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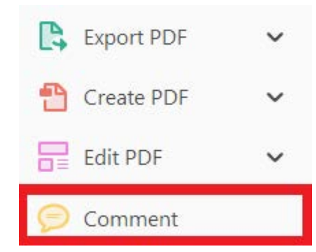


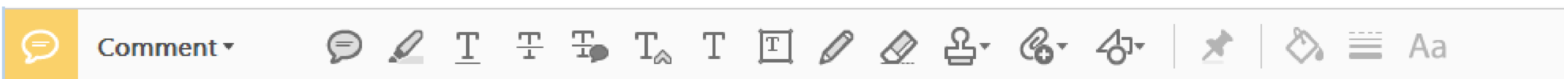


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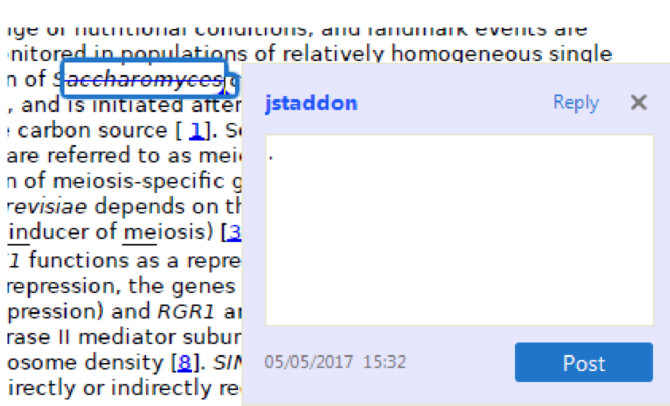


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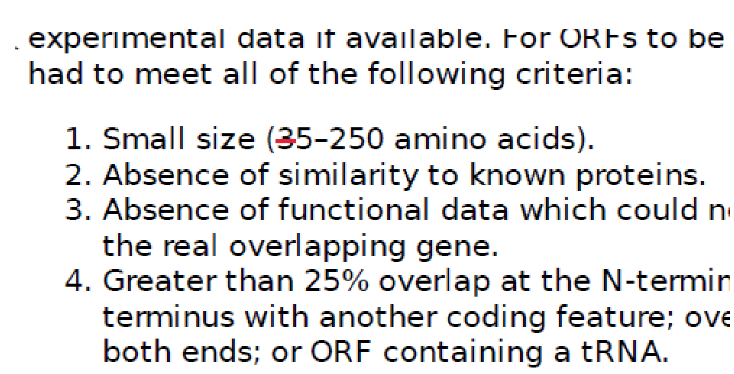


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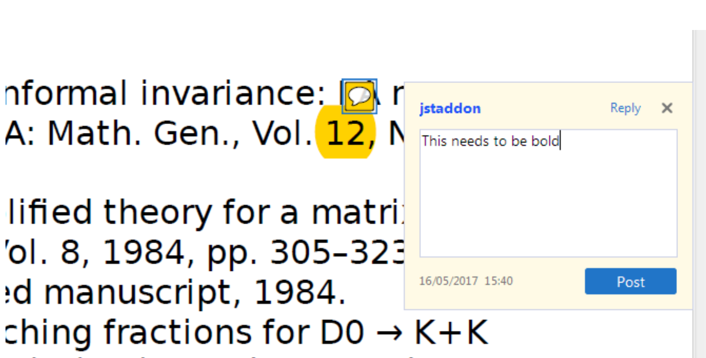


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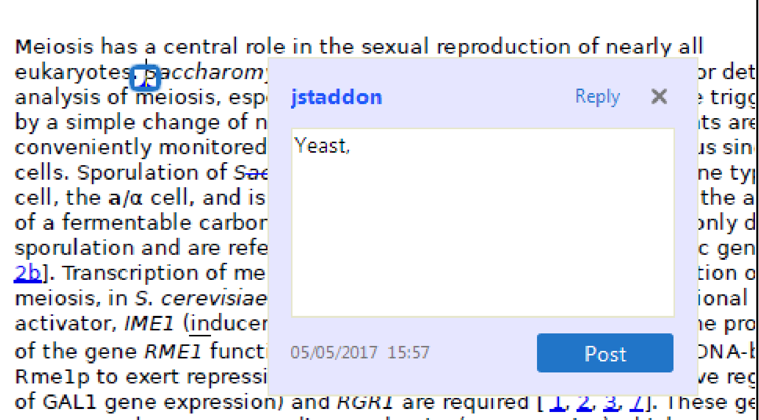

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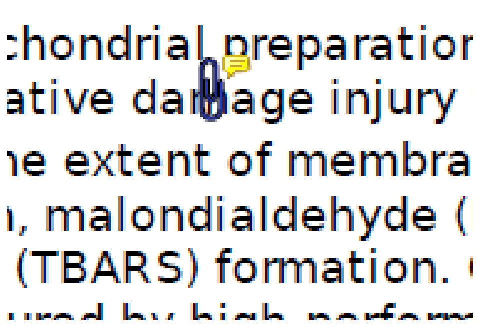

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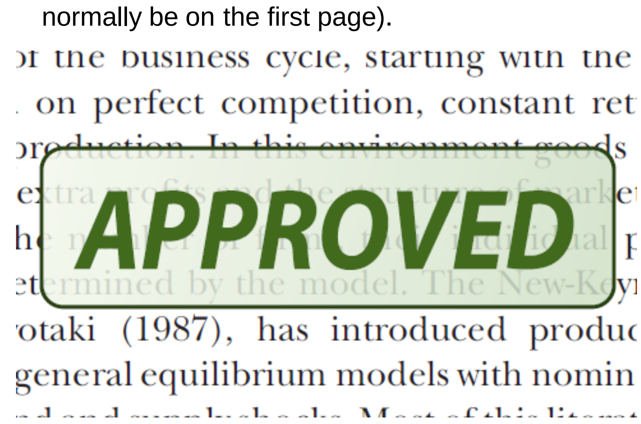


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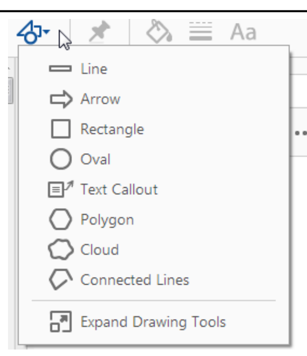


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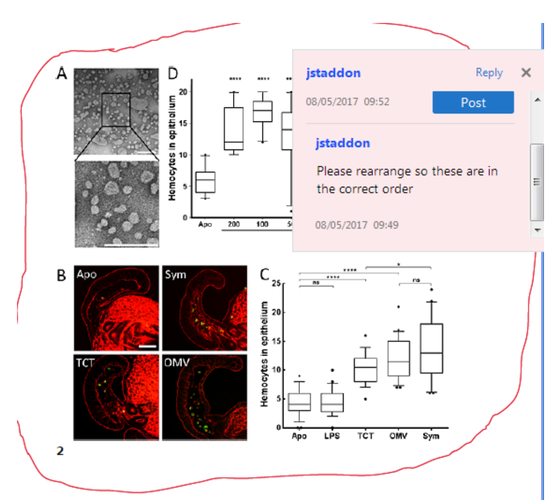


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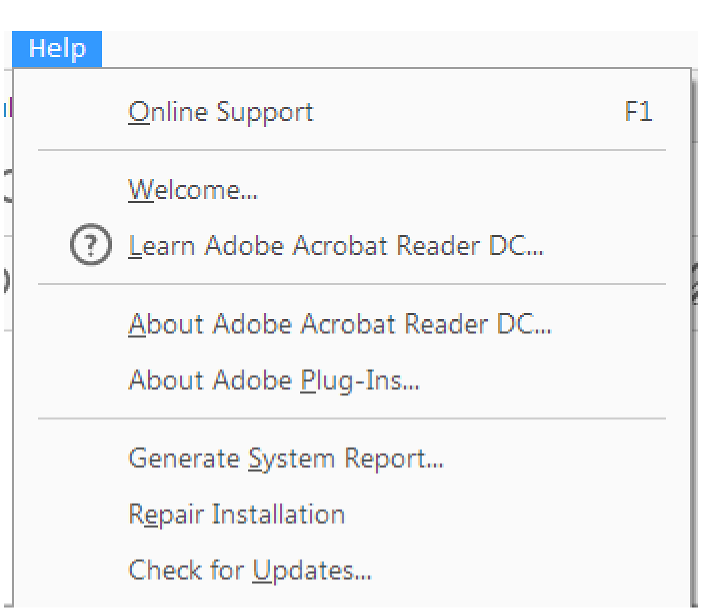
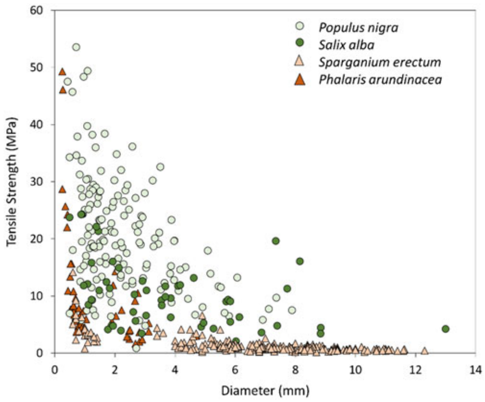


## Letters to ESEX

## Plant root and rhizome strength: Are there differences between and within species and rivers?

A.M. Gurnell, J.V. Holloway, T. Liffen, A.J. Serlet and G. Zolezzi




Relationships between the strength and diameter of roots are an important element in models used for estimating river bank stability. However, collection of data sets to support estimation of such relationships is time-consuming and the resulting data usually displays high variance. Collection and analysis of a large purpose-designed data set is needed to establish whether such relationships need to be species and site specific or whether more generalised relationships would be sufficient.

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Letters to ESEX

# Plant root and rhizome strength: Are there differences between and within species and rivers?

Q2 Q1 A.M. Gurnell,[1*] J.V. Holloway,[1] T. Liffen,[1,2†] A.J. Serlet[3] and G. Zolezzi[3]
[1] School of Geography, Queen Mary University of London, London E1 4NS, United Kingdom
[2] Swedish Environmental Protection Agency, Valhallavägen 195, 106 48 Stockholm, Sweden
[3] Department of Civil Environmental and Mechanical Engineering, University of Trento, Trento, Italy

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*Correspondence to: A. M. Gurnell, School of Geography, Queen Mary University of London, London E1 4NS, United Kingdom. E-mail: a.m.gurnell@qmul.ac.uk
†Current address: Swedish Environmental Protection Agency, Valhallavägen 195, 106 48 Stockholm, Sweden

ESPL
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ABSTRACT: The strength and architecture of roots and other below-ground organs of riparian and aquatic plants affect plant resistance to uprooting and contribute to reinforcing river bank, bar and bed materials. Therefore, root properties are an important element in models for estimating river bank stability and such models may focus on the role of plants by using root strength–diameter relationships for the particular plant species that are present.

Here we explore the degree to which there appear to be significant differences in strength–diameter relationships between and within species-specific data sets obtained for two riparian tree/shrub (*Populus nigra, Salix alba*) and two emergent aquatic macrophyte (*Sparganium erectum, Phalaris arundinacea*) species in different European river environments.

While the analysed data sets were not specifically collected to answer these research questions, the results are sufficiently compelling to make the case for the collection of a more comprehensive data set and its rigorous analysis. This would allow recommendations to be made on the degree to which (i) species-specific or more general relationships between root/rhizome strength and diameter are appropriate, (ii) such relationships are applicable within and between rivers in different geographical regions and subject to different local environmental conditions, and (iii) further (minimalist) field observations are needed to calibrate such relationships for investigations of new locales or species. © 2018 John Wiley & Sons, Ltd.

KEYWORDS: riparian vegetation; river bank stability; root strength–diameter relationships

The strength and architecture of roots and other below-ground organs of riparian and aquatic plants affect resistance to uprooting. Therefore, they have fluvial geomorphological significance by supporting the plant's crown so that it can form a component of the roughness of the channel perimeter, and also by reinforcing river bank, bar and bed materials. As a consequence, root properties are an important element in models for estimating river bank stability (Simon and Collison, 2002; Van de Wiel and Darby, 2007; Pollen-Bankhead and Simon, 2010; Thomas and Pollen-Bankhead, 2010) and a crucial contributor to analysis of the overall dynamics of river margins (Polvi *et al.,* 2014; Bankhead *et al.,* 2017). To support such modelling, measurements of the distribution of root density, diameter and area with depth within the bank profile are required, as well as root strength–diameter relationships for the plant species that are present. Examples of different types of field measurements of physical properties of roots and other below-ground organs of riparian and aquatic species can be found in the above-mentioned research, but also in many other studies including Abernethy and Rutherfurd (2001), Karrenberg *et al.* (2003), Wynn *et al.* (2004), Docker and Hubble (2008), Liffen *et al.* (2011, 2013a), Rood *et al.* (2011), Pasquale *et al.* (2012), Vannoppen *et al.* (2016), Vennetier *et al.* (2015), and Holloway *et al.* (2017a, 2017b).

A key element in much of the above research is estimation of relationships between the strength and diameter of roots or other below-ground organs. Many researchers have used a root-pulling device similar to that devised by Abernethy and Rutherfurd (2001) to measure the axial tractive force required to cause roots of different diameter to break. They have then developed relationships between tensile strength (the force per unit cross-sectional area of the root, MPa) and root diameter (mm) for different species. Typically between 40 and 100 roots are sampled to define these species-specific relationships, but, with the notable exception of Polvi *et al.* (2014), little attention has been given to whether such relationships are statistically-significantly different from one another and whether environmental or other conditions might yield significantly different relationships for the same species.

Using data sets collected with the same root-pulling device for four different species (two riparian tree-shrub species (*Populus nigra* (abbreviated Pn), *Salix alba* (Sa)) and two aquatic macrophyte species (*Sparganium erectum* (Se), *Phalaris arundinacea* (Pa)) growing in different European river environments (Table I, Figure 1), we consider the evidence for different T1 F1

**Table I.** Data sets analysed

| Species | River | Season of sampling | Number of sampling locations | Total sample size | Number of roots | Number of rhizomes |
|---|---|---|---|---|---|---|
| *Populus nigra* | Tagliamento, NW Italy | Summer | 9 (5 dry, 3 wet, 1 no moisture data) within 3 different river reaches | 154 | 154 (69 dead) | 0 |
| *Salix alba* | Adige tributary, N Italy | Summer | 1 | 52 | 52 | 0 |
| *Sparganium erectum* | Blackwater, southern UK | Spring, Summer, Autumn | 1 | 220 | 20 | 200 |
| *Phalaris arundinacea* | Adige tributary, N Italy | Summer | 1 | 50 | 18 | 32 |

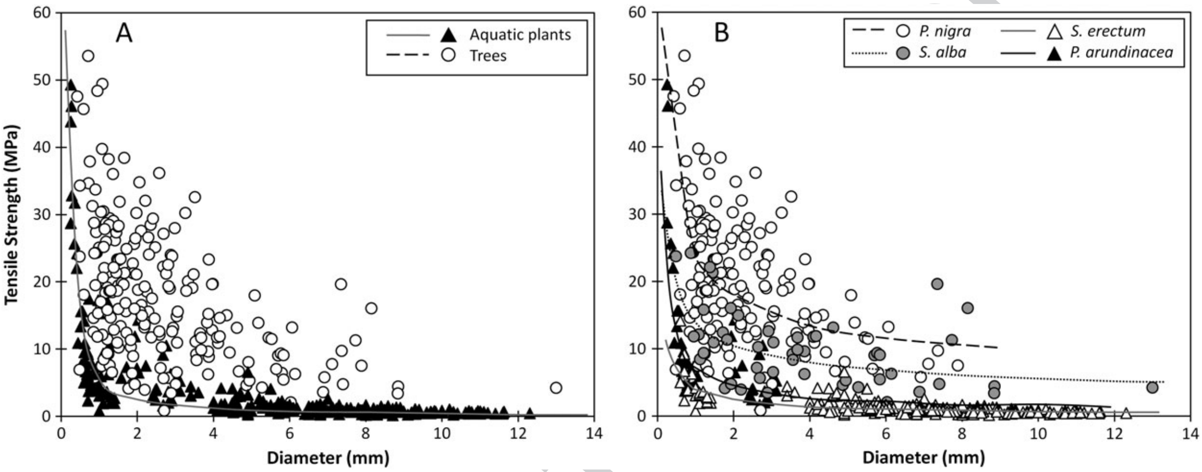


**Figure 1.** Observations and significant power relationships estimated between tensile strength and diameter of roots and rhizomes for (A) two plant groups and (B) two tree species (*P. nigra, S alba*) and two emergent aquatic macrophyte species (*S. erectum, P. arundinacea*) measured on four different rivers. For data sources and estimated regression models see Tables I and II, respectively.



inter- and intra-species contrasts in root/rhizome strength–diameter relationships. Because our data sets were not collected specifically for this purpose, we cannot answer these questions with confidence. However, we provide an initial indication of whether it would be profitable to gather and analyse a larger purpose-designed data set. Such a data set could support a more robust assessment that could establish the degree to which different root/rhizome strength–diameter relationships are actually needed for different species or for the same species under different environmental conditions.

A Generalised Linear Modelling approach was used to investigate the degree to which tensile strength (MPa, dependent variable) showed a statistically significant response to organ diameter (mm, independent variable) according to species and/or environmental conditions. Power relationships are usually estimated between these variables, and so the variables were $\log_{10}$ transformed prior to linear regression models being estimated between the dependent variable (tensile strength) and the independent variable (diameter). A simple regression model was estimated from the entire data set (Table I, $n$=476), and a series of multiple regression models were estimated to explore the degree to which significantly different models were appropriate for characterising different subsets of the data. In these analyses, species/river combinations (Pn, Se, Se, Pa), species groups (trees, aquatic plants), moisture status (wet, dry), root condition (dead, living) or month of measurement (Apr, May, Jne, Aug, Sep, Oct_Nov) were identified using dummy variables which took the value 1 when the tensile strength–diameter observations related to a particular case (e.g. a species–river combination, a species group, moisture status, root condition, month of observation) and 0 when they did not. For each multiple regression analysis, in addition to root diameter, relevant dummy variables were incorporated as independent variables, as were interactions between the dummy variables and root diameter. In this way it was possible to test whether different species or conditions (i.e. species/river combination, species group, moisture status, root condition or month of measurement) were best described by regression models with different intercept and/or slope coefficients from other conditions and thus whether a different tensile strength–diameter relationship was appropriate for a particular condition. Each multiple regression model was estimated using a stepwise procedure to select the combination of independent variables that achieved the highest coefficient of determination, adjusted for the degrees of freedom of the model ($R^2$(adj)) while including only independent variables whose slope coefficient was statistically significant ($P<0.05$) (Table II). All analyses were performed using Minitab 18 software.

First, we analysed the data set for *Populus nigra* ($n$ = 156) to consider whether different relationships may be needed to characterise a single species under different environmental conditions. These data, which show considerable scatter (Figure 1), were collected from nine different sites distributed across three different reaches of the Tagliamento River, Italy. Each reach was approximately 2 km in length and the reaches were spaced approximately 4 km and 28 km apart. Previous research has separated these nine sites into two distinct groups – wet and dry sites – according to soil moisture conditions (Holloway *et al.*, 2017a) and has shown distinct differences in the vertical profiles of root density and root area ratio according to whether data were collected at the wet or dry sites. However, no significant difference was found in the relationship between root

**Table II.** Statistically-significant ($P<0.05$ for all intercept and slope coefficients) regression models estimated between $\log_{10}$ tensile strength ($\log_{10} \tau$, dependent variables) and $\log_{10}$ diameter ($\log_{10}$ D) using measurements obtained for four different species located on different rivers (for full explanation of dummy variables see text)

| ***Populus nigra*** | | **$R^2$(adj)** |
|---|---|---|
| All *Populus nigra* root data: | | |
| $\log_{10} \tau = 1.365 - 0.388 \log_{10} D$ | | 0.168 |
| $\log_{10} \tau = 1.364 - (0.320 + 0.168\ \text{Dead}) \log_{10} D$ | | 0.179 |
| For living roots: | For intact but dead roots: | |
| $\log_{10} \tau = 1.364 - 0.320 \log_{10} D$ | $\log_{10} \tau = 1.364 - 0.488 \log_{10} D$ | |
| ***Sparganium erectum*** | | |
| All *Sparganium erectum* rhizome data: | | |
| $\log_{10} \tau = 0.985 - 1.210 \log_{10} D$ | | 0.329 |
| $\log_{10} \tau = 0.984\text{-}0.088\ \text{May} - 1.193 \log_{10} D$ | | 0.340 |
| For Apr, Jne, Aug, Spt, Oct_Nov.: | For May | |
| $\log_{10} \tau = 0.984 - 1.193 \log_{10}$ diameter | $\log_{10} \tau = 0.896 - 1.193 \log_{10} D$ | |
| **All species/river combinations** | | |
| All data: | | |
| $\log_{10} \tau = 1.197\text{-}1.186{*}\log_{10} D$ | | 0.544 |
| $\log_{10} \tau = 0.765 + 0.577\ \text{Tree} - (0.948 - 0.445\ \text{Tree}) \log_{10} D$ | | 0.858 |
| For emergent aquatic plants: | For trees: | |
| $\log_{10} \tau = 0.765 - 1.186 \log_{10} D$ | $\log_{10} \tau = 1.342 - 0.503 \log_{10} D$ | |
| $\log_{10} \tau = 1.367 - 0.240\ \text{Sa} - 0.739\ \text{Se} - 0.502\ \text{Pa} - (0.394 + 0.408\ \text{Se} + 0.305\ \text{Pa}) \log_{10} D$ | | 0.875 |
| For *Populus nigra* (Pn): | For *Sparganium erectum* (Se): | |
| $\log_{10} \tau = 1.367 - 0.394 \log_{10} D$ | $\log_{10} \tau = 0.6276 - 0.802 \log_{10}$ diameter | |
| For *Salix alba* (Sa): | For *Phalaris arundinacea* (Pa): | |
| $\log_{10} \tau = 1.127 - 0.394 \log_{10} D$ | $\log_{10} \tau = 0.865 - 0.699 \log_{10} D$ | |

tensile strength and diameter according to moisture conditions, suggesting that root tensile strength is insensitive to this environmental property, despite the fact that root profiles show distinct differences. Since 65 intact but dead roots were included in the 156 roots analysed, it was also possible to investigate whether root condition affected the root tensile strength–diameter relationship. This analysis revealed no significant difference in the intercept but a steeper decline in the tensile strength of dead roots as root diameter increased. However, $R^2$(adj) only increased slightly (from 0.168 to 0.179, Table II), indicating only a modest increase in the explanatory power of the model.

While the data for *Populus nigra*, *Salix alba* and *Phalaris arundinacea* were all collected in summer, measurements for *Sarganium erectum* were collected in different months between April and November at the same site, providing an opportunity to investigate whether the rhizomes of this species ($n$ = 200) show significant changes in tensile strength through the growing season. Once again, there was considerable scatter in the data (Figure 1) and the analysis revealed no significant difference among months apart from a reduction in the intercept term for May, which was associated with only a modest increase in $R^2$(adj) from 0.329 to 0.340. These results indicate that although other properties of rhizome profiles vary through the year (Liffen *et al.,* 2013b), there is little change in the relationship between rhizome tensile strength and diameter.

The entire data set ($n$ = 476) for the four species were obtained from different rivers and so, although it was possible to test for differences in tensile strength–diameter relationships among species, such differences may also reflect the impact of different environmental conditions. This is particularly the case for *Sparganium erectum*, where the data were collected from a lowland British river, in contrast to the transitional alpine environments of the Italian rivers from which the other data sets were collected. Table II lists the estimated regression model for the entire data set, the two plant groups (trees or aquatic plants) and the four species/river combinations (Pn, Sa, Se, Pa). By separating the data into two groups each containing two species/river combinations, $R^2$(adj) increased dramatically from 0.544 to 0.858, suggesting that despite the differences in the species and rivers within each group, the trees describe a distinctly different tensile strength–diameter relationship from the aquatic plants. When the four species/river combinations are separated and compared, there is only a modest increase in the adjusted $R^2$(adj) to 0.875 (from 0.858 for the two species groups) and there is little difference between the tree–river combinations, with *Salix alba* showing a significantly lower intercept term but with no difference in the slope of the relationships for the two species. Whether the difference in the models can be attributed to species and/or river environment, it is remarkably small and suggests that it might be possible to use combined relationships for some tree-shrub species (such as the Salicaceae family), particularly when they are growing in a similar environmental setting. However, distinct differences in both intercept and slope coefficients are found between the *Sparganium erectum* and *Phalaris arundinacea* relationships, which may be attributable to the different species considered but could also be related to the very different river environments in which the measurements were made. Further measurements for both species on the same river could help to untangle these factors.

In summary, despite the different river environments as well as species investigated, our analyses suggest that generalised tensile strength–diameter relationships might be achievable. In particular, we have shown that:

1. The same species (*Populus nigra*) growing in contrasting sites where differences in soil moisture have been shown to strongly affect root density profiles and rooting depth, shows no difference in its tensile strength – diameter relationship, although root vigour may have some effect on this relationship.
2. The same species (*Sparganium erectum*) growing at the same site shows distinct differences in the number and vertical profile of rhizomes through the annual growth cycle but remarkably little change in its tensile strength – diameter relationship.
3. Two tree species (*Salix alba, Populus nigra*) growing on different rivers show no difference in the gradient of their relationship between root tensile strength and diameter. Although the intercept terms differed, it would be interesting



 

to test the degree to which this reflected a difference in river environment rather than species. A data set drawn from a single river but covering several species would support testing of genuine differences among tree species and whether relationships could be generalised to the family rather than species level.

4. Two aquatic species showed distinct differences in their tensile strength–diameter relationships that may be attributable to species and/or river. However, it is worth stressing that *Sparganium erectum* is a true aquatic species that rarely grows beyond continuously inundated sites whereas *Phalaris arundinacea* is a wetland grass species that is found mainly at and above the water's edge. Furthermore, these species come from different families (Sparganiaceae, Poaceae). Therefore, it would be worth exploring whether plants occupying similar habitats or from the same family show greater similarities than the two species explored in our analysis.

In conclusion, gathering species-specific root/rhizome strength–diameter data is extremely time consuming and, as is clear from Figure 1, high residual variance is typical around estimated tensile strength–diameter relationships even for a single species at a single location. This raises the question of whether single species relationships are necessary. The preliminary analyses presented here suggest that considerable savings in field effort might result from a more rigorous analysis of a more comprehensive data set, to test the following hypotheses:

(i) Sufficiently reliable root/rhizome tensile strength–diameter relationships can be estimated to family level, removing the need for species-specific relationships.
(ii) Such family relationships are robust at least across rivers in the same catchment (and possibly the same biogeographical region).
(iii) Such family relationships are robust through all seasons of the year.

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