A NEW APPROACH FOR SLOPE STABILIZATION BY PLANT ROOTS ON DEGRADATION HOTSPOTS IN SOUTHERN CHINA.

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ABSTRACT

The foothills of Himalayan mountain ranges are areas where landslides and erosion are frequent. The aim of this study is to propose a new approach for slope stabilisation, by focussing on the careful management of degradation hotspots. We are studying how plant roots reinforce soil, with an emphasis on rooting strategies of plants growing under strong ecological and mechanical constraints e.g. landslides and erosion. We examined root and shoot structure as well as mechanics of local herbaceous species, shrubs and creeping plants to determine which might have a mechanically reinforcing effect on a slope, as well as ethno botanical advantages. Thus we will identify those which can be considered as "tools for eco-engineering" in this area. The use of a numerical model will enable us to simulate and calculate the Factor of Safety (FOS) of slopes for different management actions. The outcome of this study will be to determine practical recommendations for local stakeholders, who can then use suitable native species on appropriate or fragile zones to stabilize the slopes where they live and grow crops.

Key Words: Landslides, Root architecture, Biomechanics, Modelling, Eco-engineering, China

INTRODUCTION

In China, a country where two-thirds of the land is made up of hills and mountains, erosion and landslides are the result of deforestation, bad farming practice and over-exploitation of resources in the last 50 years (Liu and Diamond, 2005; Stokes *et al.*, 2008). China currently feeds 20% of the world population and possesses 7% of the world's croplands (FAO, 2007). China is also an area with high seismic activity, causing many secondary landslides. The 2008 Wenchuan earthquake, resulted in 80,000 casualties with 20 000 caused by associated geohazards, and by the end of 2008 slopes in the area were not stabilized (Wang *et al.*, 2008; Yin *et al*., 2008). A major new problem to be faced is the building of roads linking villages to towns (Stokes *et al.*, 2009). A survey along Nujiang Valley, Yunnan, showed that soil loss rates due to road building represent at least 80% of the total soil loss, and were over 600 times greater than the highest currently recorded in the USA (Sidle, 2007). China has therefore to combine sustainable land management with crop production and rural infrastructure

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development on sloping land. Within such a context, mitigation strategies need to focus on target areas of a slope, concentrating on the most fragile zones. Erosion hotspots are defined as source areas of sediments (Baigorria and Romero, 2007). These areas are also defined as sites with soil erosion rates well above soil loss tolerance levels (Poesen *et al.*, 2008). These erosion hotspots often only occupy a small fraction of a catchments' area, but may be held responsible for a very significant contribution to overall sediment production, thus leading to off-site problems. To improve hotspot management, the local ecology needs to be taken into account before a choice of species is made e.g. ethnobotanical knowledge should be used to identify the needs of local farmers and villagers, so that species can provide an income to the local community (Grosjean and Kontoleon, 2009).

Vegetation has long been recognized as a factor useful for increasing the shear resistance of soil on an unstable slope (Genet *et al*., 2005). To better understand how root systems occupy soil over time and space, and especially how root systems cross the potential shear surface of a slope, a landslide engineer needs to take into account the three-dimensional (3D) root architecture and mechanical properties of any given species. Information on how species grow should be considered, especially during the early stages of growth, as soil conditions strongly affect root growth in the first weeks after germination (Khuder *et al.*, 2007). The presence of plant roots crossing the potential shear surface results in an increase in soil cohesion through a reinforcing effect which usually augments superficial slope stability. The root – soil reinforcement model developed by Wu (1976), and elaborated upon by Waldron (1977), is widely used to estimate the additional cohesion taking into account the presence of roots in the soil (Gray and Sotir, 1996). This model states that the additional cohesion due to the presence of roots can be estimated as follows

$$C_r = R_f * T_r * RAR \quad (1)$$

where T_r is the average tensile strength of roots and RAR is the Root Area Ratio, i.e. the total root cross-section area (CSA) per unit of surface at the potential shear surface. R_f is the root orientation factor. It depends on the friction angle of the soil and on the angle of the root at rupture, relative to the failure plane (Thomas and Pollen-Bankhead, 2009). Moreover,

$$T_r = F_r / CSA \quad (2)$$

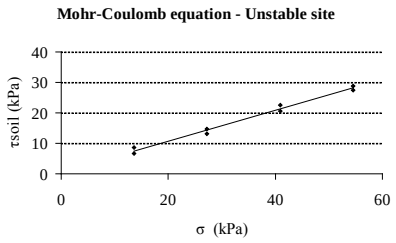
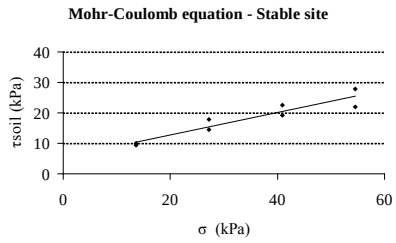
with F_r the maximum load that the root can support before it breaks. In the literature, it is often reported that F_r increases when root diameter increases (Schmidt *et al.*, 2001).

The factor of safety (FOS) for slope stability is the ratio of shear strength to shear stress. In other words, FOS = Restoring force (available shear strength) / Disturbing force (shear force), and the Restoring force is function of the soil cohesion and the additional cohesion due to the presence of roots. FOS indicates whether a slope is stable or not: if FOS < 1, the slope is prone to failure. Numerical models can be used to calculate FOS. By using such models, it is possible to determine under what conditions FOS will evolve. In order to better estimate the efficiency of native species in stabilizing slopes, we studied root architecture and measured root tensile strength of five pioneer species on steep slopes in Southern China. So as to estimate their capacity of adaptive growth on slopes where erosive soil slippage was still underway, we selected two adjacent degradation hotspots: one stabilised by vegetation and one unstable. These hotspots were located near a high-biodiversity zone, including more than 25 identified species, which plays the role of a reservoir for colonisation of degradation hotspots. We chose species growing on degradation hotspots at the beginning of the rainy season, when slopes are more prone to landslides. Among the studied species, were four naturally-grown species, *Artemisia lavandulaefolia* (Asteraceae, flowering biennal herb), *Chloris anomala* (Poaceae, grass), *Rhus chinensis* (Anacardiaceae, sprouting tree), and *Ficus tikoua* Bureau (Moraceae, creeping shrub), and one planted species, *Pueraria stricta* Kurz. (Fabaceae, shrub).

MATERIAL AND METHODS

Our study site is located in Southern China, Yunnan province, 20 km east of the border with Myanmar (N26°01'60", E098°50'60"). In this area, the river Salween flows from North to South, strictly parallel to the Mekong and the Yangtze. Due to its topographic, climatic and geologic diversity (the Salween river bed follows a major seismic fault resulting from the Indo-Eurasian collision), as well as its location, (this valley was a north-south corridor for species migration especially during glaciation periods). This area is classified as a UNESCO World Heritage site since 2003. Over 6,000 plant species exist, among which more than 300 medicinal plants can be found (http://whc.unesco.org/fr/list/1083). Altitudes range from 800 m to more than 3,000 m and slope angles can be > 50 °. This part of China is under the influence of the Indian monsoon, and described as a "warm-dry climate", which is a combination between subtropical and alpine climates. Annual mean temperature (from 1961 to 2002) is 15.2°C, and mean annual precipitation is 1,200 mm, the majority of which falls between May and October. The major soil type is a ferrallitic red clay soil, with many mineral coloured spots, e.g. iron and manganese. Except on degradation hotspots, soil and humus thickness are not limiting factors: being 0.2 – 2.0 m and 0.0 - 0.02 cm, respectively. Severe and numerous landslides occur during the monsoon season (May-October), and the slip surface of these landslides has been estimated at a mean depth of 0.5 m. We defined two hotspots of land type: one unstable, being an active landslide, and one more stable, as natural regeneration and planted shrubs have been allowed to grow undisturbed for 8 years (Table 1). Only *C. anomala* was grazed slightly by cows on the stable hotspot.

Table 1 Description of the two hotspots.

	Unstable hotspot	**Stable hotspot**
Altitude	1009 m	980 m
Slope angle	50-60°	35-45°
Area	20mx30m	100mx200m
Slope orientation	300°	300°
Sliding cause	Rain and gravity	-
pH of soil	8.33	8.42
Cation Exchange Capacity	43.84 cmol(+)/kg	51.51 cmol(+)/kg
% humidity of soil	27.48 %	27.26 %
Water retention capacity	59.99 %	69.89 %
Soil bulk density	0.78 kg/l	0.88 kg/l
Soil structure	Sandy clay loam	Clay loam
Bedrock type and depth	Limestone at 40 cm	Limestone at 30 cm
Internal cohesion C_{soil}; friction angle Φ[1]	 0.49 kPa; 27 °	 5.35 kPa; 20 °

[1]Soil mechanical properties, C_{soil} and Φ, were obtained by tests on soil samples from unstable and stable hotspots with a direct shear test machine ("Sheartest 2760", VJ.Tech), which led to the Mohr-Coulomb curve $\tau_{soil} = C_{soil} + \sigma_n * \tan\Phi$, where τ_{soil} is the soil shear strength, and σ_n the normal load applied on the soil sample ($R^2 = 0.98$ and 0.89 on unstable and stable hotspot, respectively).

Ten root systems of young individuals of each species were hand-excavated: six growing on the unstable hotspot and four growing on the stable hotspot (Table 2). Excavations were

carried out with extreme caution and without damaging the roots. Heights and widths of the plants are given, but cannot be used to determine an individual's age. As is often the case in tropical and sub-tropical climates, winter is not severe enough to arrest secondary growth and there is no clear annual ring formation in the stems.

Root system width and depth was measured for each plant and a general architectural description given. Tensile testing was carried out on fresh individual roots on the day following the excavation using a portable machine (In-Spec 2200 BT, Instron Corporation, www.instron.com) equipped with a force transducer (max. capacity 250 N or 10 N depending on root size, accuracy 0.25%). The length of each sample was at least 30 times its central diameter (Cofie, 2001). Crosshead speed was kept constant at 1.0 mm.min-1 and both force and speed were measured constantly via Instron Series IX software during each test. We measured the force required to cause failure in tension of each root. In order to avoid slippage of roots out of the clamps, the clamps were chosen according the diameter of the root and emery paper was fixed between the clamps and the roots when needed. Tests were considered successful only when specimens failed approximately in the middle third of the root. Root diameter was measured with extreme care before testing (usually, tensile tests cause a deformation of the roots) at three points along the tested root, with a microscope. The mean of these three measurements was calculated. For each species and on each hotspot, we drew the best regression curve between maximum forces and root diameters.

Table 2 Size of aerial and underground parts of plants (depth: perpendicular to the soil surface).

	n	Min.–Max. height of plant crown (cm)	Min.-Max. width of plant crown (cm)	Min.-Max. root depth (cm)	Min.-Max. distance of the longest root to the stem (cm)	Min.-Max. diameter of tested roots (mm) (**no. tests**)	Ethnobotanical uses
Artemisia lavandulaefolia							
Unstable hotspot	6	7.3 - 20.3	18.4 - 36.4	18.5 - 45.0	38.0 - 51.8	0.01 - 3.31 (**300**)	Human and cattle medicine.
Stable hotspot	4	4.6 - 17.0	13.4 - 24.0	24.0 - 4.0	34.7 - 61.0	0.02 - 1.50 (**149**)	
***Pueraria stricta* Kurz.**							
Unstable hotspot	6	15.0 - 117.0	5.3 - 31.0	30.0 - 54.0	25.4 - 97.0	0.02 - 4.56 (**296**)	Planted by government for slope stabilisation. Fixes nitrogen.
Stable hotspot	4	15.5 - 34.0	14.3 - 32.5	34.0 - 49.0	11.0 - 123.0	0.05 - 4.88 (**176**)	
Chloris anomala							
Unstable hotspot	6	6.5 - 16.5	13.3 - 20.1	13.8 - 28.2	23.5 - 31.7	0.04 - 0.56 (**205**)	Cattle forage.
Stable hotspot	4	3.9 - 12.7	5.5 - 27.6	11.0 - 37.0	19.5 - 63.5	0.01 - 0.51 (**161**)	
Rhus chinensis							
Unstable hotspot	6	10.0 - 36.0	11.0 - 36.0	5.0 - 52.0	28.0 - 117.0	0.32 - 4.20 (**85**)	Food: vinegar from leaves.
Stable hotspot	4	10.0 - 24.0	8.0 - 34.0	16.0 - 41.0	39.0 - 182.0	0.18 - 4.20 (**82**)	
***Ficus tikoua* Bureau**							
Unstable hotspot	6	3.7 - 13.0	8.0 - 16.0	2.0 - 47.0	2.0 - 10.0	0.15 - 2.47 (**39**)	Food: berries.
Stable hotspot	4	7.0 - 10.0	9.0 - 16.0	6.0 - 20.0	3.0 - 57.0	0.22 - 2.12 (**50**)	

Root tensile strength T_r was calculated for four classes of diameter: 0.0-0.5 mm, 0.5-1.0 mm, 1.0-2.0 mm, and >2.0 mm as the maximal force corresponding to the mean diameter of each class (that is 0.025, 0.75, 1.5 and 3.0 mm respectively), divided by the root CSA corresponding

to these four diameters. Roots were classified by classes of depth (by 0.1 m - slices from 0.0 - 0.1 m until the deepest roots, that appeared at 0.5 - 0.6 m), and scanned. Image analysis (using the software Winrhizo 2007, Regent Instruments) provided the root volume per class of root diameter and class of depth. Assuming that all the roots crossed perpendicularly the potential shear surface, the root volume was divided by the volume of soil to obtain the Root Area Ratio (RAR) for each class of root diameter, depth, species and hotspot. It must be noted that this RAR is a maximum value, because in reality all the roots do not cross the shear surface.
Therefore, we obtained different values of T_r depending on species, hotspot and root size (diameter), and different values of RAR depending on species, hotspot, root size and root depth. To calculate C_r, we used the Wu (1976) and Waldron (1977) model. Each T_r was multiplied by its corresponding RAR. Following the current debates on R_f values (Docker and Hubble, 2008; Thomas and Pollen-Bankhead, 2009), and considering soil structure and soil friction angle, we fixed R_f equal to 1. Finally the additional cohesion of roots for the class of depth z_1-z_2, $C_{r\,z1\text{-}z2;\,species}$, was obtained for each species and at each hotspot:

$$C_{r\,z1-z2;species} = \sum_{0.0-0.5mm}^{>2mm} \left(R_f * T_r * RAR\right)_{diameter} \qquad (3)$$

At each hotspot, we proceeded to species counting by quadrats along the slope to obtain the mean density of the five studied species per square meter. So, $C_{r\,z1\text{-}z2}$ the additional cohesion due to roots per square meters at each hotspot and at each depth equals:

$$C_{r\,z1-z2} = \sum_{species1}^{species5} \left[k_{species} * C_{r\,z1-z2;\,species_i}\right] \qquad (4)$$

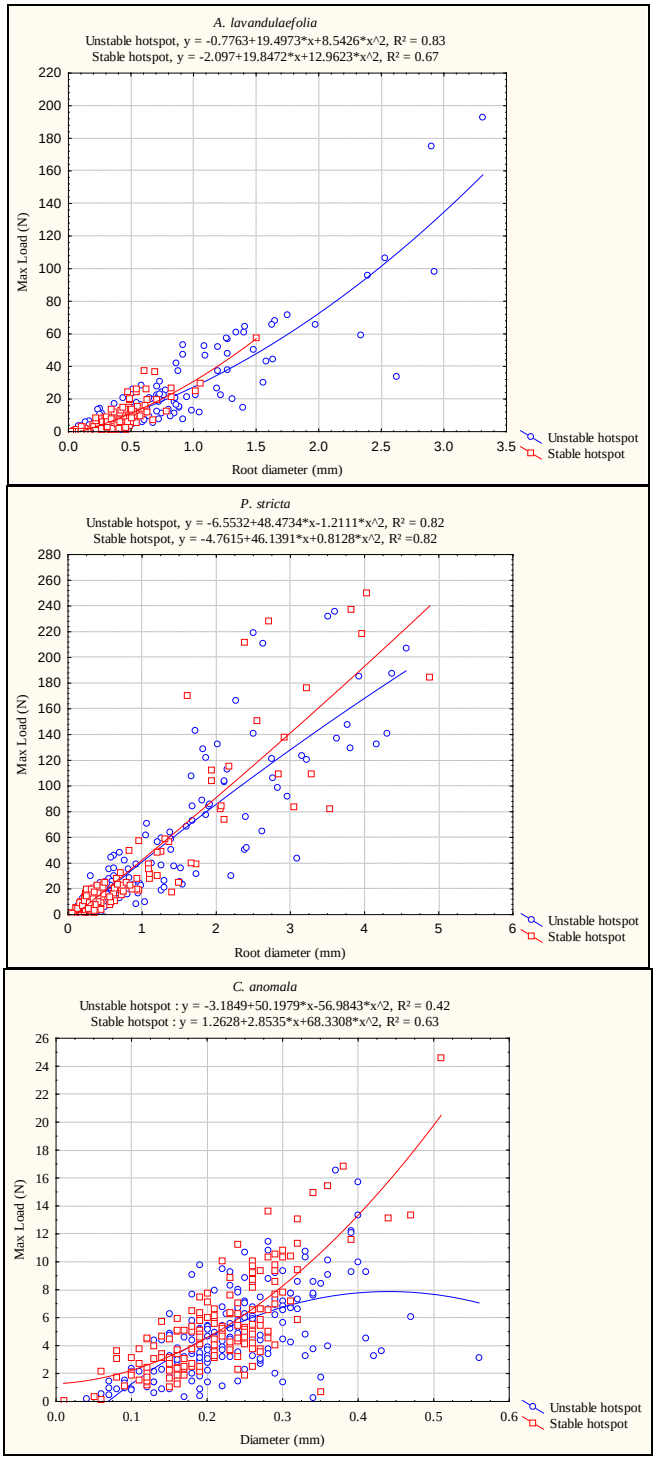
where $k_{species}$ is the number of individuals per square meter for each of the five species (most of the time < 1).
Once C_r has been calculated, it can then be added as a parameter to slope stability models, to calculate the factor of safety (FOS). We used Slip4Ex (Greenwood, 2006), a straightforward computer program developed for routine stability analysis and the assessment of the contribution of vegetation to slope stability. The slope section is drawn up and dimensions and parameters are fed in to the Microsoft Excel based program for stability calculations using the method of limit equilibrium analysis. The simplicity of the program makes it ideal for preliminary problem analysis. It enables the user to understand the nature of the analysis and explore the parameter assumptions made. Geosynthetic reinforcement may be included and vegetation effects such as enhanced cohesion, changed water pressures, mass of vegetation, wind forces and root reinforcement forces are readily included in the analysis. The SLIP4EX program is freely available on request from the Author (John Greenwood 2006). FOS for the two hotspots, with and without vegetation, was calculated, and recommendations were formulated.

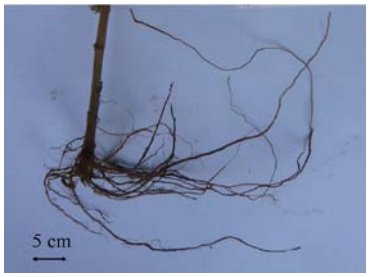
RESULTS

Root architecture

During the first stages of growth, *A. lavandulaefolia* had long lateral subhorizontal roots (macrorhizae). In general, one taproot grew deeply and long lateral roots grew obliquely at an angle of approximately 45 °. Macrorhizae extremities branched into very fine roots. Small fibrous roots (brachyrhizae) were dispersed in clusters along the long branches (Table 2, Fig. 1a). *P. stricta* possessed one differentiated taproot with long subhorizontal branches. The taproot was often long and tortuous as it reached the bedrock. Few root hairs were observed and fibrous brachyrizhae were confined in a zone around the collar and at the extremities of long

branches (Table 2, Fig. 1b). *C. anomala* possessed root systems with fine and short roots. Each plant had a small number of roots, but as individuals were clustered into tufts, a mat of roots existed under the soil surface. Individuals were able to develop a layered root system, allowing roots to emerge from the stem above the soil surface (Table 2, Fig. 1c). *R. chinensis* was able to reproduce by vegetative multiplication, with long lateral roots linking one stem to the others. Along these roots, fine and thin roots grew downwards for nutrient exploration (Table 2, Fig. 1d). *F. tikoua* is a creeping plant, comprising a strong horizontal stem growing along the ground or just underneath the soil surface. This stem grew usually perpendicular to the slope direction and possessed roots with little branching. Therefore, root orders were low for this species (Table 2, Fig. 1e).

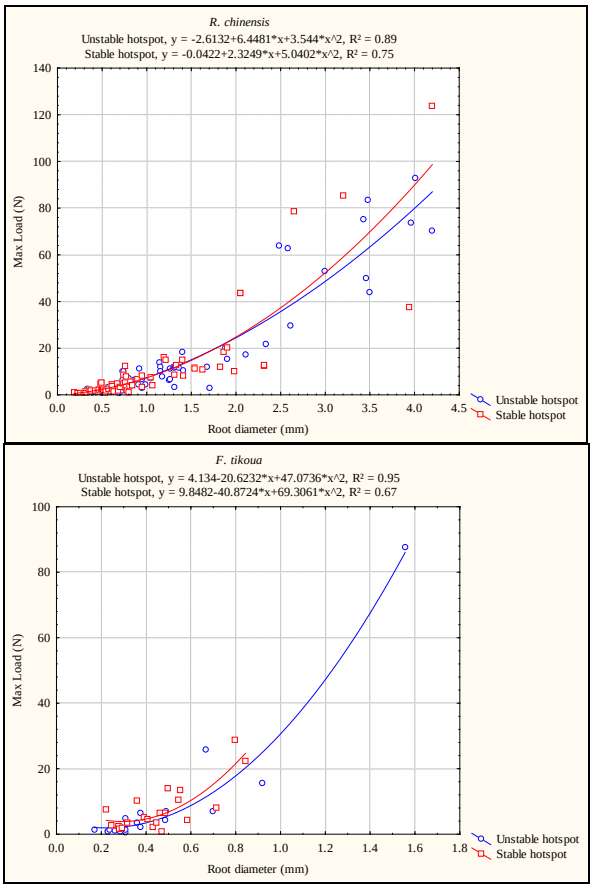




a) *A. lavandulaefolia:* long lateral roots

b) *P. stricta*: taproot system

c) *C.anomala*: fine fibrous roots



d) *R.chinensis*: sprouting roots

e) *F.tikoua*: roots distributed along creeping stem

Fig. 1 Scatterplots of Max Load (N) against Root diameter (mm) and the best-fit regression curve ($p<0.005$) (axis scales are not the same). a) *A. lavandulaefolia*, b) *P. stricta*, c) *C. anomala*, d) *R. chinensis*, e) *F. tikoua*, and their respective root systems.

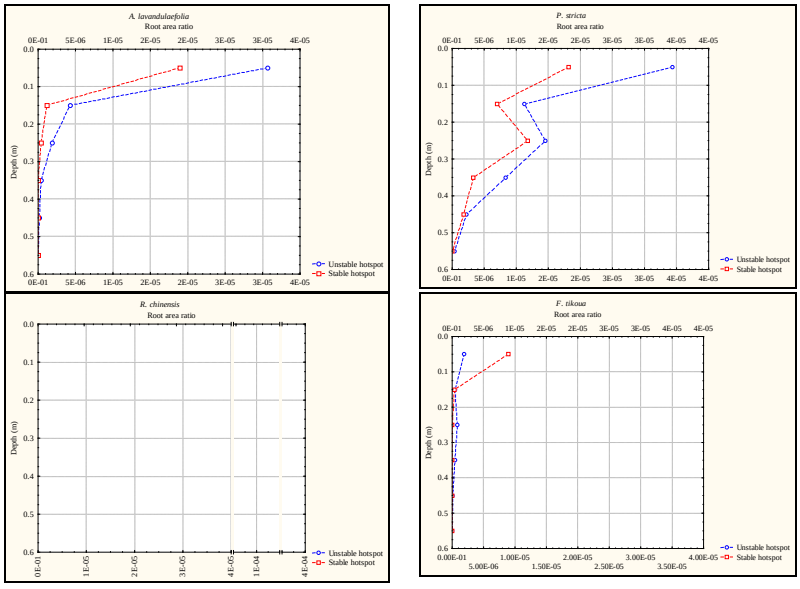
Root mechanical properties

For all species, we observed a strong relationship between the maximum load at break point and the diameter of the tested root. This relationship was a second-order polynomial (Fig. 1). The only species for which this relationship was not highly significant was the grass *C. anomala*. Only *A. lavandulaefolia* presented a higher load at break point on the unstable hotspot than on the stable hotspot, for fine roots (0.0-0.5 mm). For *A. lavandulaefolia* bigger roots, it was inversed. This was statistically different (Anova on Log10, $F_{3,405}=4,57$, $p=0.004$). For the other species, load at break point for a given diameter was higher on the stable hotspot than on the unstable hotspot.

Root distribution

For all species the most RAR was distributed in the upper 0.1 m of soil (Fig. 2). This characteristic was most striking for the caespitose grass, *C. anomala*. For *P. stricta*, RAR was high even at deeper levels in the soil, with a relative peak in RAR at 0.2-0.3 m depth. Only a small number of vertically growing taproots penetrated the bedrock to a depth of 0.6 m. At depths of 0.0-0.10 m on both hotspots and 0.1-0.2 m on the stable hotspot, *R. chinensis* had extremely high values of RAR compared to the other species (RAR increased by a factor of ten). Interestingly, *R. chinensis* also had a relatively higher RAR just above bedrock zone on the unstable hotspot. *F. tikoua* possessed the lowest RAR values, with clusters of roots growing along the creeping stem. Therefore, the ratio per unit volume of soil resulted in lower values because roots were not evenly distributed along the stems.

Three species had higher RARs on the stable hotspot: *C. anomala*, *F. tikoua* above a depth of 0.2 m and *R. chinensis* above a depth of 0.3 m. *A. lavandulaefolia* and *P. stricta* had higher RARs on the unstable hotspot.



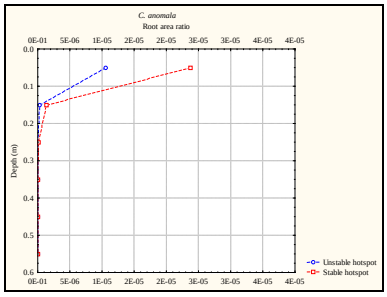


Fig. 2 Scatterplots of mean Root Area Ratio (sums of classes of diameter) against depth for each species and at each hotspot.

Root contribution to slope stability

By counting the number of individuals in quadrats, we obtained the mean floristic composition on both hotspots.

On the stable hotspot 1 m^2 contained :

1.5 *A. lavadulaefolia* + 0.125 *P. stricta* + 3.625 *C. anomala* + 1.0 *R. chinensis* + 2.875 *F. tikoua*.

On the unstable hotspot, we found :

0.167 *A. lavadulaefolia* + 0.01 *P. stricta* + 0.333 *C. anomala* + 0.833 *R. chinensis* + 1.167 *F. tikoua* / m^2.

These mixtures are not complete, because species that were present but which we did not study were not taken into account. Our approach was to consider the situation of managers planting the five species we studied: how many individuals of each of the five studied species were optimal in a degradation hotspot?

Table 3 Factor of safety values and effect of the presence of roots on both hotspots.

	FOS of bare ground	FOS of ground + vegetation	FOS of ground + 4*vegetation
Unstable hotspot	0.70	0.80	1.11
Stable hotspot	0.98	1.07	1.32

A slope is judged stable if FOS>1.

Using the Slip4Ex program, we calculated that the stable hotspot would be unstable without vegetation (Table 3). Adding the effect of the roots of the mean mixture found on the stable hotspot, the FOS for this site equalled 1.07. Therefore, we could not assume that this hotspot would stay stable under these conditions because the FOS remained close to 1.

The unstable hotspot would be very unstable without vegetation ($FOS_{\text{unstable hotspot ; without veg}}$ = 0.70, Table 3). With the reinforcing effect of roots included, $FOS_{\text{unstable hotspot ; + veg}}$ = 0.80, which is still < 1. This result was confirmed visually, as the unstable hotspot could be seen to fail, even with the presence of the current vegetation mixture. The vegetation mixture therefore should be

denser to stabilize this degradation hotspot. According to Slip4Ex, the current mixture should be multiplied at least 4 times to reach $FOS_{\text{unstable hotspot ; + veg}} > 1$ (1.11).

CONCLUSIONS

With regard to root architecture, *P. stricta* possessed a deeply growing taproot, fixing the soil through a thicker zone and thus crossing deeper potential shear surfaces. The RAR peak observed for *P. stricta* at 0.2-0.3 m may be due to a concentration and a thickening of roots just above the bedrock (found at approximately 0.3-0.4 m, Table 1), as these roots would not easily penetrate the bedrock. The very high values of RAR found at a shallow depth for *R. chinensis* were probably caused by the presence of lateral roots necessary for vegetative multiplication. These roots were thicker than the roots used for resource acquisition. As the function of such roots is to sprout aerial stems, they need to remain close to the soil surface. These coarse roots were found at slightly deeper levels on stable conditions than on unstable conditions. *R. chinensis* and *F. tikoua* also demonstrated the ability to spread easily, either by roots or by horizontal stems, and so they can link unstable areas to more stable zones. The ability of *C. anomala* to produce roots up the stem and above the soil surface is useful on slopes, when soil slippage can leave downhill roots exposed. By growing layers of roots uphill, the plant can stay anchored, although at an expense of producing deeper roots. This fast-growing herb is complementary to slower growing shrubs and trees, especially on unstable erosion hotspots where a shallow reinforcement of soil is required. Considering the mechanical properties of the roots, *A. lavandulaefolia* seems well adapted to soil slippage, as tensile resistance for fine roots (that represented the majority of roots for all the species) increased when plants grew on unstable soil, contrary to the other species.

Interestingly, *P. stricta* has been chosen by government authorities to plant on a large scale on unstable slopes. We recommend however, planting not only one species, but to encourage the revegetation of unstable slopes by planting a mixture of species that can be found naturally on these slopes. The five species we studied and which grow together have different root system architectures. This combination of species seems an optimal ecological combination for soil stabilisation. However, managers will have to control vegetation density on degradation hotspots. We suggest that revegetation should be encouraged by sewing or planting seedlings or cuttings, not on the entire slope but on the degraded hotspots, so as to rapidly obtain approximately at least 7 *A. lavandulaefolia* + 1 *P. stricta* + 13 *C. anomala* + 33 *R. chinensis* + 47 *F. tikoua* individuals per 10 m², i.e. a plant mixture representing the natural proportions of each of the five species, but at a density four times higher that that observed on unstable hotspots.

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