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Geospatial Remote Assessment for Ingress Locations (GRAIL)

Vegetation Impact on Soil Strength

A State of the Knowledge Review

Wendy L. Wieder and Sally A. Shoop

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U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

Final Report

Prepared for Army Terrestrial Environmental Modeling and Intelligence System (ARTEMIS)
U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

Under Work Item 9K3D08 for the Geospatial Remote Assessment for Ingress
Locations (GRAIL) Project

Abstract

Researchers in a variety of fields have studied using vegetation to alter or reinforce soils. However, investigating the use of vegetation with regard to impacting soil strength and therefore improving vehicle trafficability and mobility, for both military operations and training purposes, is more limited. Much of the soil-reinforcement work reported in the literature deals with trees and larger shrubs appropriate for slope and bank stabilization. Other research efforts are for agricultural or forestry applications and involve crops and, again, large trees. While larger plant species would prohibit vehicle traffic and thus be inappropriate from the standpoint of vehicle mobility, the general observations and the different types of laboratory and field tests performed in these studies still provide valuable insight. This review discusses the issue of vegetation and its effect on a variety of soil-strength parameters. It also reviews work regarding the effect of vehicle operations on vegetation and conversely the effect of vegetation on vehicle performance, or trafficability. The intent is to provide a broad knowledge base of the variety of work done with vegetation and soils with particular attention to the applicability for vehicle mobility and land management goals.

Contents

Report Documentation Page

Figures and Tables

Figures

Tables

Preface

This study was concluded for the Army Terrestrial Environmental Modeling and Intelligence System (ARTEMIS) program under Work Item 9K3D08 for the Geospatial Remote Assessment for Ingress Locations (GRAIL) project. The technical monitors were Mr. Randy Hill (CEERD-RV) and Mr. John Eylander (CEERD-RR). Initial funding was through the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC), Optimal Allocation of Land for Training and Non-Training Uses (OPAL) Program.

The work was performed by the Force Projection and Sustainment Branch (CEERD-RRH) of the Research and Engineering Division (CEERD-RR), ERDC Cold Regions Research and Engineering Laboratory (CRREL). At the time of publication, Dr. Justin Berman was Acting Chief, CEERD-RRH, and CDR J. D. Horne, USN (Ret), was Chief, CEERD-RR. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Joseph L. Corriveau.

COL Bryan S. Green was Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

APC	Armored Personnel Carrier
ARTEMIS	Army Terrestrial Environmental Modeling and Intelligence System
CERL	U.S. Army Construction Engineering Research Laboratory
CI	Cone Index
CIH	Clegg Impact Hammer
CRREL	Cold Regions Research and Engineering Laboratory
ERDC	U.S. Army Engineer Research and Development Center
GPS	Global Positioning System
GRAIL	Geospatial Remote Assessment for Ingress Locations
HEMTT	Heavy Expanded Mobility Tactical Truck
HMMWV	High Mobility Multipurpose Wheeled Vehicle
LSD	Least Significant Difference
MPC	Multipass Coefficients
OPAL	Optimal Allocation of Land for Training and Non-Training Uses
RAR	Root Area Ratio
TARDEC	Tank Automotive Research, Development, and Engineering Center
USCS	Unified Soil Classification System
VASST	Vegetation and Soil Shear Tester
VTI	Vehicle Terrain Interaction
WEPS	Wind Erosion Prediction System

1 Introduction

Researchers in a variety of fields have studied vegetation and its use to alter, stabilize, or reinforce soil surfaces or soil masses. Slope and streambank stabilization, erosion control, and agricultural crop yield are areas of significant work. Other researchers have looked at the effects of a variety of tracked and wheeled vehicles on vegetation. However, investigating vegetation with regard to impacting soil strength, and therefore improving off road vehicle mobility and performance, is more limited and an area of interest to the military.

For the purposes of the supporting military off road vehicle use, the focus is twofold: (1) improve understanding of the interaction between vehicle and vegetated terrain to support vehicle mobility for military operations and (2) improve vehicle performance and trafficability, while maintaining the ground-surface integrity to preserve military training lands as part of a land management strategy. Military operations involve a variety of terrains, and understanding the impact of vegetation on soils characteristics assists remote deployment planning and allows effective vehicle operations while minimizing terrain impacts. This review discusses the use of vegetation in several soil-improvement applications and the effect of vegetation on a variety of soil-strength parameters. It discusses the main study areas found in the literature; testing procedures used to evaluate soils, roots, and root–soil composites; the specific issues of vehicle impacts on soils and vegetation; and finally vehicle–terrain interactions.

The literature reviewed provided a broad knowledge base of the work done with vegetation and soils in a variety of arenas, some work being more applicable to vehicle trafficability, land management, and vehicle mobility than others. Much of the work reported in the literature deals with trees and larger shrubs appropriate for slope and bank stabilization. While larger plant species would prohibit vehicle traffic and thus be inappropriate from the standpoint of vehicle mobility, the general observations and the different types of laboratory and field tests performed in these studies still provide valuable insight.

2 Slope Stabilization

Stabilizing slopes to minimize landslips is a common use of vegetation as soil reinforcement. Because most soils have very low strength in tension, the roots of surface vegetation act as a fiber network and provide tensile strength to the soils, analogous to the reinforcing steel in concrete. This is especially helpful in saturated soils that are even less likely to have strength in tension. Schmidt et al. (2001) investigated slope stabilization of forested areas with the intent of looking at the age and type of vegetation as a variable in the effectiveness of the slope stabilization. The vegetation studied included coniferous and deciduous trees with significant understory and also replanted areas that had previously been clear-cut. They found that reinforcement could not be predicted only by age of the vegetation but that it is also strongly affected by the vegetation mix, especially when comparing natural forests to those previously cut. Terwilliger and Waldron (1991) found that both small and large slips were more likely on slopes with evenly distributed, low magnitude reinforcement, such as under grasslands, than on hillsides with scarce but relatively large root reinforcements, such as under chaparral (an evergreen shrub common in California). The chaparral offered randomly spaced but relatively high magnitude reinforcement of the soil surface. The magnitude of the root reinforcement depends on a number of factors, including the total number of roots, the area of the thickest root, and the ratio of the cross-sectional area covered by roots to the total cross-sectional area of the soil-shearing surface.

Preti and Giadrossich (2009) looked at Spanish Broom, a shrub used for slope bioengineering stabilization through root reinforcement. Their investigation included laboratory testing of root tensile strength; measurement and calculation of mean root number, mean root diameter, root area ratio (RAR); and calculation of root cohesion and the factor of safety for the slope. The RAR is the ratio between the cross-sectional area occupied by roots and the cross-sectional area of the rooted soil. RAR varies with species, location, and depth and is also strongly influenced by genetics, local soil, and climate and by forest or other land management practices (Bischetti et al. 2005).

Using their tensile-strength testing data and models by others (see Section 5.1), Preti and Giadrossich (2009) found that planting a steep slope with Spanish Broom provides a considerable increase in cohesion of the surface soil layers. However, their more thorough look at the Wu (1976) and Waldron (1977) root–soil model for soil cohesion indicated a tendency to overestimate the root cohesion. Section 5.1 will discuss this further.

Ali (2010) looked more closely at the mechanical properties of roots for slope stabilization. He investigated both the tensile strength of roots and the pullout strength of the plant. He worked with three species of trees and found the following: (1) Pullout capacity exhibited two peaks—the first indicating the failure of the lateral roots, the second the failure of the taproot. (2) Root tensile strength decreases with increasing root diameter, as Section 7 will discuss.

Abdullah et al. (2011) conducted field-shear box tests on three plants, two trees and a shrub, commonly used for slope stabilization in Malaysia. The soil type of the test area was not identified. They noted that plants with heart root systems, where both large and smaller roots descend diagonally from the stem or trunk, provide a greater increase in soil cohesion compared to taproot systems, where a strong main root descends vertically from the underside of the stem or trunk. Heart root systems also contribute more root coverage for a wider area of the topsoil, reducing shallow landslides. Their results indicated that the shear strength of most root-reinforced soil samples increased gradually with increasing plant stem diameter.

Hu et al. (2013) investigated using direct shear and triaxial tests for both rooted and unrooted soils by using five shrub types while analyzing strategies for reducing shallow landslide activity. They also directly tested roots in single tensile and shear tests and found that the internal friction angles of both the root–soil composite systems and the soil without roots were similar. However, the cohesion forces of the root–soil composite were notably higher than the soil without roots, increasing by 29.4%–394.6%. Their preliminary findings indicated the greater the percentage of secondary phloem (bast fiber) and xylem (wood fiber) in the root cross section, the higher the root strength (single tensile resistance and tensile strength).

3 Erosion Control

Using vegetation to prevent surface erosion, without intent to provide any additional surface strength, has also been widely studied. Brown et al. (2010) looked at the root depths of native and amenity grasses used as roadside plantings. Amenity grasses are those used to create high-quality green areas, such as parks or, in the case of this report, public roadsides. For the 21 grasses studied, 16 were native, and 5 were amenity. Using soil columns containing four plants, with *n* indicating the number of replicate columns, they found a variety of root depths as shown in Figure 1. Also, visually estimating the percent of vegetation cover, they observed a significant difference in the survival rate of the different grasses planted at a roadside location (Figure 2). In Figure 2 the percent cover values are means with the least significant difference (LSD) values also given. They concluded that the ability to establish and maintain a sodded surface is a significant consideration, as grasses that do not survive cannot provide benefits, and that grasses with shallower root depth tend to produce sod that sloughs under heavy rain conditions.

Gyssels et al. (2005) completed a review of the impact of plant roots on the resistance of soil to water erosion. They found that vegetation cover is the most important parameter for splash or interrill erosion, whereas for rill and ephemeral gully erosion, the plant roots are at least as important as the vegetation cover. From a hydrological point of view, plants reduce soil erosion rates by intercepting raindrops, enhancing infiltration, transpiring soil water, providing additional surface roughness, and adding organic matterial to the soil. The comparison by Gyssels et al. (2005) of previous studies showed a large discrepancy between data gathered in the field and data obtained from laboratory experiments. They attribute this discrepancy to thigmomorphogenesis, the change in morphology and the mechanical properties of a plant due to the contact disturbances such as friction with neighboring plants or passing animals, wind, rain, changes in soil pressure, and other factors. Plants grown in natural conditions will be shorter and stockier with more supportive features and, therefore, stronger than plants grown in a controlled laboratory setting. They concluded that more in-field root research is needed as the current knowledge about root morphology and its impact on soil erosion by water is limited.

Figure 1. Plant height, root depth, and root mass distributions for roadside grasses. (Reprinted by permission from Brown et al. 2010, Fig. 3.)

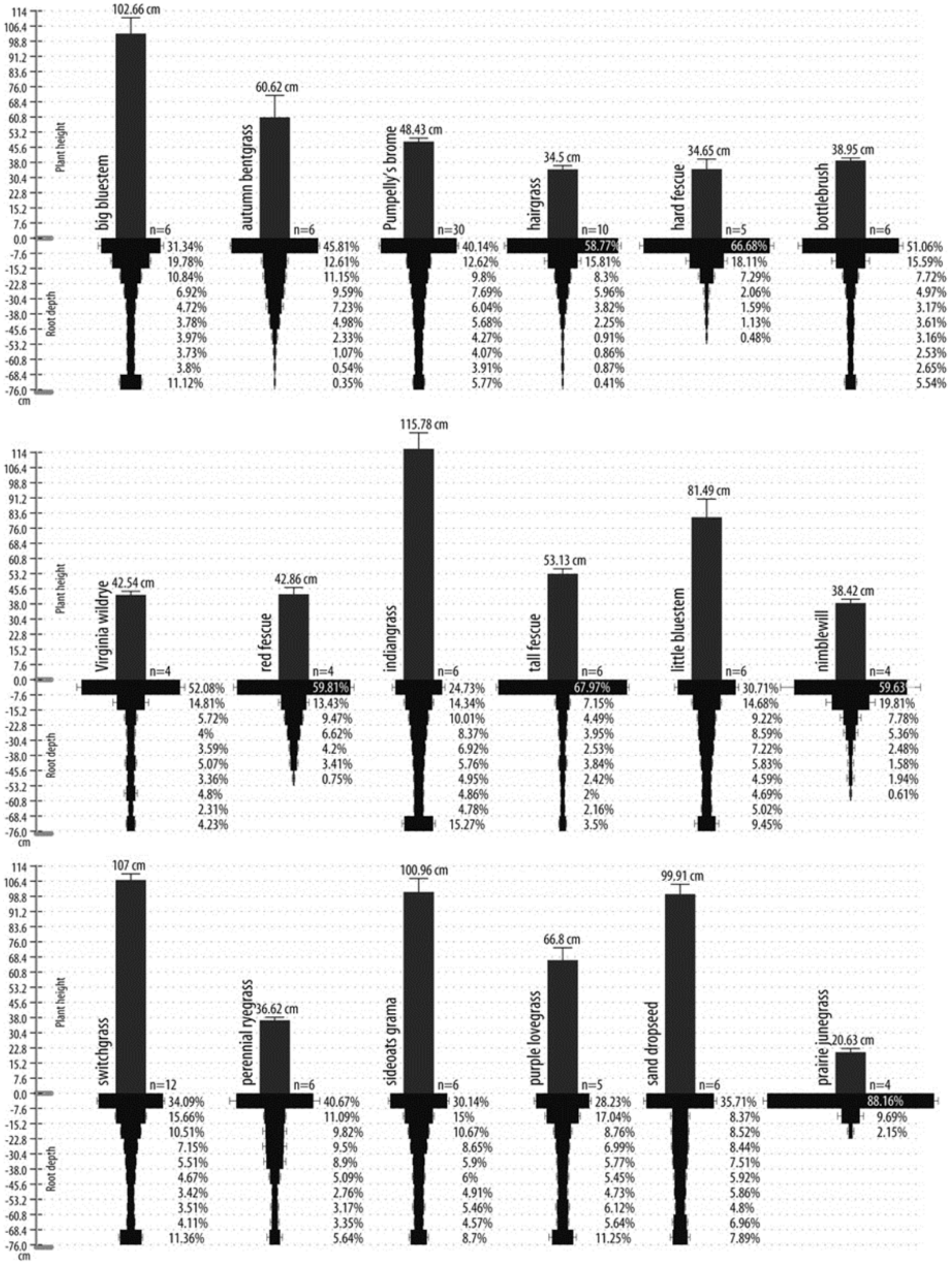
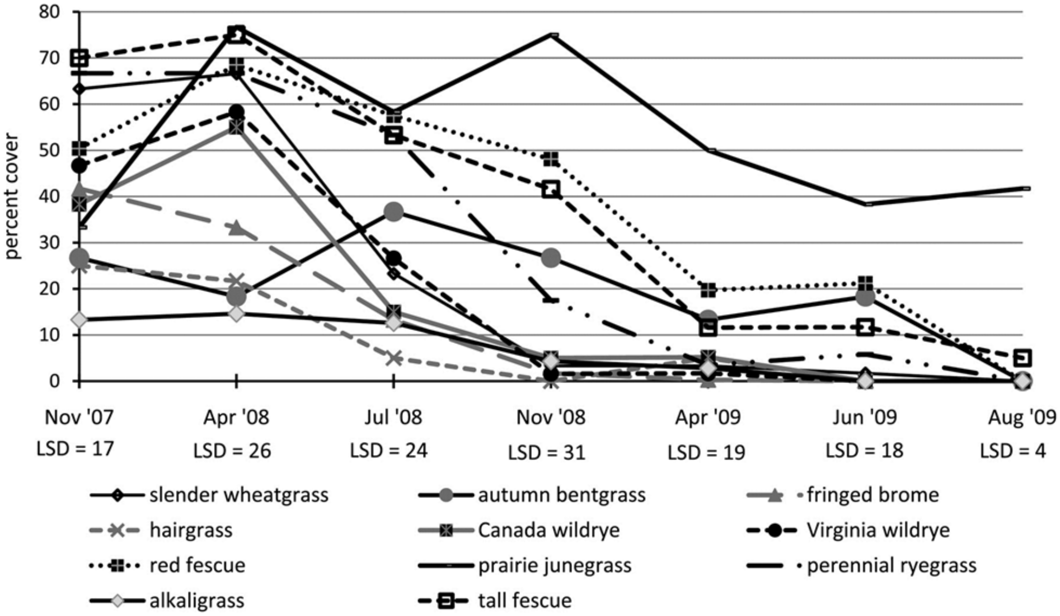


Figure 2. Survival of grass species along Rhode Island Route 4. Survival was measured through visual estimates of percent cover. (Reprinted by permission from Brown et al. 2010, Fig. 5.)



The use of vegetation to control wind erosion is also of interest to both the agricultural community and the military. The Wind Erosion Prediction System (WEPS) model developed by the U.S. Department of Agriculture, Agriculture Research Service, is a process-based daily-time-step wind erosion model developed for use on cultivated agricultural lands. Retta et al. (2103, 2014) have been working with WEPS to adapt and modify the model for use for military rangeland management applications. To provide suitable data, they have conducted trafficking studies at Fort Riley, Kansas, and Fort Benning, Georgia. Section 8 will discuss their results further.

4 Uprooting, Overturning Root Mechanics

The mechanics of plant root systems have also been studied from several aspects. Crook and Ennos (1993) investigated root lodging, which is the failure of a plant by rotation of the plant's root–soil anchorage cone versus buckling of the stem. This work looked at the diameter of the root–soil cone of four varieties of winter wheat and the bending strength of the roots themselves. Fourcaud et al. (2008) modeled tree overturning using a two-dimensional finite element model of the root morphology while Stokes et al. (1996) modeled tree root systems and pullout resistance.

Ennos (1990) performed uprooting tests on leek seedlings and came to the following conclusions. The anchorage force provided by roots will be proportional to their length but only up to a critical length. Roots longer that this will break before their lower regions are stretched.

The equation for the critical length is as follows (Ennos 1990):

$$L_{crit} = \frac{\sigma R}{2\alpha\tau} \tag{1}$$

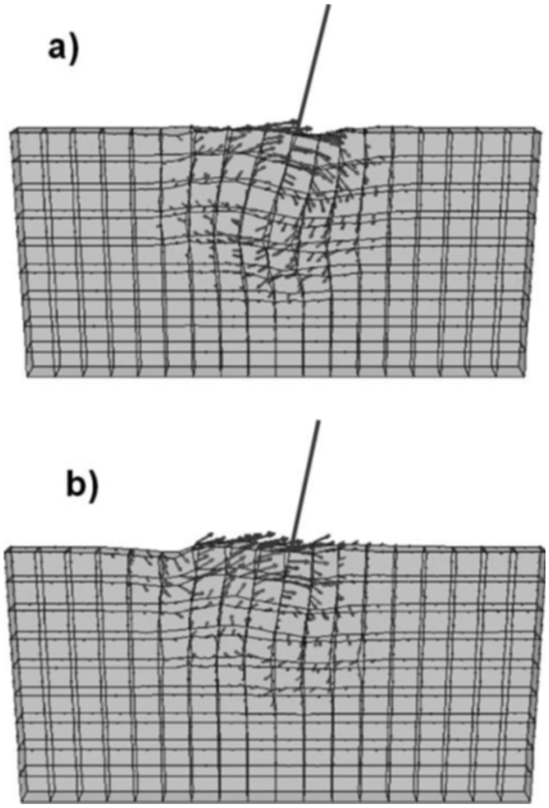
where

σ = root breaking stress;
R = radius of the root;
α = relative strength of the root–soil bond, which can vary from 0 (no bond) to 1; and
τ = soil strength.

In whole root systems, failure occurs proximally before the fine distal roots are mechanically stressed, so they have no anchorage function. Ennos (1990) states, "Resistance to an upward force will be most economically achieved by having many strengthened proximal roots, as in the adventitious root systems of grasses, sedges and stoloniferous dicots" (i.e., legumes and forbs with extensive, shallow secondary root systems).

Dupuy et al. (2007) developed a three-dimensional finite element model for tree anchorage that allows varying soil conditions and real root-system architecture so that the effects of parameters such as moisture content can be evaluated (Figure 3). They found that virtual experiments are easier to perform than complex field experiments where trees are physically manipulated and the root systems are damaged as the tree fails.

Figure 3. Three-dimensional finite element model of displacement fields for tree overturning in (*a*) clay-like soil and in (*b*) sand-like soil. (Reprinted by permission from Dupuy et al. 2007, Fig. 6.)



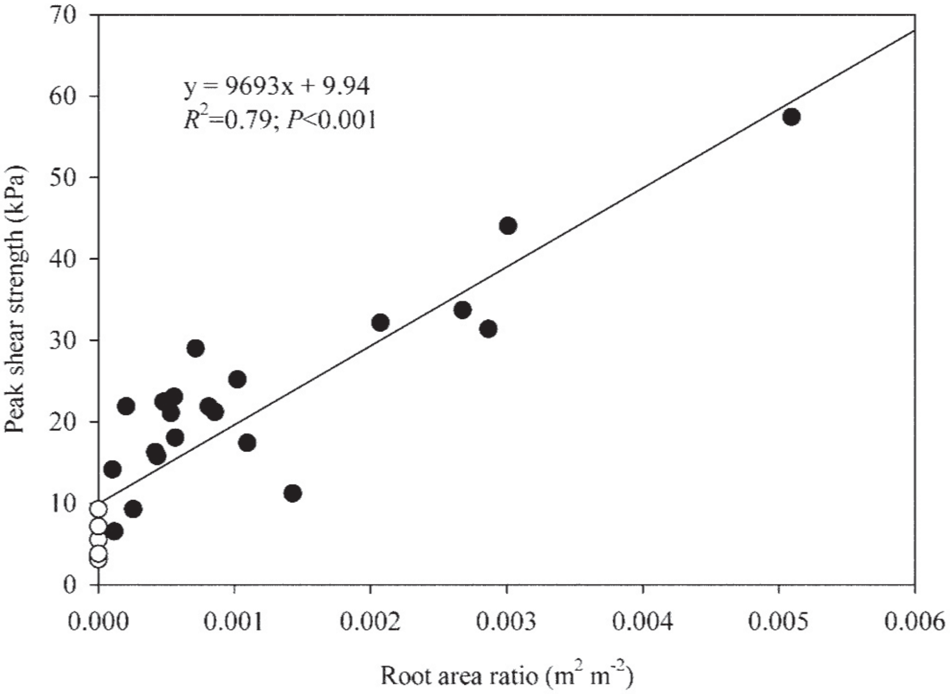
5 Impact of Vegetation on Soil Strength

The impact that vegetation has on soil properties has been studied from varied agricultural, forestry, agronomy, and engineering perspectives. The agricultural sciences frequently look at the influence of crops on the physical properties of soils. Gerard and Mehta (1971a, 1971b) looked at the impact of radish root growth and plant density on soil compaction and permeability with depth. They found the roots' effect on the soil varied with age of the plant and the density with which the plants are placed.

5.1 Laboratory shear

Several researchers have performed laboratory shear tests on soil samples with a variety of soil and vegetation combinations. Mickovski et al. (2009), through using willow roots in a laboratory setting, found a strong correlation between the RAR and the reinforcement the roots provided to the soil in shear testing, as shown in Figure 4. However, they noted that modeling must consider the root failure mechanism and that models of soil reinforcement by plant roots typically do not consider the role of root stiffness and root–soil adhesions. Waldron (1977), Waldron and Dakessian (1981), and Waldron et al. (1983) compared the reinforcement of alfalfa, barley, and yellow pine versus clear soil. Their results varied depending on the depth of the shear surface. Waldron and Dakessian (1982) sheared soil specimens planted with seven grass species, two legumes, and two trees. They found that several of the grasses, planted in early fall and laboratory shear tested the following spring, gave about a threefold increase in shear resistance at the 0.3 m depth in homogeneous saturated clay loam. One-year-old alfalfa produced a fourfold increase.

Figure 4. Peak shear strength versus the RARs on the shear plane for fallow (○) and willow planted (●) samples. (Reprinted by permission from Mickovski et al. 2009, Fig. 9.)



Waldron's work (Waldron 1977; Waldron and Dakessian 1981) and a paper by Gray and Barker (2004) discuss the derivation of a model for the shear strength of rooted soils based on the general Coulomb equation for soil shear strength:

$$S = c + \sigma tan\phi \tag{2}$$

where

S = the shear resistance of soil,
c = soil cohesion,
σ = total normal stress on the shear plane, and
ϕ = soil angle of internal friction.

For soils reinforced by roots, the equation becomes (Waldron and Dakessian 1981)

$$S_R = c + \Delta S + \sigma tan\phi \tag{3}$$

where

S_R = the reinforced shear resistance of the rooted soil and
ΔS = the contribution of the roots to the soil shear resistance.

Based on a model where the root fibers, acting perpendicular to the shear surface, add tension strength to the soil, the general equation for ΔS is (Gray and Barker 2004)

$$\Delta S = t_R(sin\theta + cos\theta tan\phi) \tag{4}$$

where

θ = the angle of distortion of the fiber or root and
t_R = the mobilized tensile strength of the root fibers per unit area of soil.

Gray and Barker (2004) state, "The mobilized tensile stress of the root fibers t_R will depend on the amount of fiber elongation and the fixity of the roots in the soil matrix. Full mobilization can occur only if the fibers elongate sufficiently and if imbedded root fibers are prevented from slipping or pulling out. The latter requires that the fibers be sufficiently long and frictional, constrained at their ends, and/or subjected to high enough confining stresses to increase interface friction. Accordingly, three different response scenarios are possible during shearing of a root-reinforced soil composite, namely roots break, stretch, or slip."

5.1.1 Root breaking mode

Shear-strength increase to the soil from full mobilization of root-fibers tensile strength requires calculation of the average tensile strength of the root, T_R, and the fraction of the soil cross section occupied by roots, A_R/A_S, the RAR. The mobilized tensile stress of the root fibers per unit area of the soil in this case is given by (Gray and Barker 2004)

$$t_R = T_R \frac{A_R}{A_S}. \tag{5}$$

Substituting Equation (5) into Equation (4) gives the predicted shear-strength increase from full mobilization of root tensile strength (Gray and Barker 2004):

$$\Delta S = T_R \frac{A_R}{A_S}(sin\theta + cos\theta tan\phi) \quad (6)$$

Wu et al. (1979) found that the value of the quantity ($sin\theta + cos\theta tan\phi$) is insensitive to the value of θ and is close to 1.2 for the range of θ normally considered (48°–72°). Therefore, Equation (6) becomes (Gray and Barker 2004)

$$\Delta S = 1.2T_R \frac{A_R}{A_S}. \quad (7)$$

Equation (7) is also commonly written as (Wu et al. 1979)

$$\Delta S = 1.2t_R. \quad (7a)$$

It should be noted that others have found Equation (7) and the use of the value 1.2 for the quantity ($sin\theta + cos\theta tan\phi$) inaccurate. Pretti and Giadrossich (2009) suggest that this model overestimates the value of soil cohesion by more than 200%. Fan and Su (2008) and Nyambane and Mwea (2011) stated similar findings (see Section 5.3).

5.1.2 Root stretching mode

Lack of sufficient fiber elongation coupled with strain compatibility requirements may prevent mobilization of root-fibers tensile or breaking strength. In this case, the calculation of the mobilized tensile strength, t_R, will be governed by the amount of elongation and the fiber tensile modulus, E_R. A force-equilibrium analysis yields the following expressions for the mobilized tensile stress per unit area of soil (Gray and Barker 2004):

$$t_R = k\beta \frac{A_R}{A_S} \quad (8)$$

where

$$k = (4z\tau_b \frac{E_R}{D})^{\frac{1}{2}} \quad (9)$$

and

$$\beta = (sec\theta - 1)^{1/2}. \quad (10)$$

Substituting Equations (8), (9), and (10) into Equation (4), the predicted shear-strength increase from mobilization of root tensile resistance from stretching will be given by (Gray and Barker 2004)

$$\Delta S = k\beta(A_R/A_s)(sin\theta + cos\theta tan\phi). \tag{11}$$

This expression indicates that shear-strength increases vary inversely with the square root of the root diameter. Accordingly, at equal RAR, numerous smaller-diameter roots will be more effective than a few large roots.

5.1.3 Root slipping mode

If the roots are very short, unconstrained, and subject to low confining stresses, they will tend to slip or pull when the root–soil composite is sheared. They will, however, continue to contribute reinforcement. At incipient slippage, the maximum tension in a root-fiber, T_N, is given by (Gray and Barker 2004)

$$T_N = 2\tau_b {}^{L}\!/_{D}. \tag{12}$$

The shear-strength increase or reinforcement from *n* slipping roots of one size class is given by (Gray and Barker 2004; Gray and Ohashi 1983 as cited in Gray and Barker 2004)

$$\Delta S = (\pi\tau_b nLD/2A_S)(sin\theta + cos\theta tan\phi) \tag{13}$$

with

$$\tau_b = h_r\gamma(1 - sin\phi)ftan\phi. \tag{14}$$

If there are j slipping root size classes with n_i roots in each size class, then Equation (13) becomes (Gray and Barker 2004)

$$\Delta S = (\pi\tau_b/2A_S)(sin\theta + cos\theta tan\phi)\sum_{i=1}^{j} n_i L_i D_i. \tag{15}$$

For the above equations, the parameters are defined as follows:

A_R = the total cross-sectional area of all roots;
A_S = area of the soil shear surface, with A_R/A_S deigned as the fraction of soil cross section occupied by roots, or the RAR;

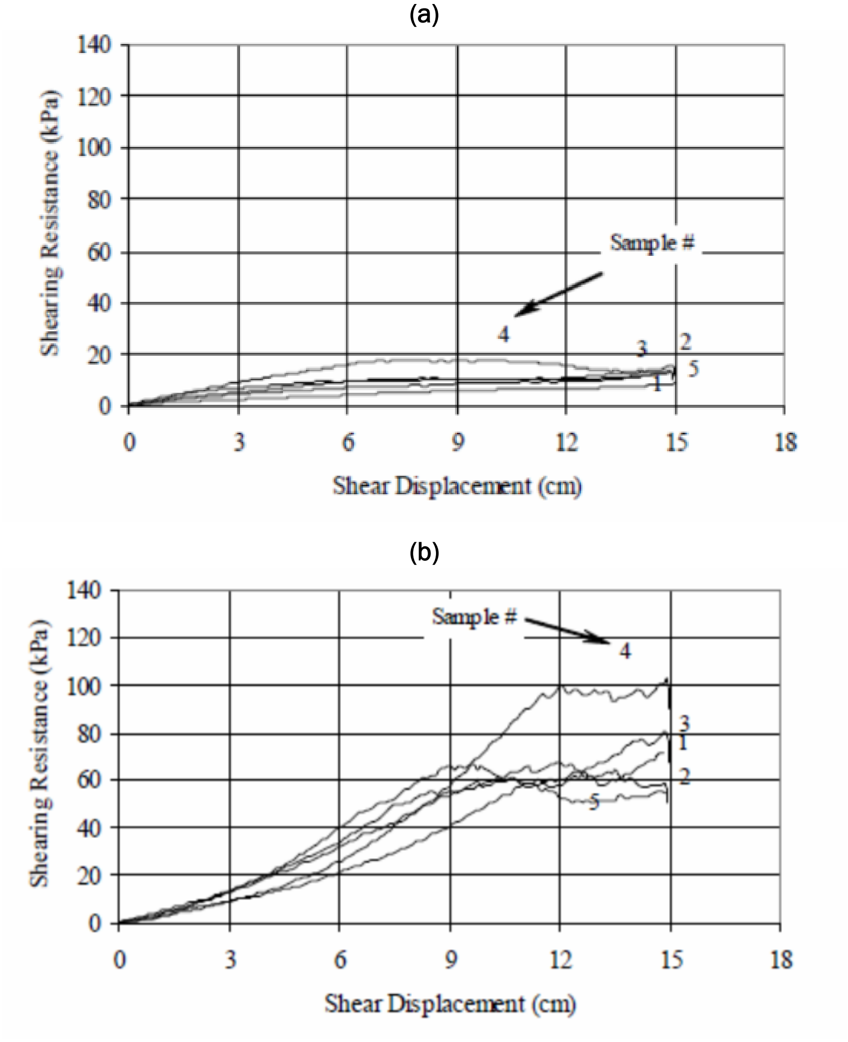
z = thickness of the shear zone;
τ_b = limiting bond or interface friction stress between root and soil;
E_R = root-fiber tensile modulus;
D = root diameter;
n = number of roots;
L = root length;
h_r = the depth below the ground surface;
γ = soil density; and
f = the coefficient of friction between the root fiber and the soil (ranges between 0.7 and 0.9 for soil and wood—soil and roots are likely at the higher end of the range).

Under field conditions, roots occur in different sizes and lengths and can have different tensile strengths and degrees of fixity. Accordingly, all three mechanisms may occur simultaneously. Waldron and Dakessian (1981) illustrated the model by measuring the Young's modulus, tensile strengths, and diameters of pine and barley roots. They then applied these data, along with measured root diameter distributions, to the model. Comparing the model simulations with experiments, they found that the soil-root bond was the most important unmeasured model parameter. Its value, rather than root strength, limited root reinforcement in the saturated clay-loam soil for both species of plant used.

These models are idealizations of actual conditions, but they show what parameters are important and how they affect shear strength. Furthermore, laboratory studies have validated the trends and relationships predicted by these simple force-equilibrium models (Gray and Barker 2004). However, as mentioned, various researchers are still investigating the value of the coefficient in Equations (7) and (7a).

Goldsmith (2006) tested field samples in a laboratory shear box for sedge, switchgrass, and two tree species. The site soil was loamy sand derived from glacial outwash and lacustrine deposition. She found a relative strength increase of 472% for switchgrass, 445% for black willow, 262% for tussock sedge, and 216% for cottonwood for the same displacement (Figure 5). The shear stresses in most of the rooted blocks were still increasing at the end of the test (maximum displacement of about 15 cm), indicating that root tensile failure did not occur during the shear tests. Root elongation or slipping rather than breaking was the most common condition during failure.

Figure 5. Shear stress versus horizontal displacement for (*a*) fallow soils and (*b*) root permeated soils vegetated with switchgrass. (Reprinted by permission from Goldsmith 2006).



Ali and Osman (2008) performed similar tests on laboratory-prepared soil–vegetation blocks. Their vegetation included one grass, two shrubs, and one tree. The soil was a silty sand. The test samples were prepared by compacting soil in 1 m high columns in which the plants were then placed and allowed to grow 6 or 12 months. One column was prepared for each plant type, with an additional control column in which no vegetation was planted. Shear tests were then performed at specific root depths (0.1 m, 0.5 m, and 0.9 m) by cutting the root–soil columns into five samples each. Prior to shear testing, each sample was saturated to remove the effect of soil suction on the shear strength. They found that roots significantly contribute to the increase in soil shear strength after 6 and 12 months, as shown in Figures 6 and 7. The roots increased the cohesion component of shear strength (i.e., the value of intercept on the shear stress versus normal stress plot) as shown in Figure 8. However, they observed no significant change in the angle of friction.

Pirnazarov et al. (2013) and Pirnazarov and Sellgren (2015) developed a new laboratory shear test for tree-root-reinforced soils that applies shear on two planes and accommodates several different arrangements of roots (Figure 9). This simulates the wheel–soil interaction where shearing occurs in two vertical planes that are parallel with the direction of the applied wheel load and perpendicular to the root layer (for trees) as shown in Figure 10. Their main purpose was to assist the engineering process for development of new generation, high-performing, and more eco-friendly forestry machines for operation in European forests. They also discuss the available models for the shear strength of rooted soil slopes, discussed further in Section 5.1, and the modifications to these models for application for trafficability and mobility simulations (Wu 1976; Waldron 1977; Waldron and Dakessian 1981 as cited in Pirnazarov and Sellgren 2015).

Figure 6. Maximum shear stress versus normal stress after 6 months for vetiver grass sample. (Reprinted by permission from Ali and Osman 2008, Fig 3.)

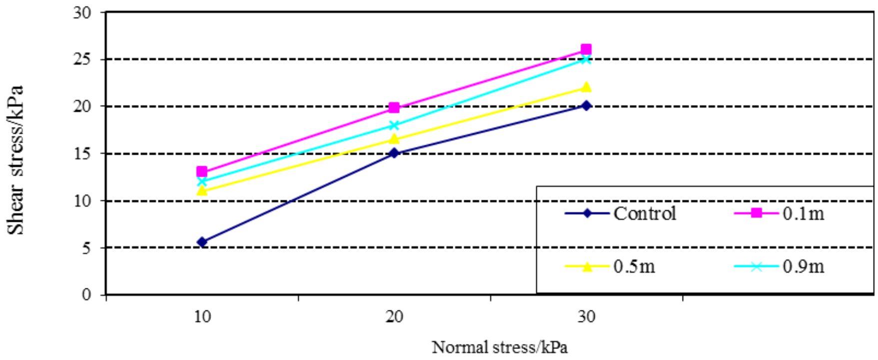


Figure 7. Maximum shear stress versus normal stress after 12 months for vetiver grass sample. (Reprinted by permission from Ali and Osman 2008, Fig. 4.)

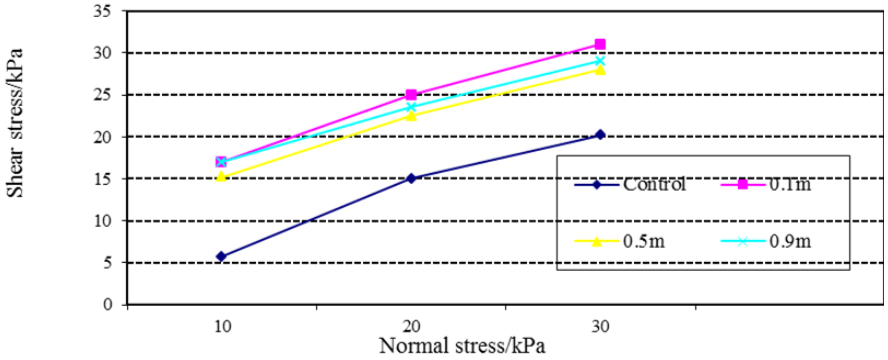


Figure 8. Values of cohesion (c′) for vetiver-grass-reinforced soils at various depths. (Reprinted by permission from Ali and Osman 2008, Fig. 5.)

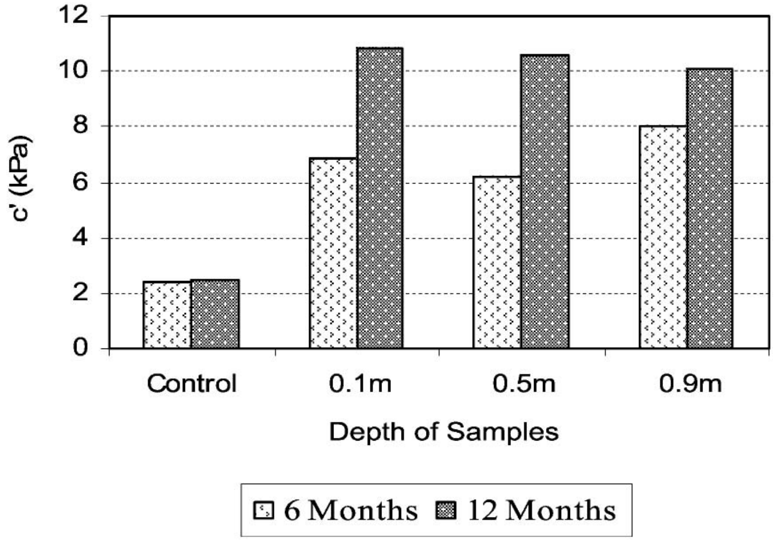


Figure 9. Root–soil shear laboratory test rig (*top*) and the possible placement of roots (*bottom*). (Reprinted by permission from Pirnazarov and Sellgren 2015, Fig. 4.)

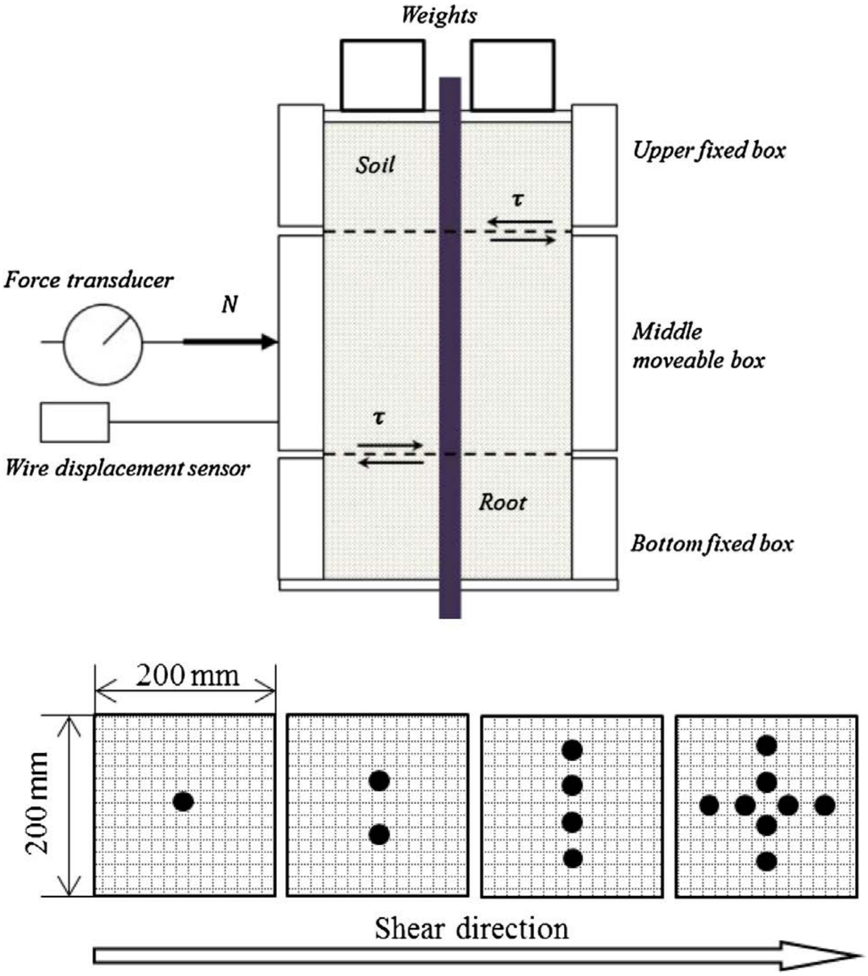
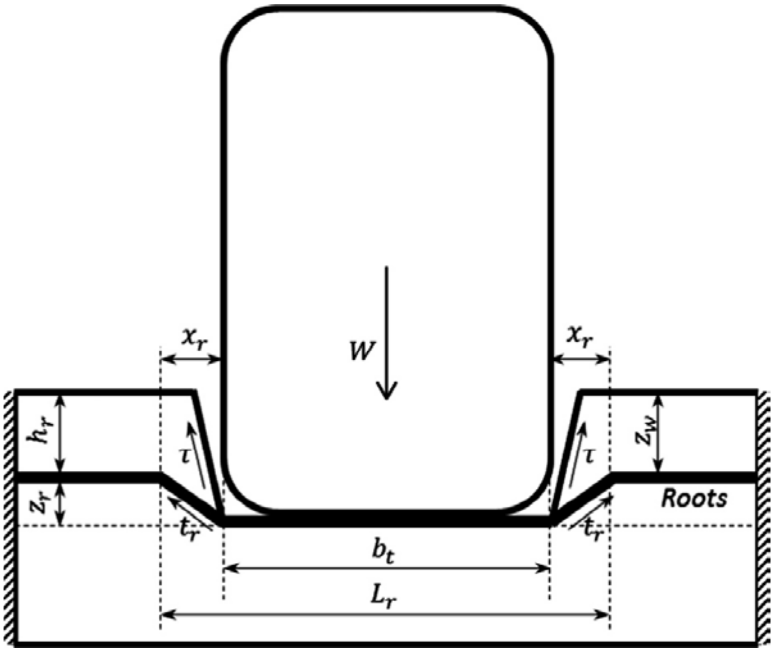


Figure 10. Wheel interaction with root-permeated soil. (Reprinted by permission from Pirnazarov and Sellgren 2015, Fig. 3.)



Preliminary results from measurements with the device show that the normal shear stress in a rooted soil increases proportionately to the number of root specimens and the ratio of root cross-sectional area to the soil area of the shear planes. Also, roots can be treated as an additive factor to soil cohesion while not affecting soil friction as long as the roots remain unbroken. Pirnazarov and Sellgren (2015) did not consider root breaking as this is not consistent with sustainable forestry practices. Finally, they proposed a root-permeated-soil bearing capacity based on a rut depth of less than 0.1 m:

$$Q_r = (c + 2\Delta S)N_c + 0.1\gamma_s N_\emptyset + \frac{b}{2}\gamma_s N_\gamma \tag{15}$$

For the above equation, the parameters are defined as follows:

b = width of loading surface (m);
c = soft soil cohesion (kPa);
N_c, $N_\emptyset$, N_γ = soil bearing coefficient;
Q_r = ultimate bearing capacity of the root-permeated soil (kPa);
ΔS = soil reinforcement by roots (kPa); and
γ = soil weight density (N/m^3).

5.2 Laboratory triaxial tests

Liu et al. (2011) performed laboratory triaxial testing on soils reinforced with different quantities of Manila grass. They found that there is an optimal quantity of Manila grass roots that affects the strength and capacity for resisting deformation of soils reinforced with roots. They also provided a numerical simulation, using finite element analysis, of this work (Huang et al. 2011). The only concern with this study is the lack of information on the sample preparation; it is not clear if the roots were grown or simply mixed into the soil. Based on the very precise quantities of the roots—0.20, 0.40, 0.60, 0.80, and 1.00 g per layer—we infer that the root matter was “mixed” into the samples rather than being a naturally grown root systems. No mention was made of root orientation within the samples.

Zhang et al. (2010) also performed triaxial (confined) compression tests on soils with three configurations of tree roots and four confining pressures (Figure 11). They found that roots have more impact on soil cohesion than on friction angle and that the presence of roots in soil increased the soil shear strength from 6.9% to 24%. These samples were prepared by placing single roots in specific orientations within the soil, 5.1 mm diameter root segments, 35 mm or 70 mm in length, as shown in the schematic in Figure 12. This leads to the question: If the roots are not grown in the soil, either in the field or in a prepared test specimen, is there an element of root–soil strength that is not captured, such as the slippage strength attributed to fine hair-like roots within the soil matrix?

Kleinfelder et al. (1992) performed unconfined compressive-strength tests on 122 samples taken from stream-bank soils. They found that sample compressive strength emulated an elastic condition in highly rooted samples and developed negligible compressive strength in samples containing very small amounts of roots. Additionally, compressive strength was found to increase nonlinearly with the increase in very fine root-length density according to the equation

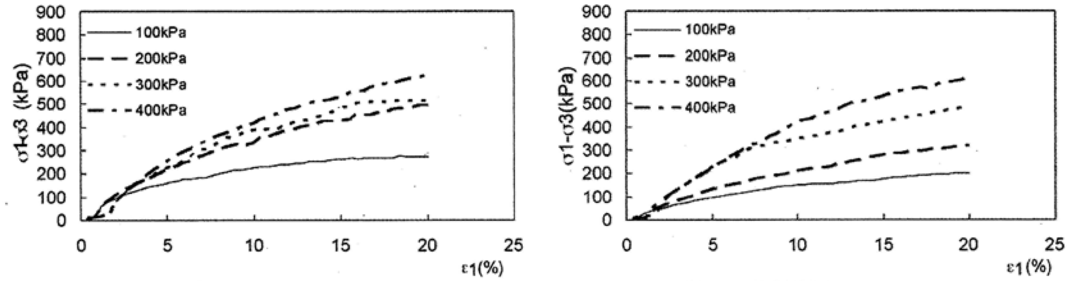
$$Y = 49870(1 - e^{-0.838VFR})^{1.027} \tag{16}$$

where

Y = unconfined compression strength (kPa) and

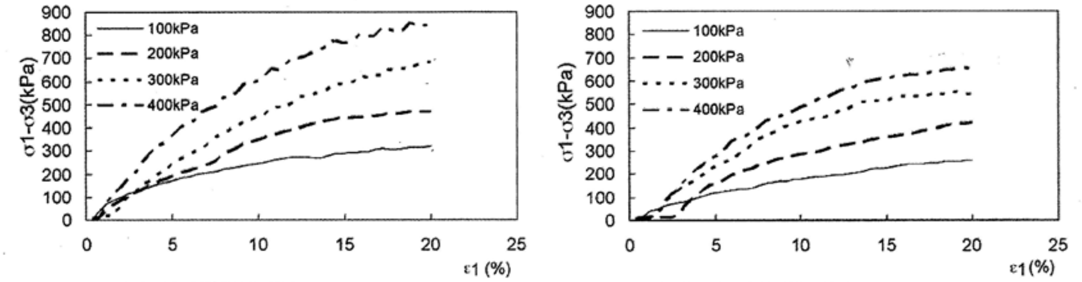
VFR = very fine root-length density (mm/mm^3), defined as the length of very fine roots (<0.5 mm in diameter) as measured within the volume of each sample.

Figure 11. Principal stress difference versus axial strain for *Robinia pseucdoacacia* (Black Locust) roots. (Reprinted by permission from Zhang et al. 2010, Fig. 4.)



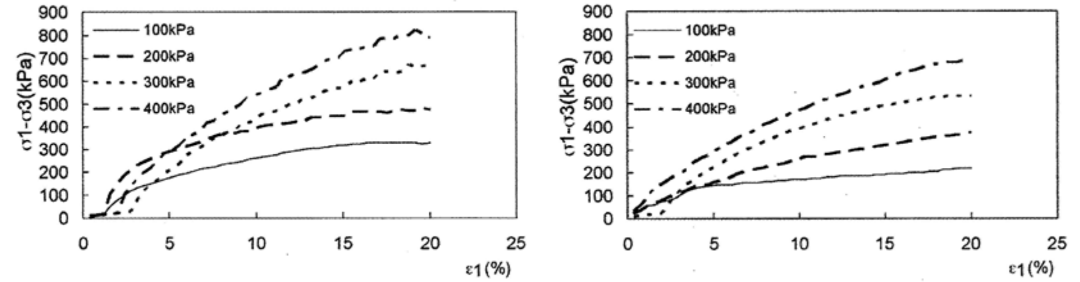
Plain soil, 12.7% SWC

Plain soil, 20.0% SWC



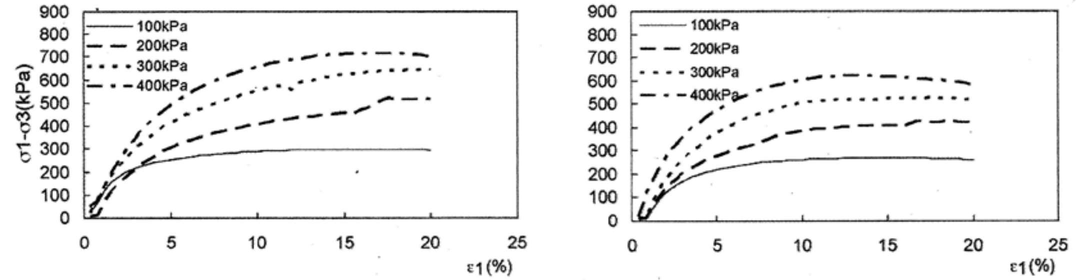
Soil with HR, 12.7% SWC

Soil with HR, 20.0% SWC



Soil with VR, 12.7% SWC

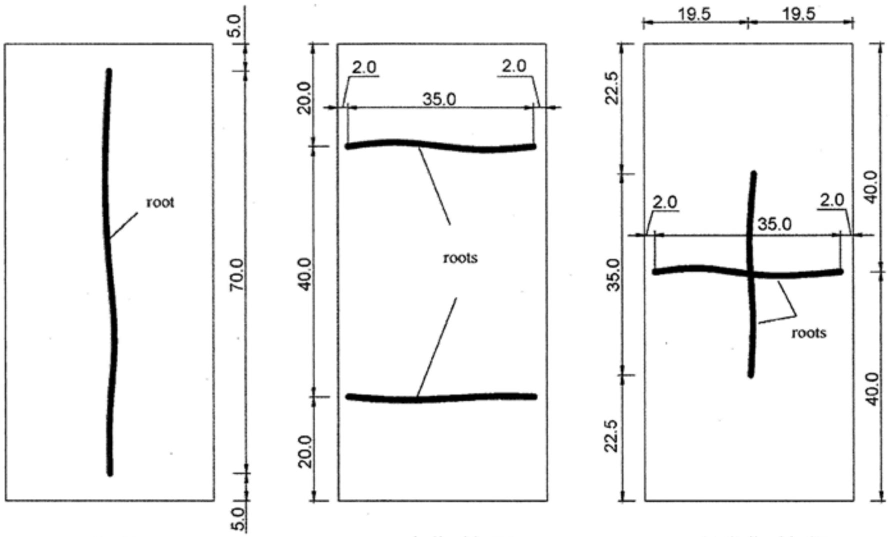
Soil with VR, 20.0% SWC



Soil with CR, 12.7% SWC

Soil with CR, 20.0% SWC

Figure 12. Schematic diagram of three types of root–soil composites tested. (Reprinted by permission from Zhang et al. 2010, Fig. 2.)[1]

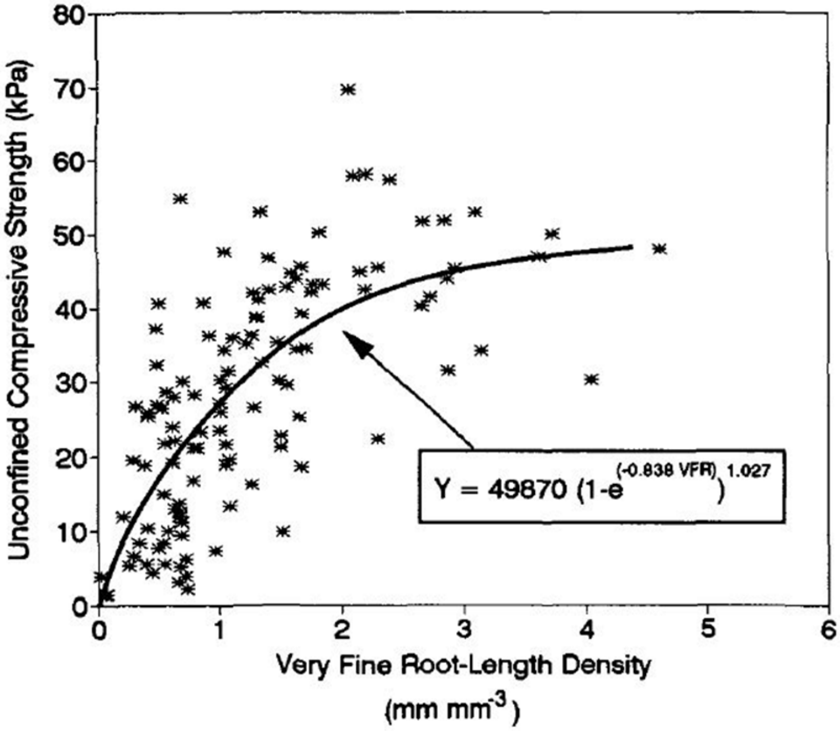


(a) Soil with VR (b) Soil with HR (c) Soil with CR

[1] VR = vertical root; HR = horizontal root; CR = cross root

This relationship is shown graphically in Figure 13. For their samples, they found that Nebraska sedge imparted the most stability and compressive strength to the soil.

Figure 13. Very fine root-length density versus unconfined compressive strength at 40% deformation. (Reprinted by permission from Kleinfelder et al. 1992, Fig. 1.)



5.3 In situ shear

Fan and Su (2008) performed in situ shear box tests for soils planted with Prickly sesban, a small tree, and laboratory tensile-strength tests of the plant's roots. Tests were performed at various soil moisture contents, their premise being that an increase in soil moisture content results in a decrease in soil shear strength. Therefore, the contribution of roots to shear strength in root-reinforced soils becomes increasingly important at high moisture contents. They found that the shear strength of root-reinforced soils may be up to 100% greater than that of root-free soils at shallow depth during or after heavy rainfall events (i.e., at high moisture contents, 80%–85% saturation). In addition, an approximately linear relationship exists between the additional shear strength (ΔS) provided by roots and the average mobilized tensile force in roots per unit area of soil (t_R), expressed as (Fan and Su 2008)

$$t_R = \sum\left(\frac{\boldsymbol{T_i n_i a_i}}{\boldsymbol{A}}\right) \tag{17}$$

where

T_i = ultimate tensile strength of roots in size class i,
n_i = number of roots in size class i,
a_i = mean cross-sectional area of roots in size class i, and
A = area of the shear plane.

Their experiments resulted in ratios of $\Delta S/t_R$ of about 0.39 and 0.42 in terms of the peak and the residual shear strength, respectively. These results are considerably less than the theoretic value (1.2) of models derived by Wu et al. (1979) and discussed previously (see Equations [7] and [7a]). Fan and Su's (2008) experimental data showed that the additional shear strength provided by roots calculated using the tensile properties of roots may be overestimated by Wu's model, as previously discussed in Section 5.1.

Nyambane and Mwea (2011) did similar work to Fan and Su (2011), also using the models from Section 5.1. Using nine different plant species (grouped as grasses, shrubs, and ferns), their work included only laboratory root-tensile-strength testing.

This testing gave Nyambane and Mwea values for the parameters used in Equation (17) and allowed them to calculate t_R. Then, using Equation (4), setting θ equal to 45° and using a value for ϕ of 25° for their test soils, Nyambane and Mwea determined a ratio of $\Delta S/t_R$ of 1.04, again lower than the value of 1.2 suggested by Wu et al. (1979). They were then able to calculate the values of ΔS from the tensile data for each plant species root type. Their calculated values of maximum shear strength that could be imparted by the roots to reinforce the soil were 155 kPa for shrubs, 197 kPa for grasses, and 188 kPa for tree ferns. They propose further work to compare these prediction results with root pullout resistance tests to validate the models.

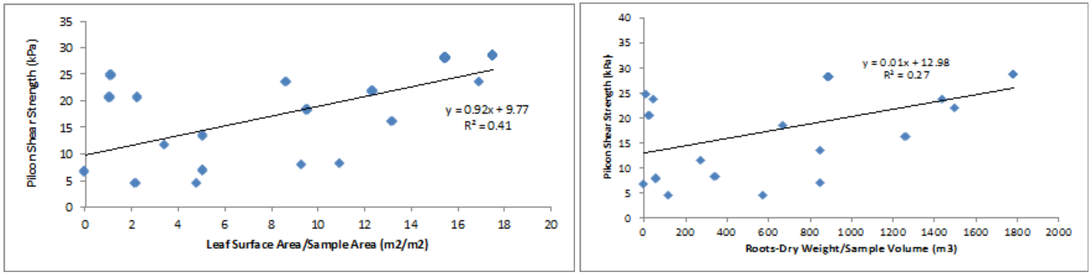
As part of the U.S. Army Optimal Allocation of Land for Training and Non-Training Uses (OPAL) program, Affleck et al. (2011) and Shoop et al. (2013) looked at the effect of ground cover, also referred to as biomass, on soil surface strength and surface shear with the use of the Godwin drop cone (also known as the dynamic drop cone penetrometer), trafficability cone penetrometer, Clegg Impact Hammer (CIH), and Pilcon shear vane. For this effort, six test sections were constructed of three soils—fine sand, clay-loam, or Charlton silt-loam soils—with or without vegetation (seeded or sod grasses) at the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), in Hanover, NH. Using either grid or plug vegetation sampling techniques, this work used several standard measures to quantify the above and belowground biomass and then analyzed the relationships between various biomass quantification parameters and the four strength/shear measures for those specific vegetation conditions.

With regard to surface shear, Shoop et al. (2013) found that the Pilcon shear vane test (Figure 14) was one of the better instruments for measuring the impact of vegetation on terrain strength. It should be noted that in the OPAL study, the vegetation was in the form of continuous turf or sod and not individual plants. The small diameter of the Pilcon shear vane (19 mm) would make readings in areas with discontinuous or random vegetation vary significantly depending on where the test was performed in relation to the vegetation.

Figure 14. Pilcon shear vane used on a vegetation test section (Shoop et al. 2013).

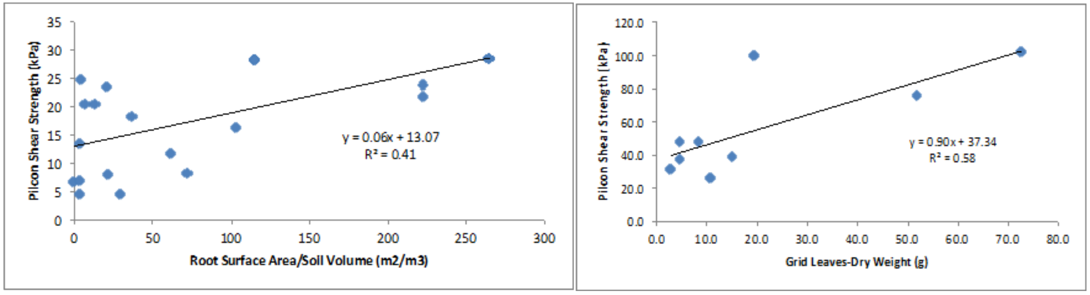
For sand, they found an increase in biomass resulted in increased shear strength as measured by the Pilcon shear vane for nearly all measures of biomass, three of which are illustrated in Figure 15a–c. Conversely, for clay, the shear strength was influenced only by the aboveground biomass with the weight of the leaves showing the strongest trend in Figure 15d. The belowground biomass showed no impact on the shear strength of the clay. They suggest this is likely because this clay is a normally competent soil unless very wet and that roots from the newly established vegetation had little influence.

Figure 15. A sampling of the trends showing how biomass increases soil shear strength as measured using the Pilcon vane shear test (Shoop et al. 2013).



(a) Sand

(b) Sand

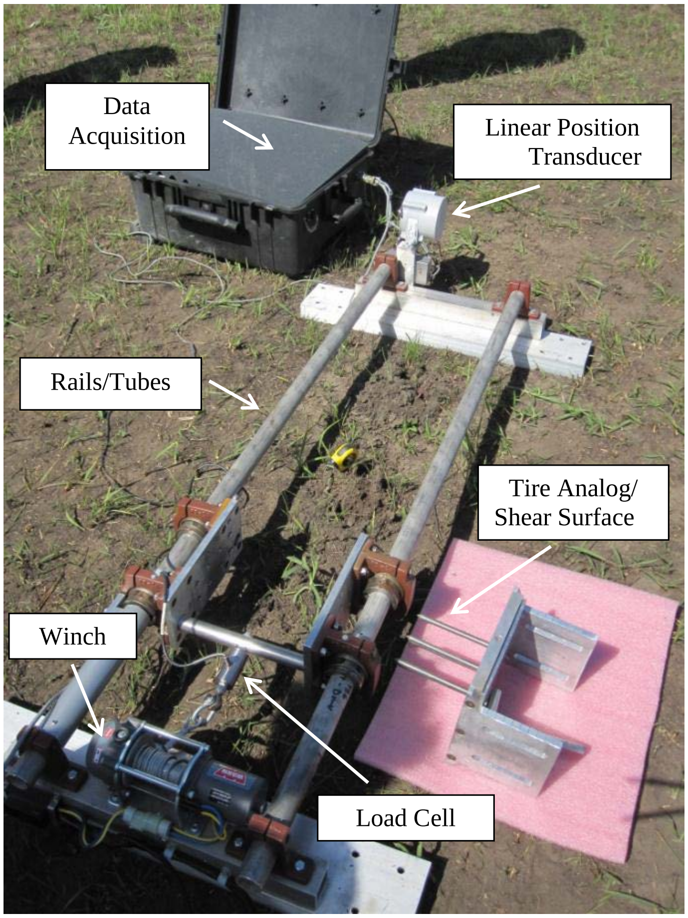


(c) Sand

(d) Clay

Additionally, a new method for measuring and quantifying the vegetated soil shear strength was developed under this part of the OPAL program (MacDonald et al. 2012; MacDonald and Shoop 2013). Figure 16 shows the Vegetation and Soil Shear Tester (VASST) field instrument's basic features. Initial testing with the device observed that the trends present in data collected with the VASST follow those present in data collected with four standard soil-strength instruments (the Godwin drop cone, the trafficability cone penetrometer, the CIH, and the Pilcon shear vane) at the six test sections constructed at ERDC-CRREL. Preliminary assessment showed VASST data bore a strong relationship to the Pilcon shear vane and that generally VASST was more sensitive to vegetation than traditional soil-strength measures (MacDonald and Shoop 2013).

Figure 16. Primary components of the VASST (MacDonald et al. 2012).



5.4 In situ Strength

As mentioned in Section 5.3, Shoop et al. (2013) and Affeck et al. (2011) looked at the effect of ground cover with regard to soil surface strength by using the data from the Godwin drop cone, the trafficability cone penetrometer, and the CIH taken at the six large-scale ERDC-CRREL test sections. Investigating only penetration (Godwin drop cone) and deceleration (CIH) yielded somewhat different trends between the two sets of measurements, with the bare clay surface having the best strength performance overall. However, the clay with sod was the most resistant to penetration (Affleck et al. 2011).

Shoop et al. (2013) looked more closely at the relationships between the amount of biomass and all three strength measurements. They found that the aboveground biomass parameters were generally better indicators of impact on strength. Table 1 provides a summary of their findings of the most useful biomass measures for characterizing vegetated soil strength.

Table 1. Summary of the best biomass indicators of terrain strength. (Adapted from Shoop et al. 2013.)

Sand	Clay	Overall
1. Aboveground Leaf Weight (grid) 2. Aboveground Leaf Weight (plug) 3. Leaf Length/Sample Area 4. Leaf Surface Area	1. Aboveground Leaf Weight (grid) 2. Leaf Length/Sample Area 3. Root Ave Diameter	1. Aboveground Leaf Weight (grid) 2. Aboveground Leaf Weight (plug) 3. Root Length/Soil Volume 4. Root Surface Area

Shoop et al. (2013) suggest that the hardness of the soil surface is most closely related to the reading from the CIH. For the sand, the biomass had essentially no influence on the CIH readings, as shown by Figure 17a, with a slope and correlation coefficient of near zero. The results are similarly inconclusive for the clay soils (Figure 17b). None of the trend lines for sand or clay were of any significance for any of the biomass measures. They suggest the lack of any trends for strength as measured with the CIH could be due to the dynamic nature of the measurement being influenced by the elasticity in the vegetation actually cushioning the impact of the hammer and decreasing the readings.

They found the trafficability cone penetrometer Cone Index (CI) was a good measure of vegetated soil strength (Figure 18a–c) but showed some “confounding effects” for the sands at depths below the biomass layer (Figure 18d). Nearly all of the aboveground biomass parameters showed impacts on CI for sand, with the belowground biomass impacting CI to a lesser extent. The leaf length and the root diameter biomass measures showed strong impacts on CI for clay (Figure 18c).

As measured by the Godwin drop cone, strength increased with increased biomass, with the trends clear for several of the biomass measures although above-surface biomass was more important than belowground biomass for both sand and clay. Figure 19 provides an example of the trends between aboveground biomass and the drop cone penetrometer values for both soils. While trends were present, they were not as strong as with the cone penetrometer measurements. Shoop et al. (2013) hypothesized that this may partly be due to the analysis being primarily linear because a natural log fit to the same data set for the clay yields a much higher correlation coefficient (0.67 for a natural log fit and 0.38 for a linear fit), as seen in Figure 19b.

In another effort under the OPAL program, Koch et al. (2010) looked at the cumulative interactions between soil strength, soil moisture content, and vegetative cover for 15 vegetated plots prepared at the ERDC Construction Engineering Research Laboratory (CERL) in Champaign, IL. Five soil treatments were tested, each with three replicates: bare surface, turfgrass, native grass mixture, native forb mixtures, and a mixture of the previous three. Soil-strength parameters were measured with the dynamic (Godwin) drop cone penetrometer, the trafficability cone penetrometer, and the CIH. Surface and subsurface biomass were collected and weighed monthly. Soil moisture was measured with a time-domain reflectrometry soil-moisture probe and dielectric moisture meters. They found that soil-strength parameters increased as vegetation was established (Figure 20). Lower variability was observed with the CIH than with the drop cone. A high correlation was observed between the CIH and the trafficability cone penetrometer values at 5 cm soil depth. Soil moisture was significant in soil strength, but more data is needed for developing a model.

Figure 17. CIH measurements (Shoop et al. 2013).

(a) Sand. (b) Clay.

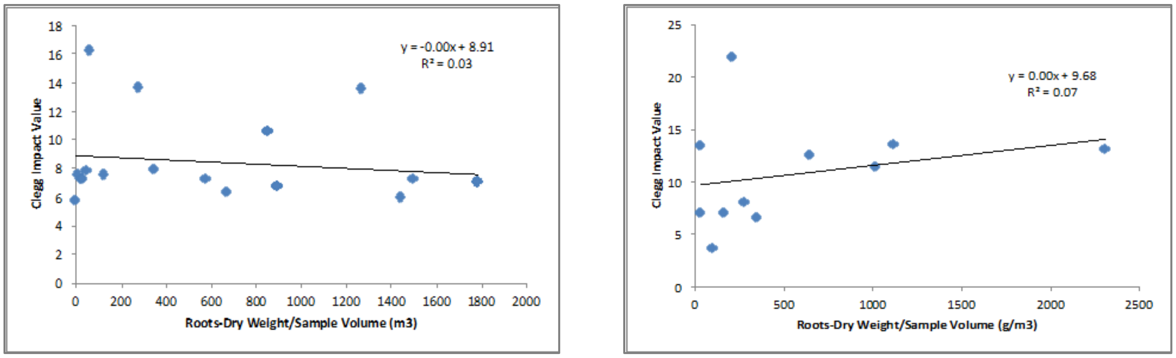
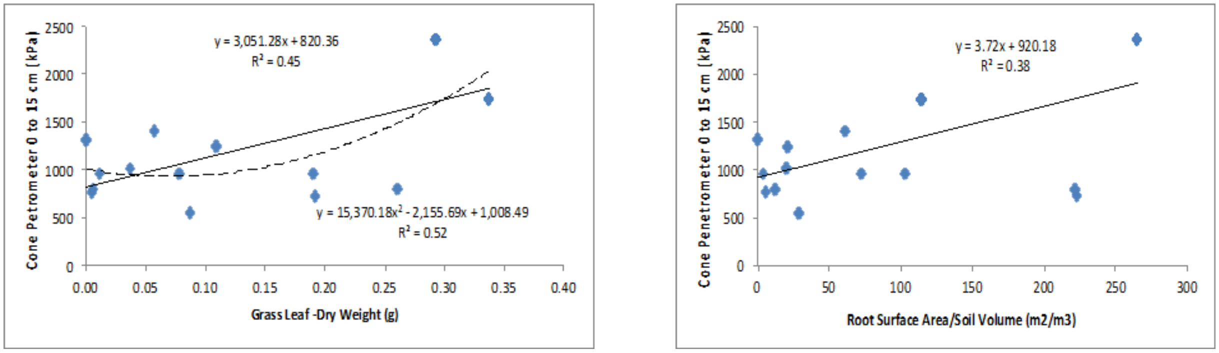


Figure 18. Trafficability cone penetrometer measurements (Shoop et al. 2013).

(*a*) Sand (0 to 15 cm depth CI). (*b*) Sand (0 to 15 cm depth CI).



(c) Clay (0 to 15 cm depth CI). (d) Sand (15 to 30 cm depth CI).

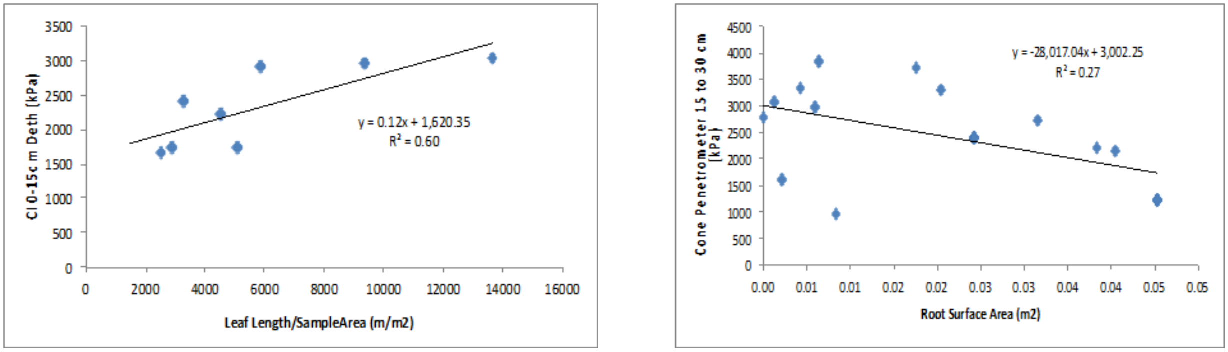


Figure 19. Godwin drop cone penetrometer measurements (Shoop et al. 2013).

(a) Sand. (b) Clay.

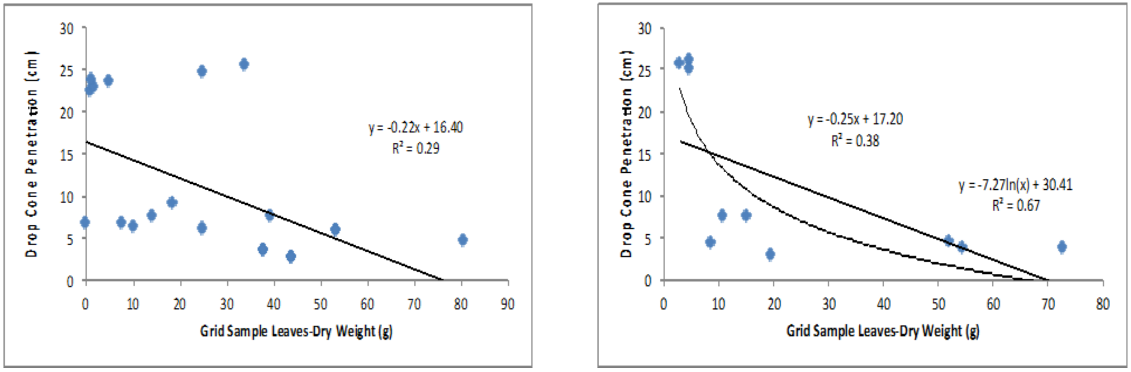
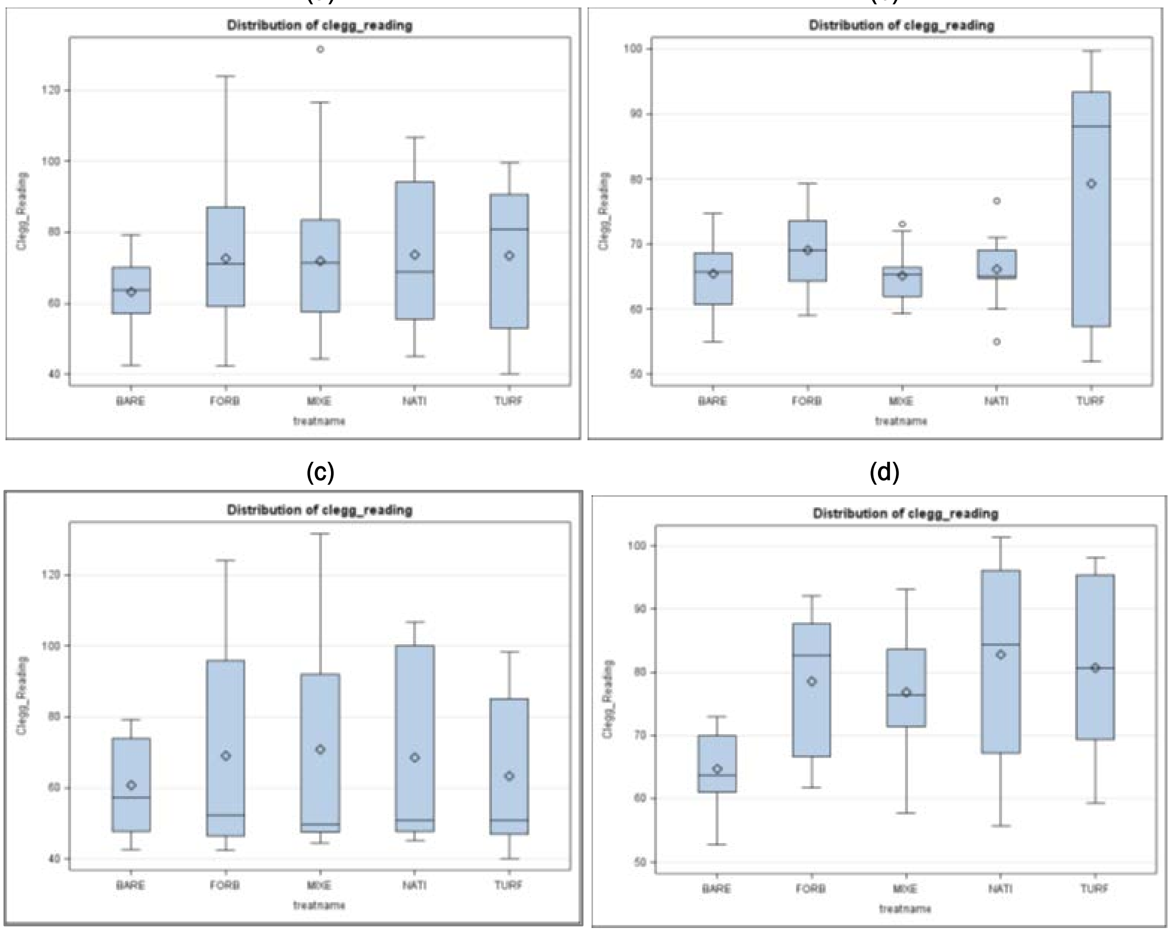


Figure 20. Distribution of CIH readings by treatment for (*a*) the entire year after seeding, (*b*) pre-emergence to seedling, (*c*) seedling to seed formation, and (*d*) seed formation to plant death (Koch et al. 2010).


(a) (b) (c) (d)

5.5 Others

Angers and Caron (1998) took a very inclusive look at plant-induced changes in soil structure. Their study discussed root penetration, modification of the soil-water regime, soil enmeshment, rhizosphere effects, and carbon inputs. They did not discuss whether these factors would affect the strength of the soil at an engineering or mobility level, but the list of means by which vegetation changes soil structure included several parameters not commonly investigated by engineers. Along the same vein, Pierret et al. (2007) examined the origins and variations in soil physical, chemical, and biological properties and the interplay between roots and soils and the activities of earthworms.

6 Impact of Soils on Roots

Conversely, the influence of soil characteristics on root development has also been studied. Grimes et al. (1975) looked at the development of cotton and corn roots in two field soils of different strength characteristics. They found that the field-measured soil strength, measured using a penetrometer, was effective for diagnosing or predicting mechanical root growth restrictions of well-drained soils. Grimes et al. (1975) stated, “Use of the penetrometer to characterize mechanical impedance in the field showed a high degree of utility by permitting direct comparisons of strength between soils that differed widely in textural class.” Additionally, they found that the resistance to either root growth or penetrometer varies inversely with water content. Thompson et al. (1987) included bulk density and penetration resistance and found both to be useful predictors of root-system performance for soy and corn. Higher values of bulk density and penetration resistance resulted in lower root-length density. Unger and Kaspar (1994) and many others also looked at the adverse effect of soil compaction on root growth.

Gerard et al. (1982) looked at the physical soil factors that influence root growth by using laboratory testing and regression analysis to determine the most influential factors. They found that root growth, for both soils tested and at all depths, was significantly influenced by soil strength, volumetric water content, voids, and clay content.

Other investigations, though involving various aspects of vegetation and soil interaction, were more for the purposes of maintaining healthy soils from a crop perspective than for soil strength (Manlay et al. 2002).

Larney and Kladivko (1989) looked at the differences in soil strength under various tilling conditions. This would be analogous to some types of trafficking. Generally, they found that areas under crop rows had higher cone penetration and lower vane shear values, or were less compacted, than other areas where equipment had compacted the soils.

Raper (2005) reviewed the agricultural research related to soil impacts caused by vehicle traffic in agricultural fields. These impacts include soil compaction and rut formation, which negatively affect rainfall infiltration, rooting, and crop production while potentially increasing soil erosion and runoff. He recommended several ways to minimize the effects of vehicle traffic on soils when trafficking is necessary. These included reducing axle loads; allowing soil to dry prior to traffic; using conservation tillage systems, which minimize vehicle traffic; using controlled traffic patterns to eliminate random vehicle traffic across fields; and subsoiling (tilling below depths of 35 cm) to eliminate compacted soil profiles.

Kirby and Bengough (2002) looked at the question of why roots grow thicker in compacted soil even though it requires greater force for a large object to penetrate soil than it does for a small one. They examined the advantage of thickening in terms of the stresses around a root penetrating with constant shape (no root thickening) versus the stresses around an expanding cylinder or sphere (root thickening), as has been studied previously. They combined experiments and finite element simulations of the stresses around pea roots growing in two soils, sandy loam and clay loam, each compacted at four different levels. Measurements included the diameter of pea roots and the critical-state properties of the soils. At a penetration resistance of about 1 MPa, the diameter of the roots in the sandy loam was about 40% greater than that at 0.7 MPa; and at 2 MPa, it was about 60% greater. In the clay loam, there was less thickening—about 10% greater at 1 MPa and about 20% greater at 1.5 MPa.

Using a critical state finite element model, Kirby and Bengough (2002) predicted the maximum axial stresses to be at the very tip of the root cap. When friction was assumed between the root and the soil, shear stresses were predicted with smaller values at the tip than just behind the tip. When the interface between the soil and the root was assumed frictionless, there were by definition no shear stresses. In the frictionless case, the advantage of root thickening on relieving peak stress at the root tip diminished. The axial and shear stresses were predicted to be smaller in the clay loam than in the sandy loam and may explain why the roots did not thicken in this soil although its resistance to penetration was similar. Their results suggest that the local values of axial and shear stresses experienced by the root near its tip may be as important in constraining root growth as the total penetration resistance.

7 Root Strength

Plant root strength has also been thoroughly investigated for many species and may help predict soil-strength impacts of different vegetation. Beck et al. (1988) concluded that for maize, "vertical root pulling resistance was most closely related to mass of the root system and the tensile strength of individual roots." De Baets et al. (2008) also looked at soil-strength models based on the work by Wu et al. (1979) and others. Their results show that while grasses planted in soil increase soil shear to a large extent in the top 0–0.10 m of the soil, several shrubs strongly reinforced the soil to a greater depth (0–0.5 m).

The tensile strength of individual plant roots has received significant attention in the last decade. Bischetti et al. (2005) and Liu et al. (2012) looked at the tensile strength of tree and shrub roots, respectively. They found a power law relationship between decreasing tensile strength with increasing root diameter.

De Baets et al. (2008) looked at root tensile strength and root distribution for Mediterranean grasses, herbs, shrubs, and small trees. Their results also confirmed that root tensile strength (T_r) decreases with increasing root diameter (D), following the power law equation:

$$T_r = aD^{-b} \tag{18}$$

with the coefficients a and b (sometimes referred to as α and β) varying by species. Three of the shrub species they tested did not show this relationship, however. They discuss these results in terms of the higher cellulose content of finer roots and other sources of variability in root strength, including the thickness of root bark.

Xiao (2004), as cited in Hu et al. (2013), stated "that the main factors affecting the tensile and shear strength of single roots include the percentage of phloem fibers and wood fibers and the degree and rate of periderm lignification. The elongation rate of single roots varied directly with the percentage area of secondary phloem, and inversely with the percentage area of xylem. The reinforcement effects of plant roots reflect their tensile, compression and bending resistances, which in turn are determined by their composition of cellulose, semi-cellulose, lignin, protein and pectin."

Hu et al. (2013) themselves, working with five species of shrubs and shallow landslide stabilization, reported that the primary factors that impact single-root tensile and shear forces are xylogen and bast fiber percentages, periderm lignification, and rate of periderm lignification.

Zhang et al. (2014) continued this line of work and confirmed that for Chinese pine, a tree typically used for slope stabilization, the tensile strength decreased with increasing root diameter. Investigating further to examine the relationships between root chemical composition and tensile strength, they found that tensile strength increased with increasing lignin content and decreasing cellulose and alpha-cellulose content. Also, the ratios of lignin to cellulose and lignin to alpha-cellulose decreased with increasing root diameter. They concluded that the relationship between the lignin and cellulose content and root diameter must be considered to determine why roots with different diameters exhibit different tensile strengths.

Looking at turf versus individual root strength, Ross et al. (1991) investigated the turf strength and root characteristics of ten turfgrass cultivars. A cultivar is a variety of plant that has been created and selected intentionally and maintained through cultivation. They applied both a turf, or sod, tearing strength test and a vane shear test performed on the bottom of the sod layer. They found that sod tearing strength was very strongly inversely related to the interior link length and mass of roots. Modulus of work is defined as the energy required per unit area (J/m^2) to break turf samples in the test apparatus used. The interior link length is the interbranch distances between internodes. There was no correlation between the tearing strength and measured vane shear strengths.

8 Vehicle Impacts

A significant body of research has been emerging in the past two decades that focuses on the preservation of the ground surface under the influence of vehicle traffic, both military and civilian (i.e., recreation and other public activities). These research efforts look at the typically negative effects of off-road vehicle traffic on vegetation and soils and do not often include measurements of, or correlations with, ground surface strength.

Some of these studies, however, are worth noting as they provide methods for the measurement and analysis of data defining vegetation response to vehicle traffic. Of particular note are the special issues of the Journal of Terramechanics specifically dedicated to research papers dealing with the impact of vehicle traffic on military lands (Anderson and Shoop 2005).

Hansen and Ostler (2005) developed a technique for assessing vehicle impacts to vegetation in arid environments. They found that reduction in shrub cover due to vehicular traffic is a function of track type (wheeled versus track), the plant cover prior to disturbance, the survivability characteristics of the plant species, and the degree of previous plant damage. Anderson et al. (2007) and Retta et al. (2013, 2014) investigated the relationship between trafficking intensity (i.e., number of passes and straight and turning movements) and reduction in vegetative cover and biomass within the vehicle tracks for both tracked and wheeled military vehicles at military bases in different geographical and climate regions of the United States. Palazzo et al. (2005) looked at native versus non-native grasses and their response to tank tracking. Jorgenson et al. (2010) looked at the specific case of long-term damage from vehicle traffic on Arctic tundras.

Following the need for further work in the vehicle impact area but with the inclusion of soil strength or surface bearing capacity as a parameter, Howard et al. (2011) implemented a four-year field experiment to determine the effects of trafficking, burning, and haying/cutting on vegetated soil strength at Fort Riley, KS. Under the OPAL program, they sampled and quantified biomass in and outside of vehicle tracks, measured soil volumetric water contents, and measured soil strength by using a standard trafficability cone penetrometer and CIH. Vehicle trafficking was provided by an M1 tank. Light trafficking included three passes in the fall; heavy trafficking was three passes each in the spring and fall. Their initial results suggested that biomass is significantly less in the vehicle track than either out of the track or for control vegetation plots. They found no significant difference in soil strength and made the assumption, based on past research, that soil strength does "recover" within a short time after minimal vehicle impacts.

Further work by Kane et al. (2013) at Fort Riley evaluated the multipass terrain impacts of four commonly used tracked and wheeled military vehicles. The four vehicles used were M1A1 Main Battle Tank, M113 Armored Personnel Carrier (M113 APC), M998 High Mobility Multipurpose Wheeled Vehicle (M998 HMMWV), and M985 Heavy Expanded Mobility Tactical Truck (M985 HEMTT) as described in Table 2. Measurements included vehicle impact type, vegetation pile height, disturbed width, percent severity of impact, cone index and soil penetration from the soil drop cone, and soil moisture. GPS (global positioning system) equipment in each vehicle allowed velocity data to be gathered.

Table 2. Study vehicle parameters. (Adapted from Kane et al. 2013.)

Vehicle	Mobility Mechanism	Vehicle Weight (kg)	Track/Tire Width (cm)	Track Length/Wheelbase (cm)
M1A1 Tank	Tracked	57,200	63.0	460
M113 APC	Tracked	11,700	38.0	270
M985 HEMTT	Wheeled	24,900	31.0	530
M998 HMMWV	Wheeled	3,500	29.5	330

The disturbed width (DW) in centimeters and impact severity (IS) on a scale of 0–100 were assessed along 14 spiral paths subjected to a maximum of eight consecutive passes. Measurements were taken at 696 points. Multipass coefficients (MPC) were determined for each vehicle for each turning condition by using Equation (19), the predictive cumulative impact equation:

$$CIW_n = CIW_1 \, x \, n^{1/a} \tag{19}$$

where

CIW = cumulative impact width ($DW \times IS$)
n = the number of passes, and
a = the MPC.

All CIW values across all pass treatments for a specific turning radius were then entered into statistical analysis software; and for each CIW, the software calculated a solution using nonlinear regression for the multipass coefficient, a. Table 3 gives values for a calculated from the testing data. Their results indicated that tracked vehicles have higher values of a than wheeled vehicles do, with coefficients increasing with vehicle weight and the sharpness of turns. The intent is to further use these data to develop impact coefficients for a predictive model of vehicle multipass impacts. Li et al. (2007) previously worked developing models to predict DW and IS with data from tracked military vehicles field tests at Yakima Training Center, WA; Fort Riley, KS; and Camp Atterbury, IN.

Liu et al. (2010a) also examined the Fort Riley spiral data and, using statistical analysis, found that the vehicle parameters (vehicle type, weight, velocity, and turning radius) and soil parameters (soil texture and moisture) are statistically significant for rut formation.

Table 3. Calculated multipass coefficients and error by vehicle and turning radius. (Adapted from Kane et al. 2013.)

Vehicle	Turning Radius	Number of Points	First Pass CIW (cm)	MPC (a)	Average Error	Average Total Error	Average Percent Error (%)
M1A1	Straight (>80 m radius)	20	45.7	1.57	15.83	5.87	16.1
	Intermediate (30 to 80 m radius)	8	100.9	3.1	25.00	3.92	15.96
	Sharp (<30 m radius)	36	169.7	4.44	43.66	6.60	17.44
M113	Straight	12	10.3	1.13	18.11	6.70	39.55
	Intermediate	3	24.6	1.34	37.30	13.50	36.75
	Sharp	27	59.1	2.31	38.20	11.68	30.48
M985 HEMTT	Straight	12	23.7	1.18	31.14	5.85	32.79
	Intermediate	n/a	n/a	n/a	n/a	n/a	n/a
	Sharp	24	86.6	2.13	59.33	26.75	29.55
M998 HMMWV	Straight	12	6.2	1.04	14.12	9.51	39.01
	Intermediate	8	7.1	0.98	24.21	15.53	44.72
	Sharp	28	13.5	1.07	36.26	21.55	45.92

Pirnazarov et al. (2012) and Palaniappan et al. (2013) looked at both tracked and wheeled forestry-vehicle configurations to develop models that could be used for dynamic simulations of forestry machines operating on rough, soft terrain to predict both machine performance and damage to soils. They looked at ground pressure, rut depth, sinkage, soil penetration (using the cone penetrometer), motion resistance, tractive, effort, and drawbar pull. They then compared existing models from the literature with data obtained in field testing with both the wheeled and tracked equipment.

The number of models they reviewed was significant (i.e., rutting, contact pressure, bearing capacity, and tractive effort); but in general, they found the field test data did not match well with existing models that were developed for specific vehicles and soils conditions. However, in many cases, the existing models could be modified to better fit the data. Overall, they found that taking in to account the performance parameters of the vehicles, tracked vehicles are a better option in terms of protecting soft forest soils.

9 Vehicle Terrain Interaction

Another effort that is of great interest and possible utility in incorporating vegetative impacts on vehicle performance and terrain disturbance is the Vehicle Terrain Interaction (VTI) model (Liu et al. 2010b; Bozdech et al. 2012a, 2012b). This physics-based, deformable soil model was developed for use in the U.S. Army's Tank Automotive Research, Development, and Engineering Center's (TARDEC) real-time vehicle motion simulator (Bozdech et al. 2012a). Vehicle turning forces, including turning radius, velocity, and dynamic weight effect, were integrated into the VTI model to allow accurate prediction of rut formation during vehicle turning operations on yielding soils. In the modified model, the resultant force on a single tire is a dynamic variable correlated with the vehicle's turning forces. Liu et al. (2010b) used field tests with an eight-wheeled light armored vehicle to provide data that were analyzed with predictions from the VTI, which showed that the VTI could be used to predict the influence of turning on soil rutting. Rut depths for both tracks were predicted well for turning operations.

Bozdech et al. (2012b) also worked to provide more accurate estimates of soil engineering properties associated with a given soil type based on the Unified Soil Classification System (USCS) soil types for the VTI model. They used statistical analysis of previously gathered soils data to better predict bulk density, angle of internal friction, cohesion, shear deformation modulus, and soil rebound constants based on a given soil's USCS classification. The estimation requires the soil's average clay content and grain size distribution data along with the Rating Cone Index value .

Bozdech et al. (2012a) combined the soil engineering property work with a look at the vertical soil deformation of a single soil element due to the surface loading from the U.S. Army's Stryker vehicle tires, the power dissipated by the vehicle while turning due to lateral bulldozing of the soil, and the power required for a single tire to longitudinally bulldoze the soils. The model provided for reasonable estimates of the soil elements variation in bulk density and the associated power dissipated by the tires to the soil element. The power exerted on the soil element by the tires decreased as the number of tire passes increased, and the incremental increase in bulk density due to the pass of each tire decreased as the number of passes increased. The increase in bulk density increased as the degree of saturation of the soil element increased.

The average lateral displacement of the soil and the power requirement for the Stryker vehicle while turning were also characterized by Bozdech et al. (2012a). The average lateral displacement from all eight of the Stryker vehicle's tires and the associated power requirement tended to increase as the travel speed increased and the vehicle turning radius decreased. The maximum travel speed at the tire sinkage (vertical soil deformation) of 0.05 m increased as the vehicle turning radius increased. The longitudinal bulldozing component of the model indicated that the power required to overcome the longitudinal bulldozing from a single Stryker tire increased as the tire sinkage, vehicle travel speed, and the soil's angle of internal friction increased.

Shoop et al. (2012; 2015), under the OPAL project, also began looking at the impact of vegetation on vehicle traction and motion resistance. Using the CRREL Instrumented Vehicle, they measured the vehicle response to the variety of biomass conditions at the OPAL test sections constructed in Hanover, NH. Results showed that biomass had a positive benefit on sandy soils with an increase in biomass increasing net traction. A linear correlation existed between several biomass parameters and traction, with the leaf weight having the strongest trend in sand (Figure 21) although the leaf surface area and root length also showed promise. Increased biomass also affected the motion resistance for the sandy soils although the relationship was weak.

For clay soil, initial results showed increased biomass had a generally increased net traction and decreased motion resistance, adding strength in a positive way for both vehicle performance measures. However, these results were not substantiated with additional data. The clearest trend showed a decrease in motion resistance with an increase in root diameter (Figure 22).

Figure 21. Example of a biomass parameter impact on traction for sandy soils (Shoop et al. 2015).

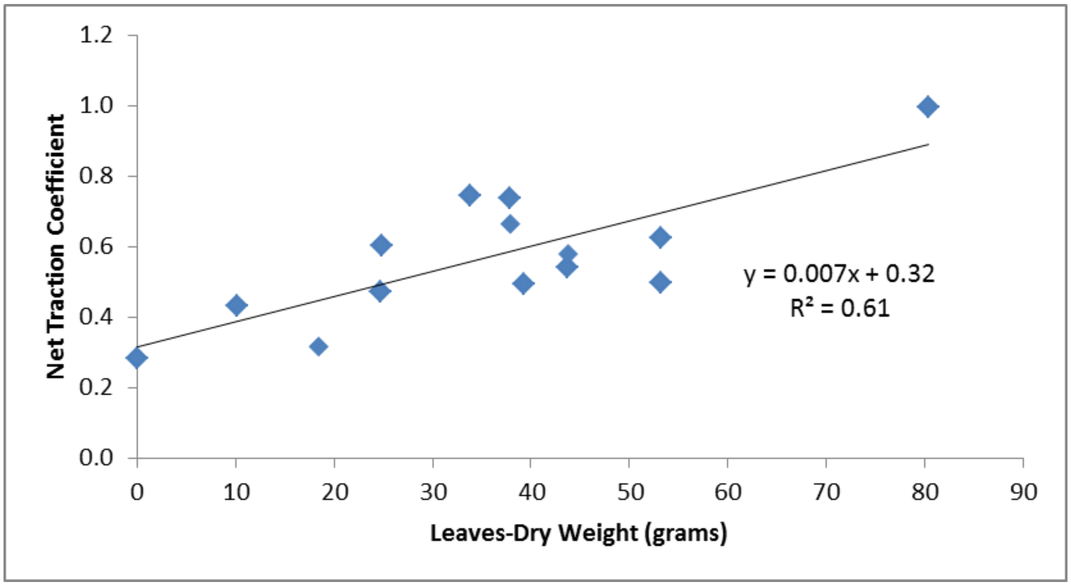
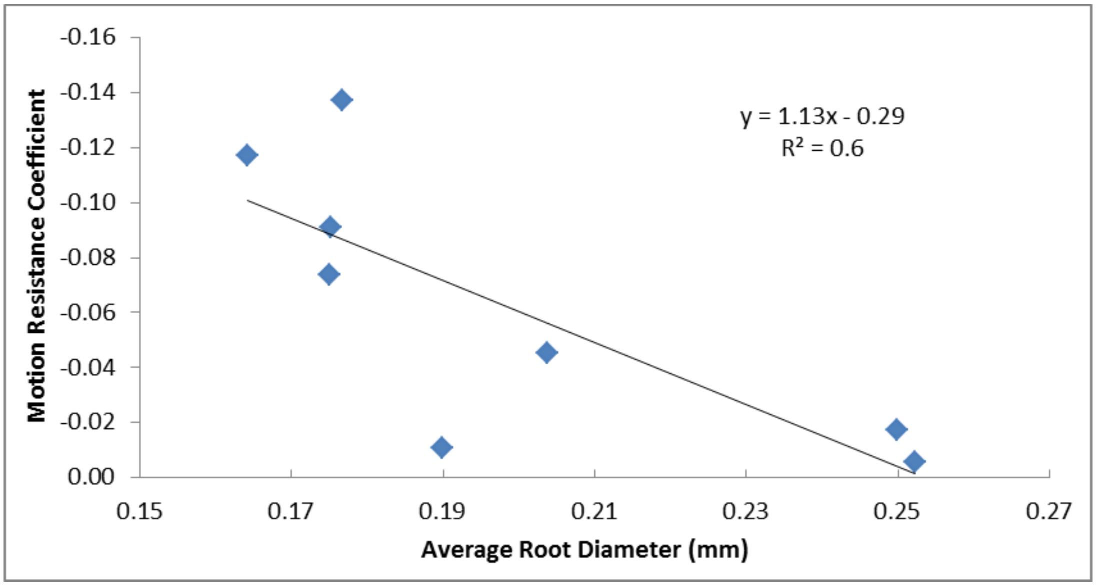


Figure 22. The biomass parameter with the greatest impact on motion resistance for clay soils (Shoop et al. 2015).



10 Conclusions

Significant work has been done on reinforcing soils with various types of vegetation and for a number of applications, primarily slope stabilization and erosion control. Other work has focused on the impact vehicles, both wheeled and tracked, have on soils and vegetation. Both sets of work have included field observations, in situ testing, laboratory testing, and development of various models to predict soil, root, and root–soil-composite behaviors.

To improve off-road vehicle mobility and for land management purposes, the species of interest are mainly grasses and small shrubs; and these have not received as much attention from the standpoint of improving soil strength. The tensile strength of grass roots and the strength parameters of grass-root–soil composites have not been tested as commonly as these parameters for larger plants. More of this type of testing is needed to provide data to define models between diameter, root composition, and root tensile strength for applicable grasses. The VASST (MacDonald et al. 2012; MacDonald and Shoop 2013) and the test device developed by Pirnazarov et al. (2015) may provide the means for obtaining more data on root–soil composites for grasses and small shrubs. Additionally, grasses and small shrubs can vary significantly in plant density over the ground surface. Studies of turf or sodded/seeded grasses may have significantly different results than field sites where the distribution of plant material may be sparse.

Observations and studies of vehicle impact have shown that the vegetation in arid areas, forests, and arctic regions (tundra) have very different responses to vehicle traffic. Current models show promise for adaption, but parameters to define the soils and vegetation need to be quantified to specific site conditions. Vegetation and soils vary greatly by geographic region, and grasses and plants that may thrive at one site may be unsuited for another or inappropriate with regard to introducing non-native species into a regional ecosystem. Operation of the CRREL Instrumented Vehicle to obtain more data on this use of vegetative reinforcement, and specifically vehicle–vegetation interaction, would fill the gap between soil and vegetation conditions and vehicle performance. Analogous work with various military vehicles, both wheeled and tracked, instrumented to measure performance on a variety of ground surface conditions would also provide valuable data.

Defining the vegetative impacts on the parameters used in vehicle mobility is an important step in integrating vegetation impacts into trafficability predictions. Several researchers have looked at models for root strength and vegetation impacts on soil strength and have developed models for the impact of vehicle traffic on vegetation and parameters such as soil rutting. Palaniappan et al. (2013) and Shoop et al. (2015) have looked at impacts of vegetation on vehicle performance, but for different applications (preservation of forest vegetation during logging operations versus basic off-road mobility). However, a model for predicting off-road vehicle performance has not yet been refined, especially one that takes into account variety in both vehicle type and site conditions. Therefore, this review documents the state of the knowledge for vegetative impact on strength and trafficability and serves as the basis for subsequent model development.

References

Abdullah, M. N., N. Osman, and F. H. Ali. 2011. Soil-Root Shear Strength Properties of Some Slope Plants. *Sains Malaysiana* 40 (10): 1065–1073.

Affleck, R., S. Shoop, C. Smith, K. Gagnon, and R. Stone. 2011. Soil Strength as a Function of Soil and Ground Cover Types. Presented at the 17th International Conference of the International Society for Terrain-Vehicle Systems, 18–22 September, Blacksburg, Virginia.

Ali, F. 2010. Use of Vegetation for Slope Protection: Root Mechanical Properties of Some Tropical Plants. *International Journal of Physical Sciences* 5 (5): 496–506.

Ali, F. H., and N. Osman. 2008. Shear Strength of a Soil Containing Vegetation Roots. *Japanese Geotechnical Society, Soils and Foundations* 48 (4): 587–596.

Anderson, A. B., and S. A. Shoop, ed. 2005. Assessing the Impacts of Military Vehicular Traffic on Natural Areas. *Journal of Terramechanics* 42 (3–4): 141–402. http://www.sciencedirect.com/science/journal/00224898/42/3-4.

Anderson, A. B., P. D. Ayers, H. Howard, and K. D. Newlin. 2007. Vehicle Impacts on Vegetation Cover at Camp Atterbury, Indiana: Part 1. Initial Impacts and Vegetation Recovery. *Proceedings of the Indiana Academy of Science* 116 (2): 126–138.

Angers, D. A., and J. Caron. 1998. Plant-Induced Changes in Soil Structure: Processes and Feedbacks. *Biogeochemistry* 42:55–72.

Beck, D. L., L. L. Darrah, and M. S. Zuber. 1988. Relationship of Root Tensile Strength to Vertical Root Pulling Resistance in Maize. *Crop Science* 28:571–573.

Bischetti, G. B., E. A. Chiaradia, T. Simonato, B. Speziali, B. Vitali, P. Vullo, and A. Zocco. 2005. Root Strength and Root Area Ratio of Forest Species in Lombardy (Northern Italy). *Plant and Soil* 278:11–22.

Bozdech, G., P. Ayers, J. Freeman, and A. Reid. 2012a. A Physics-Based, Deformable Soil Model for Estimating a Military Vehicle's Power/Energy Requirements. Unpublished article. Knoxville, TN: University of Tennessee, Department of Biosystems Engineering and Soil Science.

———. 2012b. Estimating The Soil Engineering Properties of the (Unified Soil Classification System) USCS Soil Types. Unpublished article. Knoxville, TN: University of Tennessee, Department of Biosystems Engineering and Soil Science.

Brown, R. N., C Percivalle, S. Narkiewicz, and S. DeCuollo. 2010. Relative Rooting Depths of Native Grasses and Amenity Grasses with Potential for Use on Roadsides in New England. *HortScience* 45 (3): 393–400.

Crook, M. J., and A. R. Ennos. 1993. The Mechanics of Root Lodging in Winter Wheat, *Triticum aestivum* L. *Journal of Experimental Botany* 44 (265):1219–1224.

De Baets, S., J. Poesen, B. Ruebens, K. Wemans, J. De Baerdemaeker, and B. Mays. 2008. Root Tensile Strength and Root Distribution to Typical Mediterranean Plant Species and Their Contribution to Soil Shear Strength. *Plant and Soil* 305:207–226.

Dupuy, L. X., T. Fourcaud, P. Lac, and A. Stokes. 2007. A Generic 3D Finite Element Model of Tree Anchorage Integrating Soil Mechanics and Real Root System Architecture. *American Journal of Botany* 94 (9): 1506–1514.

Ennos, A. R. 1990. The Anchorage of Leek Seedlings: The Effect of Root Length and Soil Strength. *Annals of Botany* 65:409–416.

Fan, C.-C., and C.-F. Su. 2008. Role of Roots in the Shear Strength of Root-Reinforced Soils. *Ecological Engineering* 33:157–166.

Fourcaud, T., J. Ji, Z. Zhang, and A. Stokes. 2008. Understanding the Impact of Root Morphology on Overturning Mechanisms: A Modeling Approach. *Annals of Botany* 101:1267–1280.

Gerard, C. J., and H. C. Mehta. 1971a. Influence of a Root Crop on Physical Properties of a Medium-Textured Soil. *Agronomy Journal* 63 (6): 889–892.

———. 1971b. Influence of a Root Crop on Physical Properties of a Clay Soil. *Agronomy Journal* 63 (6): 893–895.

Gerard, C. J., P. Sexton, and G. Shaw. 1982. Physical Factors Influencing Soil Strength and Root Growth. *Agronomy Journal* 74 (5): 85–879.

Goldsmith, W. 2006. Soil Strength Reinforcement by Plants. In *International Erosion Control Association, Proceedings of Conference 37*, 20–24 February 2006, Long Beach California, 3–18.

Gray, D. H., and D. Barker. 2004. Root-Soil Mechanics and Interactions. In *Riparian Vegetation and Fluvial Geomorphology*, ed. S. J. Bennett and A. Simon. Washington, DC: American Geophysical Union.

Gray, D. H., and H. Ohashi. 1983. Mechanics of Fiber Reinforcement in Sands. *Journal of Geotechnical Engineering* 109:335–353.

Grimes, D. W., R. J. Miller, and P. L. Wiley. 1975. Cotton and Corn Root Development in Two Field Soils of Different Strength Characteristics. *Agronomy Journal* 67 (4): 519–523.

Gyssels, G., J. Poesen, E. Bochet, and Y. Li. 2005. Impact of Plant Roots on the Resistance of Soils to Erosion by Water: A Review. *Progress in Physical Geography* 29 (2): 189–217.

Hansen, D. J., and W. K. Ostler. 2005. Assessment Technique for Evaluating Military Vehicular Impacts to Vegetation in the Mojave Desert. *Journal of Terramechanics* 42 (3): 193–205. http://dx.doi.org/10.1016/j.jterra.2004.12.001.

Howard, H. R., N. G. Svendsen, T. J. Cary, D. J. Koch, G. X. Gertner, S. A. Shoop, P. B. Woodford, R. M. Lacey, A. B. Anderson, and A. Fulton. 2011. The Role of Biomass in Erosional and Soil Strength Influences Under Military Land Management. In *Proceedings of the International Symposium on Erosion and Landscape Evolution*, ed. D. C. Flanagan, J. C. Ascough II, and J. Nieber. Anchorage, AK, 18–21 September, Paper number 11055. St. Joesph, MI: American Society of Agricultural and Biological Engineers.

Hu, X., G. Brierley, H. Zhu, G. Li, J. Fu, X. Mao, Q. Yu, and N. Qiao. 2013. An Exploratory Analysis of Vegetation Strategies to Reduce Shallow Landslide Activity on Loess Hillslopes, Northeast Qinghai-Tibet Plateau, China. *Journal of Mountain Science* 10 (4): 668–686.

Huang, Y., K. Lu, Y. Zhu, X. Xie, and X. Yang. 2011. Numerical Simulation on Laboratory Triaxial Test of Composite Soil with Roots. *Advanced Materials Research* 287–290: 777–780.

Jorgenson, J. C., J. M. Ver Hoef, and M. T. Jorgenson. 2010. Long-Term Recovery Patterns of Arctic Tundra after Winter Seismic Exploration. *Ecological Applications* 20 (1): 205–221. http://dx.doi.org/10.1890/08-1856.1.

Kane, J. R., P. Ayers, H. Howard, A. Anderson, and D. Koch. 2013. Multipass Coefficients for Terrain Impacts Based on Military Vehicle Type, Size and Dynamic Operating Properties. *Journal of Terramechanics* 50 (3): 175–183.

Kirby, J. M., and A. G. Bengough. 2002. Influence of Soil Strength on Root Growth: Experiments and Analysis Using a Critical-State Model. *European Journal of Soil Science* 53:119–128.

Kleinfelder, D., S. Swanson, G. Norris, and W. Clary. 1992. Unconfined Compressive Strength of Some Stream Bank Soils with Herbaceous Roots. *Soil Science Society of America Journal* 56:1920–1925.

Koch, D. J., G. G. Gertner, N. G. Svendsen, H. R. Howard, D. A. Horner, and P. M. Sullivan. 2010. Cumulative Interactions for Military Vehicle Impact Assessment. Presentation paper number 1008489. American Society of Agricultural and Biological Engineers, Pittsburgh, PA, 20–23 June. Doi:10.13031/2013.35790.

Larney, F. J., and E. J. Kladivko. 1989. Soil Strength Properties Under Four Tillage Systems at Three Long-Term Study Sites in Indiana. *Soil Science Society of America Journal* 53:1539–1545.

Li, Q., P. D. Ayers, and A. B. Anderson. 2007. Modeling of Terrain Impact Caused by Tracked Vehicles. *Journal of Terramechanics* 44 (6): 395–410.

Liu, K., P. Ayers, H. Howard, and A. Anderson. 2010a. Influence of Soil and Vehicle Parameters on Soil Rut Formation. *Journal of Terramechanics* 47:143–150.

———. 2010b. Prediction of Rut Depth During Military Vehicle Turning Maneuvers Using a Modified Sinkage Numeric. *American Society of Agricultural and Biological Engineers* 53 (4): 1019–1024.

Liu, K., X. Yang, X. Xie, C. Wu, and Y. Liu. 2011. Laboratory Triaxial Test Study on Soil Reinforce with Roots of Manilagrass. *Advanced Materials Research* 250–253:1366–1370.

Liu, X.-M., J. Liu, X. Sun, X.-J. Yao, and Y.-L. Zhang. 2012. Study on the Lateral Root Branch Tensile Mechanical Characteristics of Three Kinds of Plants at Exuberant Growth Period. 4th International Conference of Agriculture and Animal Science. *International Proceedings of Chemical, Biological and Environmental Engineering (IPCBEE)* 47:47–51.

MacDonald, K. A., and S. A. Shoop. 2013. Validation of the Vegetation and Soil Shear Tester (VASST) with Existing Soil Strength Instruments. In *Proceedings of the 7th Americas Regional Conference of the International Society for Terrain-Vehicle Systems (ISTVS)*, 4–7 November, Tampa, FL.

MacDonald, K. A., B. A. Coutermarsh, S. A. Shoop, and W. T. Burch, 2012. A New Method to Measure Vegetated Soil Shear Strength Using the Vegetation and Soil Shear Tester (VASST). In *Proceedings of the 12th European Conference of the International Society for Terrain-Vehicle Systems (ISTVS), 24–27* September, Pretoria, South Africa.

Manlay, R. J., M. Kaire, D. Masse, J. L. Chotte, G. Ciornei and C. Floret. 2002. Carbon, Nitrogen and Phosphorus Allocation in Agro-Ecosystems of the West African Savanna: I. The Plant Component Under Semi-Permanent Cultivation. *Agriculture, Ecosystems and Environment* 8:215–232.

Mickovski, S. B., P. D. Hallett, M. F. Bransby, R. Sonnenberg, and A. G. Bengough. 2009. Mechanical Reinforcement of Soil by Willow Roots: Impacts of Root Properties and Root Failure Mechanism. *Soil Science Society of America Journal* 73 (4): 1276–1285.

Nyambane, O. S., and S. K. Mwea. 2011. Root Tensile Strength of 3 Typical Plant Species and Their Contribution to Soil Shear Strength; A Case Study: Sasuma Backslope, Nyandarua District, Kenya. *Journal of Civil Engineering Research and Practice* 8 (1): 57–73.

Palaniappan, N. R., A. Pirnazarov, U. Sellgren, and B. Lofgren. 2013. Predicting the Mobility of Tracked Forest Machines Operating on Nordic Forest Soil. In *Proceedings of the 7th Americas Regional Conference of the International Society for Terrain-Vehicle Systems (ISTVS)*, 4–7 November, Tampa, FL.

Palazzo, A. J., K. B. Jensen, B. L. Waldron, and T. J. Cary. 2005. Effects of Tank Tracking on Range Grasses. *Journal of Terramechnics* 42 (3–4): 177–191.

Pierret, A., C. Doussan, Y. Capowiez, F. Bastardie, and L. Pages. 2007. Root Functional Architecture: A Framework for Modeling the Interplay Between Roots and Soil. *Vadose Zone Journal* 6:269–281.

Pirnazarov, A., and U. Sellgren. 2015. Reduced Testing and Modelling of the Bearing Capacity of Rooted Soil for Wheeled Forestry Machines. *Journal of Terramechnics* 60:23–31.

Pirnazarov, A., M. Wijekoon, U. Sellgren, B. Lofgren, and K. Andersson. 2012. Modeling of the Bearing Capacity of Nordic Forest Soil. In *Proceedings of the 12th European Regional Conference of the International Society for Terrain-Vehicle Systems (ISTVS)*, 24–27 September, Pretoria, South Africa.

Pirnazarov, A., U. Sellgren, and B. Lofgren. 2013. Development of a Methodology for Predicting the Bearing Capacity of Rooted Soft Soil. In *Proceedings of the 7th American Regional Conference of the International Society for Terrain-Vehicle Systems (ISTVS)*, 4–7 November, Tampa, FL.

Preti, F., and F. Giadrossich. 2009. Root Reinforcement and Slope Bioengineering Stabilization by Spanish Broom (*Spartium junceum* L.). *Hydrology and Earth System Science* 13:1713–1726.

Raper, R. L. 2005. Agricultural Traffic Impacts on Soil. *Journal of Terramechanics* 42:259–280.

Retta, A., L. E. Wagner, J. Tatarko, and T. C. Todd. 2013. Evaluation of Bulk Density and Vegetation as Affected by Military Vehicle Traffic at Fort Riley, Kansas. *Transactions of the American Society of Agricultural and Biological Engineers* 56 (2): 653–665. http://dx.doi.org/10.13031/2013.42687.

Retta, A., L. E. Wagner, and J. Tatarko. 2014. Military Vehicle Trafficking Impacts on Vegetation and Soil Bulk Density at Fort Benning, Georgia. *Transactions of the American Society of Agricultural and Biological Engineers* 57 (4): 1043–1055. http://dx.doi.org/10.13031/trans.57.10327.

Ross, S. J., A. R. Ennos, and A. H. Fitter. 1991. Turf Strength and Root Characteristics of Ten Turfgrass Cultivars. *Annals of Applied Biology* 188:433–443.

Schmidt, K. M., J. J. Roering, J. D. Stock, W. E. Dietrich, D. R. Montgomery, and T. Schaub. 2001. The Variability of Root Cohesion as an Influence on Shallow Landslide Susceptibility in the Oregon Coast Range. *Canadian Geotechnical Journal* 38:995–1024.

Shoop, S, T. Cary, B. Coutermarsh, and J. Stanley. 2012. Effect of Vegetation Biomass on Vehicle Traction and Motion Resistance. In *Proceedings of the 12th European Regional Conference International Society for Terrain-Vehicle Systems (ISTVS), 24–27* September, Pretoria, South Africa. http://istvs.org/publications.

Shoop, S., W. Wieder, K. MacDonald, T. Carey, and H. Howard. 2013. Experimental Measurement of Biomass Impact on Soil Strength. In *Proceedings of the 7th Americas Conference of the International Society for Terrain-Vehicle Systems (ISTVS)*, 4–7 November, Tampa, FL.

Shoop, S. A., B. Coutermarsh, T. Cary, and H. Howard. 2015. Quantifying Vegetation Biomass Impacts on Vehicle Mobility. *Journal of Terramechanics* 61:63–76.

Stokes, A., J. Ball, A. H. Fitter, P. Brain, and M. P. Coutts. 1996. An Experimental Investigation of the Resistance of Model Root Systems to Uprooting. *Annals of Botany* 78:415–421.

Terwilliger, V. J., and L. J. Waldron. 1991. Effects of Root Reinforcement on Soil-Slip Patterns in the Transverse Ranges of Southern California. *Geological Society of America Bulletin* 103:775–785.

Thompson, P. J., I. J. Jansen, and C. L. Hooks. 1987. Penetrometer Resistance and Bulk Density as Parameters for Predicting Root System Performance in Mine Soils. *Soil Science Society of America* 51:1288–1293.

Unger, P. W., and T. C. Kasper. 1994. Soil Compaction and Root Growth: A Review. *Agronomy Journal* 86:759–766.

Waldron, L. J. 1977. The Shear Resistance of Root-Permeated Homogeneous and Stratified Soil. *Soil Science Society of America Journal* 41 (5):843–849.

Waldron, L. J., and S. Dakessian. 1981. Soil Reinforcement by Roots: Calculation of Increased Soil Shear Resistance from Root Properties. *Soil Science* 132 (6): 427–435.

———. 1982. Effect of Grass, Legume, and Tree Roots on Soil Shear Resistance. *Soil Science Society of America Journal* 46 (5):894–899.

Waldron, L. J., S. Dakessian, and J. A. Nemson. 1983. Shear Resistance Enhancement of 1.22-Meter Diameter Soil Cross Sections by Pine and Alfalfa Roots. *Soil Science Society of America Journal* 47:9–14.

Wu, T. H. 1976. *Investigation of Landslides on Prince of Wales Island, Alaska*. Geotechnical Report No. 5. Columbus, OH: Ohio State University, Department of Civil Engineering.

Wu, T. H., W. P. McKinell, and D. N. Swanson. 1979. Strength of Tree Roots and Landslides on Prince Wales Island, Alaska. *Canadian Geotechnical Journal* 16 (1): 19–33.

Xiao, D. S. 2004. Theory of Improving Slope Shear Strength by Vegetation. [In Chinese.] *Basis of Foundation* 1 (2):63–65.

Zhang, C.-B., L.-H. Chen, Y.-P. Li, X.-D. Ji, and X.-P. Liu. 2010. Triaxial Compression Test of Soil-Root Composites to Evaluate Influence of Roots on Soil Shear Strength. *Ecological Engineering* 36:19–26.

Zhang, C.-B., L.-H. Chen, and J. Jiang. 2014. Why Fine Tree Roots Are Stronger Than Thicker Roots: The Role of Cellulose and Lignin in Relation to Slope Stability. *Geomorphology* 206:196–202.

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14. ABSTRACT

Researchers in a variety of fields have studied using vegetation to alter or reinforce soils. However, investigating the use of vegetation with regard to impacting soil strength and therefore improving vehicle trafficability and mobility, for both military operations and training purposes, is more limited. Much of the soil-reinforcement work reported in the literature deals with trees and larger shrubs appropriate for slope and bank stabilization. Other research efforts are for agricultural or forestry applications and involve crops and, again, large trees. While larger plant species would prohibit vehicle traffic and thus be inappropriate from the standpoint of vehicle mobility, the general observations and the different types of laboratory and field tests performed in these studies still provide valuable insight. This review discusses the issue of vegetation and its effect on a variety of soil-strength parameters. It also reviews work regarding the effect of vehicle operations on vegetation and conversely the effect of vegetation on vehicle performance, or trafficability. The intent is to provide a broad knowledge base of the variety of work done with vegetation and soils with particular attention to the applicability for vehicle mobility and land management goals.

15. SUBJECT TERMS

Biomass, Plants, Shear strength of soils, Soil, Soil mechanics, Stabilization, Terrain, Trafficability, Vehicle mobility

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