7 trees of each species were for uprooting test. Bulk soil samples were collected from the 0 to 30 cm layer. The samples were transported to the laboratory, air-dried, crushed to break the clods and passed through a 2-mm sieve to separate the fine particles from coarse fragments. The soil particle size analysis was performed by hydrometer method (Sheldrick and Wang, 1993). The soil texture was classified as loamy sand soil, which contained 75.1% sand, 15.3% clay and 9.6% silt. The average soil dry weight was 12.3 kN m^{-3} and the average soil moisture content was 23.5%.

Growth and root system morphology

Tree height and root collar diameter of 7 sampled trees of each species were measured with measuring tape and digital caliper. Tree root systems were completely exposed by the hand excavation method (Böhm, 1979). The rooting depth, root distribution, root number and length were measured. Photos of plant root systems were taken for further measurements of morphological traits. For each plant, root morphological traits, that is, taproot length, total root length, external root surface root area and root tip number were measured with the WinRHIZO*Pro* Image Analysis System (Regent Instruments, Quebec, Canada) (Bouma et al., 2000). Water displacement method was used for measuring total root volume (Pang et al., 2011). Then, roots and stems were dried in an oven at 75°C till constant weight for biomass measurement. Root functional traits, that is, root mass density (RD in kg m^{-3}, root dry mass per unit volume of soil), root length density (RLD in km m^{-3}, root length per unit volume of soil), root tissue density (RTD in g cm^{-3}, root dry mass per unit volume of root), specific root length (SRL in m g^{-1}, root length per unit root dry mass), and root to shoot ratio (R/S, dry root mass divided by dry leaf and shoot mass) were calculated (Stokes et al., 2009; Burylo et al., 2009, 2012; Poorter et al., 2012; Gould et al., 2016). All root traits were pooled together and analyzed.

Uprooting test

The rest of the seven plants each of Australian pine and sea hibiscus were used for vertical uprooting tests. Before vertical uprooting test, tree height and root collar diameter were measured, and the stem was cut off at 20 cm above the base, and the bark was removed to prevent slippage of the pulling device. The vertical uprooting test was carried out with an *in situ* pullout instrument (U-Soft USPA-003, U-Soft Tech, Taipei, Taiwan) equipped with a load cell (Kyowa 5T, LUK-5TBS, Tokyo, Japan) connected to a loading recorder and control unit, and fixed on a triangular steel frame. The raw data of uprooting resistance and displacement were obtained through a portable computer system. Subsequently, the instrument was connected to the pulling device and a constant vertical pulling force was applied automatically with a speed of 2 mm min^{-1}, recording the change in resistance and displacement along the way, until the resisting force dropped sharply and the plant uprooted (Lee et al., 2017).

Data analysis

Variations in data of growth and root morphological traits between Australian pine and sea hibiscus plants were analyzed by SPSS 22.0 software (SPSS, Chicago, IL., USA) using t-tests, one-way analysis of variance (ANOVA) and Scheffé's method. The relationships between uprooting resistance and morphological traits

Table 1. Growth and biomass of 10-year-old *C. equisetifolia* and *H. tiliaceus* plants.

Species	Height (cm)	RCD (mm)	TL (cm)	RB (g)	SB (g)
C. equisetifolia	273.4±30.0^{a}	32.3±4.0^{b}	19.9±6.3^{b}	82.3±2.0^{b}	627.9±98.9^{b}
H. teliaceus	180.0±45.0^{b}	65.8±12.2^{a}	31.6±9.5^{a}	744.9±7.3^{a}	2419.0±414.2^{a}

RCD: Root collar diameter; TL: Taproot length; RB: Root biomass; SB: Shoot biomass. All values are the means ± standard error of 7 replicates. Values in the same column with different superscript letters significantly differ at 5% significant level.

were analyzed using the Microsoft Excel regression analysis (version from Office 2013).

RESULTS AND DISCUSSION

Plant growth

Statistical analysis showed that there were significant differences in growth and biomass between Australian pine and sea hibiscus plants. Sea hibiscus plants had significantly higher average root collar diameter, taproot length, root biomass and shoot biomass than that of Australian pine plants (Table 1). However, mean height of Australian pine plants was significantly higher than sea hibiscus plants. Australian pine is a deciduous tree, which can grow straight to over 30 m in height in Australia (Subbarao and Rodríguez-Barrueco, 1995), whereas sea hibiscus is a medium sized tree 5 m in height, and has numerous sprawling branches. The effect of windbreak for Australian pine is noticeable on reducing wind-blown soil erosion on the lee side due to its tall trunk and canopy. Usually, the effect can cover an area up to 10 times the height of the Australian pine windbreak. However, the effect of windbreak for sea hibiscus is for sheltering agricultural areas and providing sand dune stabilization due to its short trunk, sprawling branches and wide canopy. In general, the vulnerability of trees to wind damage increases with tree height (Peltola et al., 1999). Zubizarreta-Gerendiain et al. (2012) also indicated that the susceptibility of trees to wind damage is largely affected by tree species-specific, tree height and rooting characteristics. Thus, Australian pine is more vulnerable to wind damage, which coincides well with wind damage frequency in windbreak plantations. Additionally, Australian pine-infested beaches are more prone to sand loss and erosion due to the allelochemical leachates, which reduce germination and establishment of native vegetation (Wheeler et al., 2011). The results demonstrated that sea hibiscus plants develop longer taproot and larger biomass than Australian pine plants in coastal sand dune areas. Thus, sea hibiscus plants play a more important role in sand dune stabilization than Australian pine plants.

Root system morphology

Sea hibiscus plants developed bigger and deeper root systems than Australian pine plants (Figure 1). The pattern of root growth in 10-year-old Australian pine plants showed that the taproot developed to a depth of 26 cm, with many smaller lateral roots grew horizontally (Table 1 and Figure 1a). In contrast, for sea hibiscus plants, its taproot extended to a depth of 41 cm, with many bigger lateral roots which grew horizontally and vertically (Table 1 and Figure 1b). The types of root system architecture of 10-year-old Australian pine and sea hibiscus plants were classified into taproot system and heart root system, respectively. The effects of wind loading on tree root system development have been well documented (Crook and Ennos, 1996; Nicol and Ray, 1996). Dupuy et al. (2005) indicated that overturning resistance was greatest in tap- and heart-root systems whatever the soil type. Saifuddin and Normanzia (2016) reported that Leucaena (*Leucaena leucocephala* (Lam.) de Wit), with taproot system, is suitable for slope protection. Stokes et al. (2007) found that Silver fir (*Abies alba* Mill.) with taproot system and European beech (*Fagus sylvatica* L.) with heart root system were more resistant to overturning than Norway spruce (*Picea abies* L.) with plate-like root system. The results revealed that sea hibiscus plants developed larger and deeper root system than that of Australian pine plants. The analysis of morphological parameters by WinRHIZO*Pro* revealed that sea hibiscus plants had significantly larger total root length (70%), external root surface area (60%), and root volume (126%) than Australian pine plants (Table 2). However, there was no significant difference in total root tip number between Australian pine and sea hibiscus plants. Analysis of root functional traits showed that the root density (RD), root tissue density (RTD) and root to shoot biomass ratio (R/S) of sea hibiscus plants were significantly higher than that of Australian pine plants. On average, sea hibiscus plants had significantly higher RD (245%), RTD (300%) and R/S (138%) than Australian pine plants. However, Australian pine plants had significantly higher specific root length (SRL, 400%) than sea hibiscus plants (Table 3). Our data clearly demonstrates that sea hibiscus plants allocate more biomass to roots than Australian pine plants. Coutard et al. (2008) indicated that in young Sweet cherry (*Prunus avium*), mechanical wind stimuli increase the allocation of biomass towards roots. Nwoke et al. (2016b) also suggested that plant species with the desirable traits of high values of relative root dry weight, high values of root density and low values of specific root length can be used

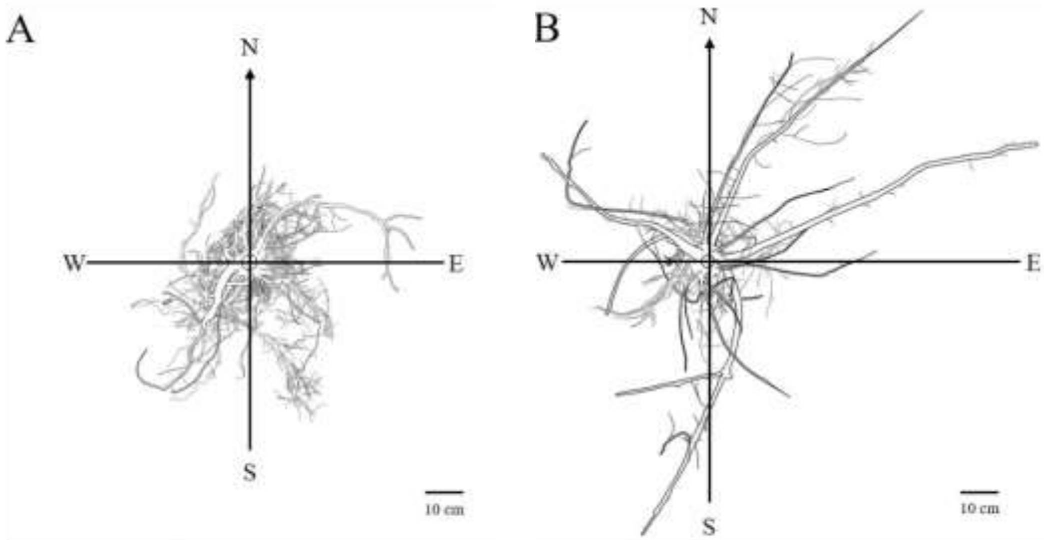

Figure 1. Root system morphology and distribution of 10-year-old *C. equisetifolia* (A) and *H. tiliaceus* (B) plants.

Table 2. Root morphological traits for 10-year-old *C. equisetifolia* and *H. tiliaceus* plants.

Species	TRL (cm)	ERSA (cm^2)	RV (cm^3)	RT
C. equisetifolia	1563.6±141.5^b	2788.1±448.1^b	826.5±62.1^b	3237.0±292.9^a
H. teliaceus	2667.1±135.8^a	4506.6±687.6^a	1871.6±32.2^a	3601.8±145.1^a

TRL: Total root length; ERSA: External root surface area; RV: Root volume; RT: Root tip number. All values are the means ± standard error of 7 replicates. Values in the same column with different superscript letters significantly differ at 5% significant level.

Table 3. Root functional traits for 10-year-old *C. equisetifolia* and *H. tiliaceus* plants.

Species	RD ($kg\ m^{-3}$)	RLD ($km\ m^{-3}$)	RTD ($g\ cm^{-3}$)	SRL ($m\ g^{-1}$)	R/S
C. equisetifolia	0.0079±0.0038^b	0.0016±0.0002^a	0.10±0.17$^{\mathbf{b}}$	0.20±0.03^a	0.13±0.03^b
H. teliaceus	0.0273±0.0113^a	0.0018±0.0003^a	0.40±0.06^a	0.03±0.00^b	0.31±0.05^a

RD: Root density; RLD: Root length density; RTD: Root tissue density; SRL: Specific root length; R/S: Root to shoot biomass ratio. All values are the means ± standard error of 7 replicates. Values in the same column with different superscript letters significantly differ at 5% significant level.

for soil and water conservation projects. This investigation showed that root systems of Australian pine and sea hibiscus plants were distributed towards northeast and southwest (Table 4). The root distribution patterns of these two species coincide with the monsoon directions. Nicoll and Ray (1996) showed that tree root systems allocated more root biomass to leeward side than the windward side in response to the prevailing wind action. Tamasi et al. (2005) also found that under wind loading, trees developed an asymmetric root distribution between the windward and leeward sides of the root system. Liu et al. (2008) reported that root system of 70-year-old Tarim salt cedar (*Tamarix taklamakanensis* M. T. Liu) had more structural root mass and length on the leeward side than the windward side relative to the prevailing wind direction. Wheeler et al. (2011) also indicated that with shallow roots and tall canopy, Australian pines are among the first trees to fall in high winds.

Root anchorage capability

In west coast of Taiwan, strong wind in monsoon seasons affects the growth and development of windbreak trees and is one of the important stresses regarding uprooting resistance. In this study, seven replicated uprooting tests were carried out to investigate the uprooting resistance of the Australian pine and sea hibiscus plants. The average maximum uprooting resistance of sea hibiscus plants was

Table 4. Root distribution of 10-year-old *C. equisetifolia* and *H. tiliaceus* plants.

Direction	*C. equisetifolia*		*H. tiliaceus*	
	Number of lateral roots	Lateral root length (cm)	Number of lateral roots	Lateral root length (cm)
NE	17±1[a]	309.8±9.3[a]	20±1[a]	400.3±16.3[a]
NW	11±1[c]	206.1±5.2[b]	11±1[c]	208.7±18.2[b]
SE	10±1[c]	112.7±5.8[c]	9±1[c]	108.5±24.5[c]
SW	14±1[b]	309.9±6.8[a]	16±1[b]	315.0±18.0[a]

NE: Northeast; NW: Northwest; SE: Southeast; SW: Southwest. All values are the means ± standard error of 7 replicates. Values in the same column with different superscript letters significantly differ at 5% significant level.

Table 5. Average maximum uprooting resistance of 10-year-old *C. equisetifolia* and *H. tiliaceus* plants.

Species	Maximum uprooting resistance (kN)
C. equisetifolia	1.03±0.36[b]
H. teliaceus	2.04±0.91[a]

All values are the means ± standard error of 7 replicates. Values in the same column with different superscript letters significantly differ at 5% significant level.

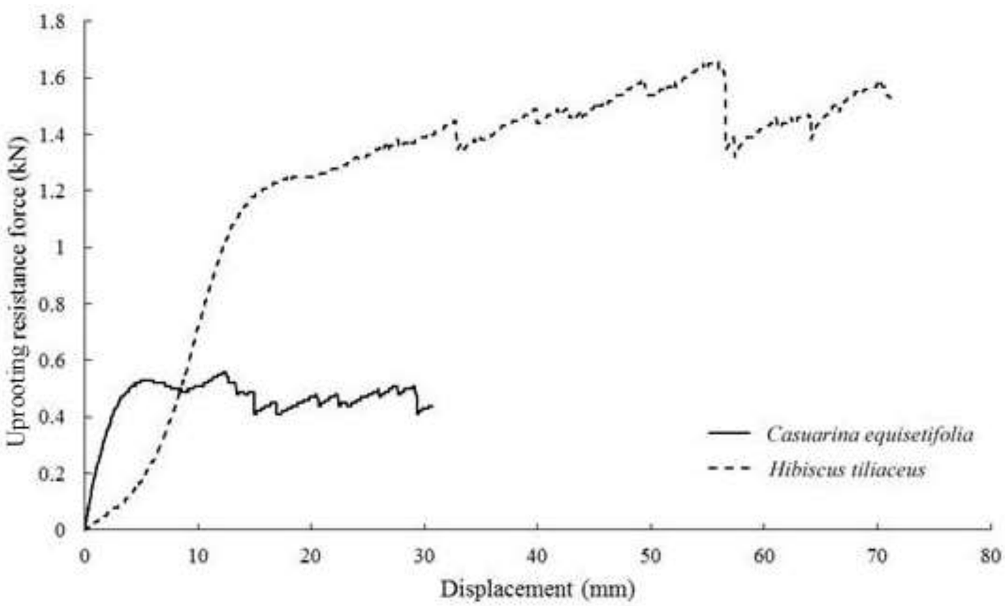

Figure 2. Uprooting resistance force-displacement curve for 10-year-old *C. equisetifolia* and *H. tiliaceus* plants.

2.04±0.91 kN, which was significantly higher than that of Australian pine plants (1.03±0.36 kN) (Table 5). The uprooting resistance-displacement curves showed a steep slope up to the maximum uprooting force (Figure 2). Stokes et al. (2005) showed that European beech (*F. sylvatica* L.) with heart root system was twice as resistant to uprooting as Silver fir (*A. alba* Mill) with taproot system and three times more resistant than Norway spruce (*P. abies* L.) with plate root system. Regression analysis showed the linear positive relationship between uprooting resistance and tree height, root collar diameter, root biomass and taproot length. The maximum uprooting resistance increased with increasing tree height, root collar diameter, root biomass, shoot biomass and taproot length, with the taproot length showing the strongest relation (Table 6). Dupuy et al. (2005) indicated that rooting depth was a determinant factor of tree anchorage in sandy soils. Burylo et al. (2009) showed that the

Table 6. Relation between morphological traits and uprooting resistance for 10-year-old *C. equisetifolia* and *H. tiliaceus* plants.

Morphological traits	Treatment	Mean±SE	Regression equation	R^2	*p*
H	*Casuarina equisetifolia*	273.4±30.0[a]	U_r = 0.010H-1.769	0.74	0.013
	Hibiscus tiliaceus	180.0±45.0[b]	U_r = 0.014H-0.450	0.79	0.007
D_r	*Casuarina equisetifolia*	32.3±4.0[b]	U_r = 0.072D_r-1.303	0.66	0.026
	Hibiscus tiliaceus	65.8±12.2[a]	U_r = 0.053D_r-1.328	0.78	0.008
R_b	*Casuarina equisetifolia*	82.3±2.0[b]	U_r = 0.025R_b-1.060	0.77	0.011
	Hibiscus tiliaceus	744.9±78.7[a]	U_r = 0.008R_b-3.888	0.77	0.010
S_b	*Casuarina equisetifolia*	627.9±98.9[b]	U_r = 0.002S_b-1.690	0.63	0.034
	Hibiscus tiliaceus	2419.0±414.2[a]	U_r = 0.003S_b-0.763	0.81	0.006
L_{tr}	*Casuarina equisetifolia*	19.9±6.3[b]	U_r = 0.051L_{tr}+0.020	0.81	0.006
	Hibiscus tiliaceus	31.6±9.5[a]	U_r = 0.072L_{tr}-0.136	0.88	0.002

H: Tree height; D_r: Root collar diameter; R_b: Root biomass; S_b: Shoot biomass; L_{tr}: Taproot length; U_r: Uprooting resistance. All values are the means ± standard error of 7 replicates. Values in the same column with different superscript letters significantly differ at 5% significant level.

maximum uprooting force is most positively correlated with stem basal diameter and taproot length is the best predictor of anchorage strength. Liu et al. (2013) showed that uprooting resistance of Chinese willow (*Salix matsudana* Koidz) was significantly positively correlated with plant height, total number of roots and root biomass. Nwoke et al. (2016a) reported that maximum uprooting force has a linear relationship with stem basal diameter. Several studies have demonstrated that uprooting resistance significantly influence the soil reinforcement capability of plants (Normaniza et al., 2008; Ali and Osman, 2008; Ali, 2010; Osman et al., 2011; Saifuddin et al., 2015). Our data showed that the maximum uprooting resistance of sea hibiscus plants is significantly higher than Australian pine plants, suggesting a superior root anchorage capability by sea hibiscus plants. Taken together, these results demonstrate that sea hibiscus develop larger root system and higher uprooting resistance than Australian pine plants. These findings are important in the application of sea hibiscus in ecotechnological projects for sand dune stabilization. This is the first report to show the growth, root morphology and anchorage capability of sea hibiscus in coastal windbreak forest. Furthermore, future researches on mixed species forest system and root-soil mechanics of coastal tree species, such as Australian pine, sea hibiscus, Alexandrian laurel (*Calophyllum inophyllum* L.) and sea mango (*Cerbera manghas* L.) are needed for windbreak restoration and sand dune stabilization projects.

Conclusion

In this study, root excavation study revealed that the root system morphologies of Australian pine and sea hibiscus were classified as taproot system and heart root system, respectively. Root systems of both species were distributed towards northeast and southwest, which coincided with the directions of winter and summer monsoons. However, sea hibiscus developed larger root collar diameter, longer taproot length, higher root and shoot biomass, and larger root volume than Australian pine. On average, sea hibiscus plants had significantly larger total root length, external root surface area and root volume than that of Australian pine plants. Root functional traits, such as RD, RTD and R/S of sea hibiscus plants were significantly higher than that of Australian pine plants. The average maximum uprooting resistance of sea hibiscus plants was twice higher than that of Australian pine plants. Regression analysis indicated the linear positive relationship between uprooting resistance and tree height, root collar diameter, root biomass, shoot biomass and taproot length. Taken together, these results clearly demonstrate that sea hibiscus has superior root system morphology and anchorage capability than Australian pine. Sea hibiscus is highly recommended for windbreak restoration and sand dune stabilization practices.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

Ali F (2010). Use of vegetation for slope protection: root mechanical properties of some tropical plants. Int. J. Phys. Sci. 5(5):496-506.

Ali FH, Osman N (2008). Shear strength of a soil containing vegetation roots. Soils Found. 48(4):587-596.

Ann PJ, Chang TT, Ko WH (2002). *Phellinus noxius* brown root rot of fruit and ornamental trees in Taiwan. Plant Dis. 86(8):820-826.

Böhm W (1979). Methods of Studying Root Systems. Springer-Verlag, Berlin.

Bouma TJ, Nielsen KL, Koutstaal K (2000). Sample preparation and scanning protocol for computerized analysis of root length and diameter. Plant Soil 218:185-196.

Burylo M, Rey F, Mathys N, Dutoit T (2012). Plant root traits affecting the resistance of soils to concentrated flow erosion. Earth Surf. Process. Landforms 37:1463-1470.

Burylo M, Rey F, Roumet C, Buisson E, Dutoit T (2009). Linking plant morphological traits to uprooting resistance in eroded marly lands (South Alps, France). Plant Soil 324:31-42.

Chang CE (1993). Malvaceae. Flora of Taiwan, 2nd Ed., Editorial Committee of the Flora of Taiwan (eds). Editorial Committee of the Flora of Taiwan, Taipei, Taiwan 3:737-743.

Chang TT (1995). Decline of nine tree species with brown root rot caused by *Phellinus noxius* in Taiwan. Plant Dis. 79(9):962-965.

Chen TH, Chiu CY, Chen JS (2008). Characteristics of lowland coastal forest soil at Szehu, Yunlin. Q. J. Chin. For. 41(4):483-492.

Coutard C, Dupraz C, Jaouen G, Ploquin S, Adam B (2008). Mechanical stimuli regulate the allocation of biomass in trees: demonstration with young *Prunus avium* trees. Ann. Bot. 101:1421-1432.

Crook MJ, Ennos AR (1996). The anchorage mechanics of deep rooted larch, *Larix europea* x *L. japonica*. J. Exp. Bot. 47:1509-1517.

Diem HG, Dommergues Y (1983). The isolation of *Frankia* from nodules of *Casuarina*. Can. J. Bot. 61(11):2822-2825.

Dupuy L, Fourcaud T, Stokes A (2005). A numerical investigation into the influence of soil type and root architecture on tree anchorage. Plant Soil 278:119-134.

Gould IJ, Quinton JN, Weigelt A, de Deyn GB, Bardgett RD (2016). Plant diversity and root traits benefit physical properties key to soil function in grasslands. Ecol. Lett. 19:1140-1149.

Lee JT, Tsai SM, Lin CH (2017). The nitrogen-fixing *Bradyrhizobium elkanii* significantly stimulates root development and pullout resistance of *Acacia confusa*. Afr. J. Biotechnol. 16(18):1067-1077.

Lee JT, Tsai SM, Lin CH (2016). Root system morphology and mechanical properties of *Casuarina equisetifolia* in the west coast of Taiwan. Q. J. Chin. For. 49(3):229-244.

Liu GJ, Zhang XM, Li XR, Wei J, Shan LS (2008). Adaptive growth of *Tamarix taklamakanensis* root systems in response to wind action. Chin. Sci. Bull. 53(2):164-168.

Liu TS, Liao JC (1980). Dendrology, 1st Ed., Commercial Press Ltd., Taipei, Taiwan 2:625-628.

Liu Y, Jia Z, Gu L, Gao J (2013). Vertical and lateral uprooting resistance of *Salix matsudana* Koidz in a riparian area. For. Chron. 89(2):162-168.

Mailly D, Ndiaye P, Margolis HA, Pineau M (1994). Fixation des dunes et reboisement avec le filao (*Casuarina equisetifolia*) dans la zone du littoral nord du Sénégal. For. Chron. 70(3):282-290.

Nicoll BC, Ray D (1996). Adaptive growth of tree root systems in response to wind action and site conditions. Tree Physiol. 16:891-898.

Normaniza O, Faisal HA, Barakbah SS (2008). Engineering properties of *Lucaena leucocephala* for prevention of slope failure. Ecol. Eng. 32:215-221.

Nwoke HU, Dike BU, Nwite SA, Nwakwasi NL (2016a). Relating uprooting resistance to stem basal diameters of plants for erosion mitigation. Int. J. Civ. Eng. Technol. 7(3):129-135.

Nwoke HU, Dike BU, Okoro BC, Nwite SA (2016b). Uprooting resistance and morphological traits of plants used in erosion mitigation. Int. J. Civ. Eng. Technol. 7(3):104-110.

Osman N, Abdullah MN, Abdullah CH (2011). Pull-out and tensile strength properties of two selected tropical trees. Sains Malays. 40(6):577-585.

Pang W, Crow WT, Luc JE, McSorley R, Giblin-Davis RM (2011). Comparison of water displacement and WinRHIZO software for plant root parameter assessment. Plant Dis. 95:1308-1310.

Peltola H, Kellomäki S, Väisänen H, Ikonen VP (1999). A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. Can. J. For. Res. 29(6):647-661.

Poorter H, Niklas KJ, Reich PB, Oleksyn J, Poot P, Mommer L (2012). Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. New Phytology 193:30-50.

Saifuddin M, Normaniza O (2016). Rooting characteristics of some tropical plants for slope protection. J. Trop. For. Sci. 28:469-478.

Saifuddin M, Osman N, Rahman MM, Boyce AN (2015). Soil reinforcement capability of two legume species from plant morphological traits and mechanical properties. Curr. Sci. 108:1340-1347.

Sheldrick BH, Wang C (1993). Particle size distribution. Soil Sampling and Methods of Analysis, Canadian Society of Soil Science (eds). Lewis Publisher, Boca Raton, FL, USA. pp. 499-512.

Stokes A, AbdGhani M, Salin F, Danjon F, Jeannin H, Berthier S, Kokutse AD, Frochot H (2007). Root morphology and strain distribution during overturning failure of trees on mountain slopes. Eco- and Ground Bio-engineering: The Use of Vegetation to Improve Slope Stability, Stokes A, Spanos I, Norris JE and Cammeraat E (eds). Springer, Dordrecht pp. 165-173.

Stokes A, Atger C, Bengough AG, Fourcaud T, Sidle RC (2009) Desirable plant root traits for protecting natural and engineered slopes against landslides. Plant Soil 324:1-30.

Stokes A, Fitter AH and Coutts MP (1995). Responses of young tees to wind and shading: effects on root architecture. J. Exp. Bot. 46:1139-1146.

Stokes A, Mattheck C (1996). Variation of wood strength in roots of forest trees. J. Exp. Bot. 47:693-699.

Stokes A, Salin F, Kokutse AD, Berthier S, Jeannin H, Mochan S, Dorren L, Kokutse N, AbdGhani M, Fourcaud T (2005). Mechanical resistance of different tree species to rockfall in the French Alps. Plant Soil 278:107-117.

Subbarao NS, Rodríguez-Barrueco C (1995). Casuarinas. Oxford & IBH Publishing Co. PVT. Ltd, New Delhi pp. 63-174.

Tamasi E, Stokes A, Lasserre B, Danjon F, Berthier S, Fourcaud T, Chiatante D (2005). Influence of wind loading on root system development and architecture in oak (*Quercus robur* L.) seedlings. Trees 19:374-384.

Tani C, Sasakawa H, Takenouchi K, Abe M, Uchiumi T, Suzuki A, Higashi S (2003). Isolation of endophytic *Frankia* from root nodules of *Casuarina equisetifolia* and infectivity of the isolate to host plants. Soil Sci. Plant Nutr. 49(1):137-142.

Telewski FW, Jaffe MJ (1986). Thigmomorphogenesis: field and laboratory studies of *Abies fraseri* in response to wind or mechanical perturbation. Physiol. Plant 66:211-218.

Wheeler GS, Taylor GS, Gaskin JF, Purcell MF (2011). Ecology and management of Sheoak (*Casuarina* spp.), an invader of coastal Florida, U.S.A. J. Coastal Res. 27(3):485-492.

Wu T, Zhang P, Zhang L, Wang GG, Yu M (2016). Morphological response of eight *Quercus* species to simulated wind load. PLoS One 11(9):e0163613.

Zubizarreta-Gerendiain A, Pellikka P, Garcia-Gonzalo J, Ikonen VP, Peltola H (2012). Factors affecting wind and snow damage of individual trees in a small management unit in Finland: assessment based on inventoried damage and mechanistic modelling. Silva Fenn. 46(2):181-196.