A PULL OUT TEST OF PHYLLANTHUS SELLOWIANUS AND SEBASTIANIA SCHOTTIANA AND DEVELOPMENT OF SOIL BIOENGINEERING CONSTRUCTIONS IN SOUTHERN BRAZIL

Master thesis by

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EIN AUSZIEHVERSUCH VON PHYLLANTHUS SELLOWIANUS UND SEBASTIANIA SCHOTTIANA UND DIE ENTWICKLUNG VON INGENIEURBIOLOGISCHEN BAUWEISEN IN SÜDBRASILIEN

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A. Preface and Acknowledgement

The work in hand presents two research themes, executed in course of a stay abroad at the Federal University of Santa Maria, Rio Grande do Sul, Brazil. Both presented studies are part of a knowledge process of soil bioengineering and research activities, facilitating its further extension of application in Brazil.

Why I compiled my Master thesis in Southern Brazil is a result on one hand of my personal course of life, on the other hand of a long term relationship between my home university, the University of Natural Resources and Life Sciences, Vienna (BOKU) and the host university, the Universidade Federal de Santa Maria (UFSM). At first, I want to explain shortly how it came to me, doing my master thesis in Brazil.

In the year 2011, I did an internship at the Universidade Federal Paulista (UNESP), organized by the students exchange program IAESTE. Besides contributing to an exciting project, researching different composting methods, I got the opportunity to learn the local language and the highly fascinating culture of Brazil. At this point I want to thank all the friends I made in the “cidade maravilhosa – Presidente Prudente” and who supported me during this time. Through this defining experience I decided to improve my Portuguese language skills and to strive further the participation in the intercultural exchange. During my master studies one of my emphases was on soil bioengineering, which brings us to the second point for my intention doing this thesis.

An already long existing cooperation between the above mentioned universities was deepened through an initial exchange of knowledge between the “Institute of Soil Bioengineering and Landscape Construction” (BOKU) and the “Departamento de Ciências Florestais” (UFSM) concerning soil bioengineering and a following common project, starting in the year 2003. The objective of this project was to investigate biological and mechanical properties of the local vegetation and implement a selection of riverbank restoration structures. This collaboration is still going on and the present master thesis is part of it. The *status quo* shows very well how soil bioengineering has already established and will be further developed in Brazil. In the very near future the first students will graduate in the recently installed master training course at the “Departamento de Ciências Florestais”. Plans for a new laboratory plus experimental garden on the campus of the UFSM are in an advanced stage and soil bioengineering projects are carried out in many parts of Brazil. All of this signals that soil bioengineering is gaining importance and highlights the relevance of research works in the field of soil bioengineering.

At this stage, I want to express my appreciation to the local people in Rio Grande do Sul for their major support in the course of the present research works and their friendship. Namely, I want to thank; Charles Mafra, Suelen Camarago, Junior Dewes, Robson Bach, “república da gurizada” as well as Prof. Dr. Miguel Durlo for his great hospitality. Special thanks go to Dr. Eng. Fabrício J. Sutili for his great advising work!

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At my home University I want to thank Prof. Dr. Florin Florineth and Ass. Dr. DI Hans Peter Rauch for advising me in such a great way. At this point, I want to express my gratitude to the “Center of International Relations - BOKU” for the “KUWI” scholarship and the “Julius Raab Stiftung” for its financial support.

In Vienna, special thanks go to my shared apartment (Familie Krebs – Daniel Maurer and Maximilian Jesch), who received me each time after being abroad and with whom I passed some gorgeous years. Two colleagues of my studies I want to mention here as well for their company during the studies - Andreas Loach and Sebastian Pawlowski. I also want to thank a recently won friend, Johanna Leary, who contributed to this work by correcting my English, very much.

I can only say that without my family all this would not have been possible and want to thank especially my brothers Christian, Felix and my sister Karoline. For always trusting in me and supporting me anytime I want to express my thanks to my parents Pauline and Josef!

B. Abstract

Soil bioengineering has become ever more applied in large parts of Brazil in recent years. The study in hand presents two research works carried out in the Federal State of Rio Grande do Sul. As a result of previous research work the two riparian species, *Sebastiania schottiana* and *Phyllanthus sellowianus* have shown very adequate morpho-physiological properties and appear to be appropriate for their application in riverbank restoration works. The aim of this study was to examine a still unknown, but crucial factor; their resistance against being pulled out. In the carried out tests, *Phyllanthus sellowianus* performed a significantly higher resistance against uprooting than *Sebastiania schottiana*. The analyses of root and shoot properties showed that *Phyllanthus sellowianus* has more favorable morpho-physiological properties regarding pull out strength, a larger amount of biomass above as well as below ground and higher anchorage abilities. The cross-sectional-area of the shoots at base, of all investigated shoot and root properties, indicated the strongest correlation of with the maximum resistance against being pulled out. The experiment showed that some root and shoot properties do have a great impact on the pullout strength and that *Phyllanthus sellowianus* can be used for slope stabilization works, since it exhibits outstanding resistance against uprooting. However, further tests on *Sebastiania schottiana* are suggested to evaluate more of its potential. The second study presents a riverbank restoration work implemented in the year 2010 and an onsite vegetation survey, performed in course of this study. Besides that, a species composition investigation in the actual plant stand, the structures of the reinforcement work, and its effectiveness were evaluated. By means of the vegetation survey it could be examined which of the applied species could establish in the long term. Most notably the species *Calliandra brevipes*, *Phyllanthus sellowianus*, *Salix humboldtiana* and *Ateleia glazioveana* showed a good development. The proportion of spontaneous vegetation increased significantly, with *Penisetum purpureum* as the most dominating species. As a whole the intervention can be assessed as functional and safe, but further plant surveys are recommended in order to observe the ongoing development of species as well as the influence of spontaneous vegetation on the stabilization effect.

C. Resumo

Bioengenharia de solos tornou-se amplamente aplicada em grande parte do Brasil nos últimos anos. Esta tese de mestrado em mãos apresenta dois trabalhos de pesquisa acadêmica realizados no estado do Rio Grande do Sul localizado no Brasil. Como resultado de trabalho de pesquisa anterior, duas espécies de plantas ribeirinhas, *Sebastiania schottiana* e *Phyllanthus sellowianus*, mostraram propriedades morfo-fisiológicas muito adequadas para aplicação em obras de restauração ribeirinha. O objetivo deste estudo foi examinar um fator das espécies ainda desconhecido, mas fundamental, sua resistência ao arranquio. Nos testes, e espécie *Phyllanthus sellowianus* mostrou maior resistência contra o desenraizamento do que a espécie *Sebastiania schottiana*. As análises das raízes e do arranquio mostraram que a espécie *Phyllanthus sellowianus* possui propriedades morfo-fisiológicas melhores em termos de resistência à retirada, maior quantidade de biomassa tanto acima como abaixo do solo e também uma maior ancoragem. A área da seção transversal na base dos brotos indicada, em ambas às espécies, uma forte correlação com a máxima resistência contra o arranquio. O experimento mostrou que algumas propriedades da raiz, tem um grande impacto sobre a força que a espécie *Phyllanthus sellowianus* possui. A espécie pode ser usada para estabilização de taludes e apresenta excelente resistência ao desenraizamento. No entanto, mais testes com a espécie *Sebastiania schottiana* são sugeridos para avaliar melhor suas potencialidades. O segundo estudo apresenta um trabalho de restauração da encosta do Rio Pardinho implementado no ano de 2010 e um levantamento da vegetação local, realizada no ano de 2013. Além de uma investigação da composição das espécies na planta foi estudado a resistência da suportar as estruturas do trabalho de reforço e a sua eficácia foi avaliada. Com a ajuda do levantamento da vegetação foi examinado quais espécies aplicadas poderiam se estabelecer a longo prazo. As espécies mais notáveis *Calliandra brevipes*, *Phyllanthus sellowianus*, *Salix humboldtiana* e *Ateleia glazioveana* podem se desenvolver ou ainda se tornar dominantes. A proporção de vegetação espontânea aumentou significativamente, onde a espécie *Penisetum purpureum* foi a espécie dominante. De um modo geral, a intervenção pode ser usada como pesquisa de plantas funcionais e seguras mas, ainda são recomendados estudos a fim de observar o desenvolvimento das espécies e a influência da vegetação espontânea sobre o efeito de estabilização.

D. Zusammenfassung

Ingenieurbiologische Maßnahmen finden immer häufiger Anwendung in Brasilien. Die vorliegende Arbeit präsentiert zwei Studien, durchgeführt im Bundesstaat Rio Grande do Sul. Vorhergehende Untersuchungen zeigten, dass die Arten *Sebastiania schottiana* und *Phyllanthus sellowianus* sehr vorteilhafte morpho-physiologische Eigenschaften für die Verwendung in der Ingenieurbiologie haben. Diese scheinen sehr geeignet für die Anwendung bei Stabilisierungsmaßnahmen von Ufern zu sein. Das Ziel dieser Studie ist es eine weitere noch wichtige Eigenschaft, den Auszugwiderstand, zu untersuchen. In den Versuchen zeigte sich *Phyllanthus sellowianus* als deutlich widerstandsfähiger gegen Auszug als *Sebastiania schottiana*. Die Analysen der Wurzel- und Sprosseigenschaften ergaben, dass *Phyllanthus sellowianus* auch deutlich günstigere morpho-physiologische Eigenschaften hinsichtlich des Auszugwiderstandes hat. Außerdem wurden eine größere Biomasse, sowohl ober- wie unterirdisch als auch höhere Bodenfestigungseigenschaften festgestellt. Bei der Untersuchung der Spross- und Wurzeleigenschaften zeigte die Querschnittsfläche an der Basis der Sprosse in beiden Arten die stärkste Korrelation mit dem maximalen Auszugwiderstand. Als Ergebnis der Studie kann die Eignung der Art *Phyllanthus sellowianus* für Ufersicherungsmaßnahmen bestätigt werden, da diese besonders resistent gegen Auszug ist. Um die Potenziale von *Sebastiania schottiana* besser evaluieren zu können, werden weitere Untersuchungen empfohlen. Die zweite Studie präsentiert eine Uferschutzmaßnahme aus dem Jahr 2010 und eine im Zuge dieser Arbeit durchgeführten Vegetationsaufnahme. Neben einer Erhebung der Vegetations-zusammensetzung im aktuellen Pflanzenbestand wurden auch die Bauweisen, die zum Uferschutz errichtet wurden, hinsichtlich ihrer Effektivität und Stabilität untersucht. Durch die Vegetationsaufnahme konnte festgestellt werden, welche der gesetzten Arten sich gut entwickeln konnten. Dabei haben sich als besonders erfolgreich die Arten, *Calliandra brevipes*, *Phyllanthus sellowianus*, *Salix humboldtiana* und *Ateleia glazioveana* gezeigt. Der Anteil an spontaner Vegetation nahm im Untersuchungszeitraum stark zu. Als besonders dominante, invasive Art zeigte sich *Penisetum purpureum.* Zusammenfassend kann die Funktion und Sicherheit der Uferschutzmaßnahme bestätigt werden. Weitere Vegetationsaufnahmen werden jedoch empfohlen, um die zukünftige Entwicklung der verwendeten Arten und den Einfluss der Spontanvegetation auf die Stabilität der Böschung zu beobachten.

1 General introduction

The first soil bioengineering projects carried out in Brazil were realized in the region of Rio Grande do Sul within river stabilization works, to protect agricultural land of small regional farmers. The soil bioengineering techniques, using living plant material for civil engineering structures can be a helpful instrument for civil engineers taking into account not only technical but also ecological, sustainable and socio-economical aspects. Success is directly linked to the knowledge of the biological and technical properties of plants (RAUCH, SUTILI, 2009). Ensuing, the acquired knowledge can be applied to the spreading area of the plants. This way it can be useful in various regions. The master thesis in hand presents two research works complementing each other. Firstly, a pull out test, investigating anchorage ability of the two riparian species, *Sebastiania schottiana* and *Phyllanthus sellowianus,* is presented. Since the strength properties of the roots and the extensiveness of the root network dictate the degree of mechanical stabilization, it is of high interest to investigate the root system of potentially useful species for soil bioengineering applications. Anchorage, provided by roots, is influenced by various factors. It appears that root systems transfer shear stress in the soil to tensile resistance in the roots and thereby reinforce the soil mechanically (ALI, 2010). Both number and size of roots which cross the slip surface are extremely important in terms of anchorage ability(DANJON et al. 2007). Additionally, root architecture like the roots orientation (ABDULLAH et al. 2011; ALI, 2010) and the branching pattern have a close relationship to anchorage strength (BALL et al. 1996; DUPUY et al. 2005). The aim of the study is to quantify the amount, branching patterns and distribution of roots in order to understand the soil stabilization effects of the investigated species. Another objective is to examine plant characteristics, which correlate to the pull out resistance, in order to draft up efficient plant strategies for future restoration works on degraded river embankments. Hence, various shoot properties are analyzed and correlated to the pull out strength. In the second part of the master thesis a case study consisting of a restoration work in an eroded river embankment is presented. Through a vegetation survey, performed two years after completion of the slope reinforcement structures, an examination of the role of vegetation on slope stability is conducted. The species composition in the actual plant stand, as well as the dominance of species, their development and the influence of spontaneous vegetation were investigated. Additionally, an evaluation of the effectiveness and durability of the applied structures was performed. The results of the research works show the role of vegetation in slope reinforcement works plus the significance of both above and below ground plant traits.

2 A pull out test to compare two riparian species, Phyllanthus sellowianus and Sebastiania schottiana in terms of root anchorage ability

2.1 Introduction and objectives

As result of research work the species *Sebastiania schottiana* and *Phyllanthus sellowianus* have proven to be flexible and rupture-resistant. Whereby *Phyllanthus sellowianus,* with its high percentage of gelatinous fibres, thick wall fibres and small-vessels (30 μm), has shown an eminently high angle of flexibility (RAUCH, SUTILI, 2009). The aim of the present study is to examine the soil anchorage ability of the investigated species by means of a pull out test. Uprooting resistance is an indicator for the stability of the soil-root matrix and expresses the stabilizing effects of plants on soil. Furthermore, it is an applicable index to compare the qualification of the species to be used in soil bioengineering works (FLORINETH, 2012). During the pullout test, force is transmitted vertically to the root system and, as a result, the root-soil bond and the strength of the roots themselves becomes tense (CUI et al. 2011). This single vertical force applied to the stem is transmitted to numerous roots, because of either lateral branching or adventitious roots from the stem base (ENNOS, 1993). To examine the role of the roots system, its characteristics were analyzed and interrelated to the performed pull out resistance of the investigated plants. The factors which influence the pull out resistance are manifold and depend on not only the roots system. It is also affected by the composition of the ground and its physical properties (grain size distribution, humidity …), the growth conditions (water, light, nutrients ...), the plant species and its age. Results obtained under controlled conditions cannot be transferred directly into practice. However, it is ceteris paribus possible, by making comparisons, to extrapolate from the root systems of different species to the pull out resistance (SUTILI, 2007).A special apparatus was designed for the experiment (RAUCH, SUTILI, 2009). It enables to implement a pull out process at a constant rate of uplift and generate a graph of the plants resistance force versus its displacement. A full description follows in chapter 2.3.4. The study aims at a presentation of a holistic view of uprooting processes, investigating both above- and below ground plant traits. The results of the experiment are divided into a presentation of the data of the pull out test, the outcome of the analyses of the root characteristics and an ensuing interrelation of the results of the pull out test and the plant morph- physiological properties.

In the course of the elaboration of the issue, following research questions were drafted;

- which of the two species *Phyllanthus sellowianus* and *Sebastiania schottiana* performs a greater resistance against uprooting?

- which plant characteristics correlate to the pull out resistance of the investigated species?

- to which extent does the root architecture influence the pull out resistance?

2.2 Study area

The study was conducted at the campus of the Federal University of Santa Maria (UFSM – CESNORS) in Frederico Westphalen which is located at a latitude of 27°21´33´´south, longitude of 53° 23´40´´ east in Rio Grande do Sul. The field site was located at a homogenous area with a dimension of 320 m². According to MORENO (1961), the regional climate is subtropical, with an average temperature of 19° C, a maximum of 38° C and a minimum of 0° C.

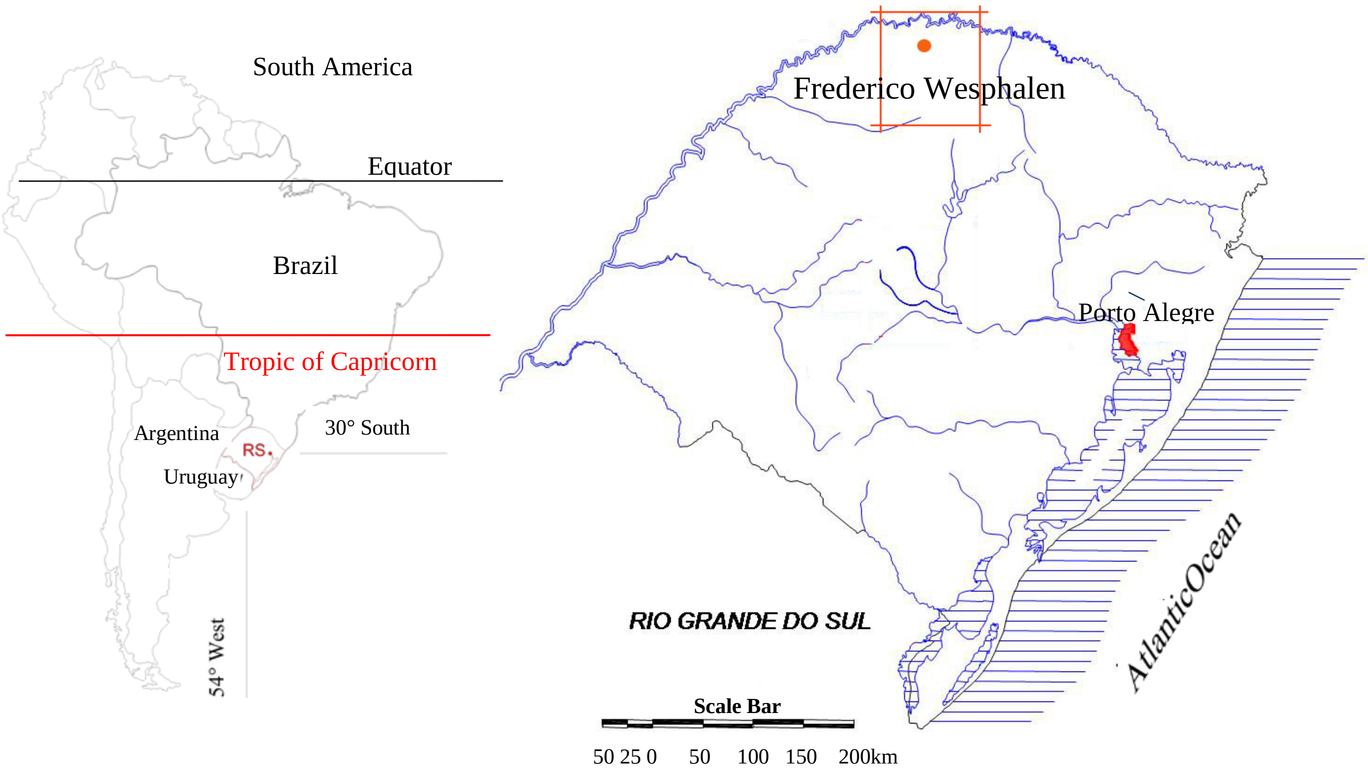

Figure 1: Location of Frederico Wesphalen in the State of Rio Grande do Sul and the position of the federal state on the South American continent.

2.2.1 Soil in the study area

Figure 2: Soil profile of a Latosol with a defuse transition of horizons.

The soil at the test site is a red latosol. It is rich in iron, aluminia, silicia and, according to DALMOLIN et al. (2008), porous, friable, well structured, normally profound, strongly weathered and presents a defuse transition of the horizons. The profile is Aox-Box-C . It is a type of soil of tropical climates with alternating hot-humid and dry periods. Latosols are formed by the process of leaching. In high temperatures and water surplus, the soluble bases, sesquioxides and silica are removed from the upper layers and deposited in the lower horizons. Residual accumulations of Fe- and Al- Oxides, coagulate irreversibly and harden. Due to strong decay, organic substances are widely decomposed without chelation or displacement of Fe- and Al- Oxides. As a result of the leaching, valuable mineral nutrients are displaced to the lower layers and the soils remain poor. Latosols are good soils for plantation. (STAHR, 1992).

2.2.2 Meteorology

The plant growth was strongly affected by an unusually long dry period from January until the end of September 2012, with sparse precipitation and low temperatures, ending shortly before the first pullout tests were executed. After a pluvial period with rising temperatures from October to December, the second test series was performed. The changed weather conditions affected a very strong growth. Especially the species *Sebastiania schottiana*, with an increase in average dry biomass from 57g in the first to 111 g in the second test showed an advanced plant development now. The biomass of *Phyllanthus sellowianus* increased as well, but not as significantly, with the average change being from 146 g to 176 g. The data was collected by the “Instituto Nacional de Meteorologia – INMET” with aid of an automated station on the Campus (UFSM – CESNORS) in Frederico Wesphalen. In Figure 3, the metereoligical conditions during the experiment are shown. From the first of February until the 14th of March there is a lack of data, due to a system failure of the meteorological station.

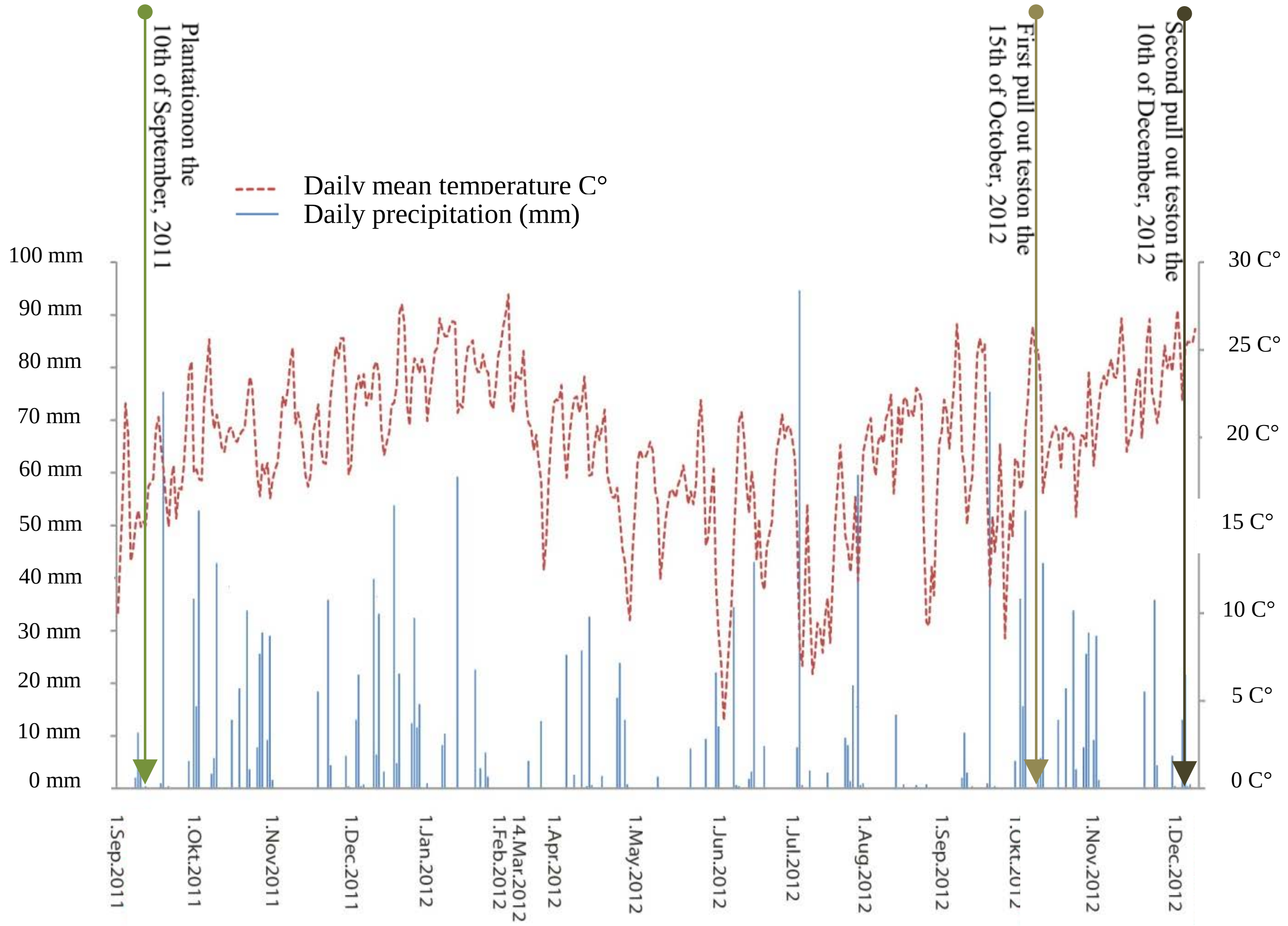

Figure 3: Meteorological conditions during the experiment (INMET, 2013)Campus, UFSM – CESNORS, Frederico Wesphalen, 01.09.2011 – 17.12.2012.

2.2.3 Preparation of testing site

For the experiment, 320 holes were excavated with a depth of 30 cm and a diameter of 15 cm. In order to facilitate a good radicular growth, a planting pattern in form of equilateral triangles with a side length of 1 m was chosen. In each hole, a live stake with a diameter ranging from 1.0 to 3.0 cm and a length of 40 cm was planted vertically. In Figure 12 it is shown how the experimental site was structured. One year after the plants had been fielded, the first series of pull out tests was executed.

2.3 Materials and methods

2.3.1 Description of species

2.3.1.1 Phyllanthus sellowianus Müll.Arg:

Family: Phylantacae
Popular names: sarandí-branco

The genus Phyllanthus belongs to the family of Phyllanthacae, within which the number of species varies widely, from 750 to 1,200. It shows a remarkable diversity, including annual as well as perennial herbs, floating aquatics, climbers, succulents and shrubs. The floral morphologies and the range of pollen types vary widely. A specific type of growth called phyllantoid branching is expressed by almost all Phyllanthus species, in which vertical stems bear deciduous, flower-bearing horizontal or oblique branches. It is found mainly in the tropical and subtropical regions (KUTTAN, HARIKUMAR, 2012).

Figure 4: Sketch of a one year old life-stake of *Phyllanthus sellowianus.*

Botanic description:

Phyllanthus sellowianus is a shrub reaching 2 – 3 m in height. It is autochthonous and has glabrous, woody, flexible stems branching from the base. The blossoming of this deciduous shrub occurs in spring, with fruit bearing in summer (HNATYSZYN et al. 1999). Leaves are simple, alternate, slightly lanceolate-eliptic, reach a length of 3 to 4 cm and have a particular characteristic; flowers arise at the base of the leaves, hence its name which derives from the Greek words phyllos, meaning leaves, and anthos, meaning flower (REITZ et al. 1988). Flowers are unisexual, very numerous and arranged in clusters at the leaves axes. The plant may be propagated by cuttings and by seeds. The habitus is similar to *Sebastiania schottiana* (SUTILI, 2007).

Figure 5: Phyllanthus sellowianus, growing along the water line.

Site requirements, Distribution and Usage

This species is very well adapted to habitats close to water bodies and, in case of flooding, protects the embankment against erosion. Its distribution area encompasses parts of southern Brazil, Uruguay and north-eastern Argentina (CABRERA, ZADINI, 1979). It develops along the borders of marginal jungles and on the banks of brooks and channels, forming diverse plant-communities (LAHITTE, HURREL, 1994).

Figure 6: Phyllanthus sellowianus growing by the water. Picture by SUTILI, 2013.

2.3.1.2 Sebastiania schottiana (Müll. Arg.) Müll. Arg.

Family: Euphorbiaceae

Popular Names: sarandi, sarandi-de-espinho (in Rio Grande do Sul) (MARCHIORI, 2000), sarandi-negro, sarandi-vermelho, içaranduba, saranduba, assobio-de-macaco and espinho-de-olho (REITZ et al. 1988).

Figure 8: Sketch of a one year old life-stake of *Sebastiania schottiana.*

Botanic description

Sebastiania schottiana can be characterized by its shrub habitus and as loosely growing, with long thorny branches, reaching a height of 3 to 3.5 m. Leaves are simple, alternate, with a short petiole (2-4 mm), membranous, lanceolate with a length between 1 and 5 cm and 4-15 mm in width, apex obtuse, entire margin, one or two glands and have 7-10 secondary evident veins on each side of the main vein. It has small yellow flowers, assembled in ears over small, short twigs (1-2 cm). Seeds are dispersed autochorily. The fruit has the form of a capsule approximately 5 mm in diameter (MARCHIORI, 2000).

Figure 7: Simple, alternateand lance-olate leaves of *Sebastiania schottiana.*

Site requirements, Distribution and Usage

According to REITZ et al.(1988), it is rheophil and resistant to extreme moisture or draught, has a dense root system and wiry, flexible stems capable to withstand the forces of flooding water. It is heliophytic, selectively hygrophytic or xerophytic and can grow in very sandy soils. As it has adapted to withstand the force of the floodwaters acting on riverbanks, it has great ecological value in the recovery of degraded areas and in the fixation of embankments at perennial watercourses (REITZ et al. 1988).

Figure 9: Plants of *Sebastiania schottiana* growing by the water. Picture by SUTILI, 2013.

Production of seedlings is difficult due to the irregular ripening of the fruits. The seeds lose their fertility quickly, which in turn makes it difficult to collect them when they reach their point of maximum physiological maturity. A viable alternative to optimize the production of seedlings is propagation by cutting (FRASSETTO, 2007).

2.3.2 Course of the study

The study was performed in two series of tests. The first tests were executed on the 15th of October, 2012. After the measurements of the plant properties, 38 plant individuals of each species were pulled out and subsequently the generated data were analyzed. Initially it was planned to excavate ten plant individuals of each species, leading to the pull out tests. However, this was inhibited by heavy rain falls after two plants of each species had already been excavated. Since a continuous pluvial period, which provoked a strong plant performance, followed, it was decided to procedure a second series of pull out tests at a later time. On the 10th of December the same year, the second round of pull out tests with a total of 8 plant individuals for each species was executed. This time, subsequently to the pull out tests, root material, which remained in the soil, was excavated and the root architecture of the plant individuals was analyzed. As fewer tests were performed in the second test series, the analyses of the gathered uprooting resistance data were used in a descriptive way only. That means that the correlation analyses between the plant morphological characteristics and the uprooting resistance were performed solely with the data gathered in the first test series. The gathered data of the second test series were used to describe the correlation between the plant growth and uprooting resistance.

2.3.3 Pull out test

According to DUPUY et al. (2005), a range of pull out tests had already been carried out to characterize the tensile force of roots. However, the results varied because the experimental techniques differed from author to author. In most of the tests, the shape of the root systems and their topology were not taken into consideration. Usually, every single generic property of a root, standing alone, is only poorly correlated with its pull out resistance. For this reason the present study aims at a holistic view on the morpho-physiological properties of the above and below ground parts of the investigated species. A previous study by CUI et al. (2011) showed that the strongest correlation of plant traits with uprooting resistance are exhibited by the plant height and stem diameter at base, indicating that the strongest grown plants do perform the highest uprooting resistance. In the present study, the cross sectional area of the shoots at base (CSA) was calculated since this value was assumed to express best the strength of the plant growth. In calculations using the CSA, shoots with a bigger diameter are valued stronger than in those which are based only on the stem diameter at the base of the shoots. Additionally, this value can be used as an easily applicable index in field work. In the following results of the test series, the gathered graphs and statistical analyses are presented first. In order to improve the results, the root architecture and various root properties of the species were analyzed and will be elucidated further on.

2.3.4 Pull out measuring device

To implement the experiment, a special apparatus, based on a tripod supporting a force of up to 168 kN, was designed and fabricated. It is portable and adjustable to irregular surfaces. The tripod supports a continuous-torque electric winch with adjustable lift speed. Since the pulling rate can influence the pull out capacity, it is crucial that the pull out process is performed at a constant rate of uplift. This is ensured by the electronically driven winch instead of manual propulsion. The guy wire of the winch passes through a centering guide which is mounted at the top of the tripod. A force transducer with a max. support of 10 kN, which is installed between the centering guide and the plant, is connected to a carrier frequency amplifier that interprets the signals and sends them to a laptop computer that instantly stores the data and generates a time versus force graph. Afterwards, the time values can be transformed into displacement values, thus generating force versus displacement graphs. The peak in the generated graph indicates the maximum force required for a plant to be uprooted. The arrangement of the apparatus is shown in Figure 10.

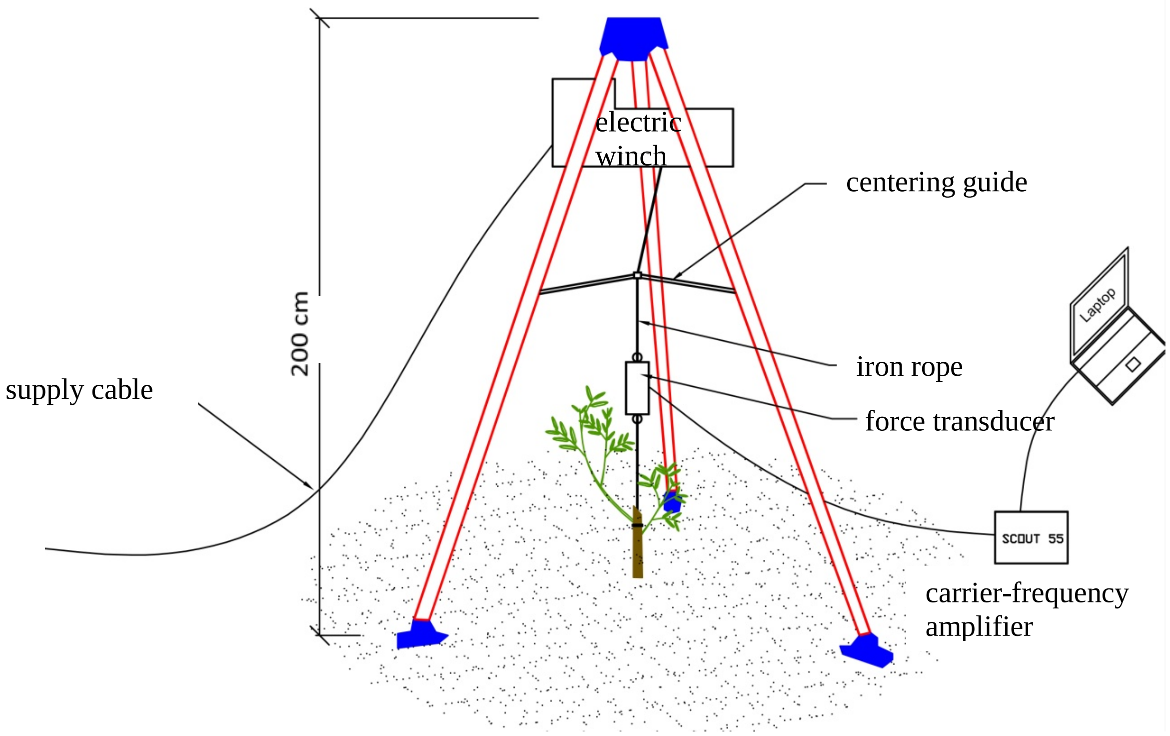

Figure 10: Diagram showing the arrangement of the equipment used for pull out testing (RAUCH, SUTILI, 2009).

2.3.5 Selection of plants

Due to the high mortality rate of *Sebastiania schottiana* and the fact that none of *Phyllanthus sellowianus* died, only the most representative plants of *Phyllanthus sellowianus* were selected in order to receive the same amount of plants (see Figure 12). The distribution of the plants in relation to their height showed a tendency for bigger plants to grow on the higher parts of the investigation area. In order to get a representative selection, each row was observed separately and its most representative plants were chosen. Each selected plant was identified with a specific number and the ground surface around the plants was cleared to facilitate the setting of the equipment. In the next step, the lengths of the shoots were measured with a yardstick and the diameter of each shoot as well as the diameter of the stem, were taken using a venire caliper. Additionally, the dry bio mass of the plants was measured in the laboratory after the pull out test.

Figure 11: (A) Experimental site after clearing (B) Taking the diameter, using a venire calliper (C) Measuring height, using a yardstick. Campus, UFSM – CESNORS, Frederico Wesphalen, 10.10.2012.

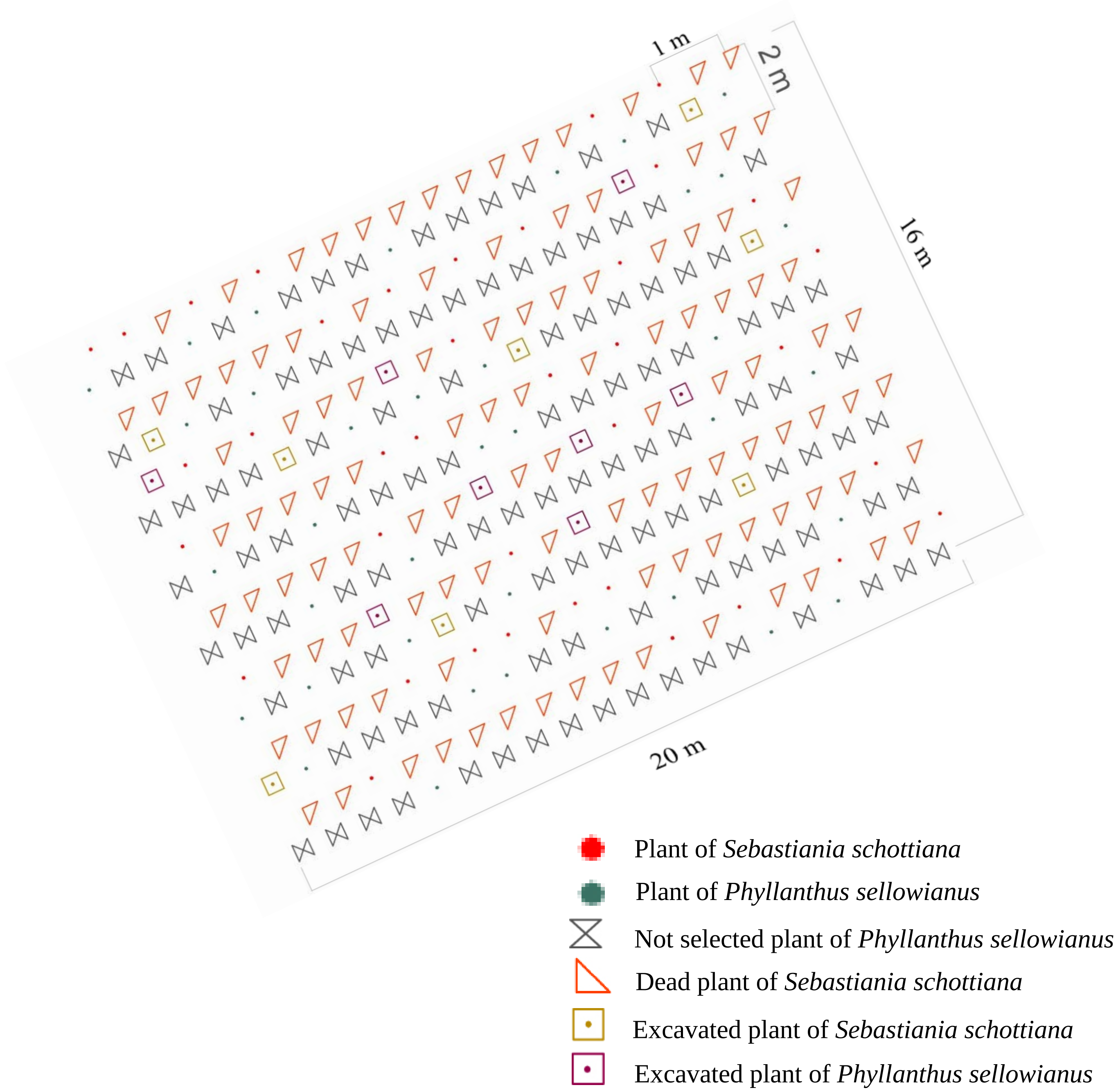

Figure 12: Diagram showing the arrangement of the testing field and the selection of plant individual for pull out tests and excavation method. Campus, UFSM – CESNORS, Frederico Wesphalen, 10.10.2012.

2.3.6 Execution of the pull out test

The first series of pull out tests was performed on two days within one week under similar weather and soil conditions. It was important that no rain showers had occurred the previous days, so that the soil was dry. The power for the equipment was taken from a twelve volt tractor battery. Firstly, the equipment was moved to the experimental site and the tripod was assembled. Next, the tripod was moved above the plant, so that the centering guide of the winch and the stem were in line. The legs of the tripod were stretched, so that it was in a firm position, and the linking wires of the tripod´s legs were tightened. The winch was linked to the testing plant by a cord. In order to achieve a graph which starts simultaneously with the force conducted to the root system, a little tension was performed to stretch the cord. Subsequently, the data series was set to zero. The motor was switched on to generate force, tensing the roots and pulling the plants out of the soil. At the same time, the software, which records 30 data per second, was initiated. The test was continued until the entire root system was pulled out of the soil. Since the own weight of the plant was still recorded after being uprooted, these data were deleted afterwards. In total, out of the 40 pull out tests performed,38 viable results were achieved for each species. The rest had to be discarded due to some software errors and a ripped rope. The same procedure was repeated in the second series of pull out tests with an achievement of 8 data per species.

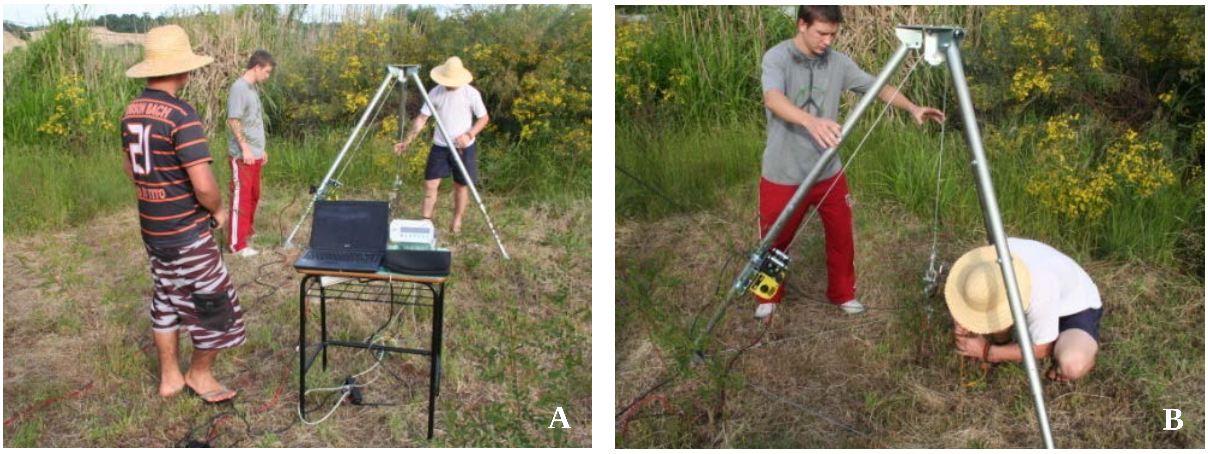

Figure 13: (A) Setting of the equipment. (B) Tying the plant to the apparatus. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

Figure 14: (A, B, C) Uprooting process of a *Sebastiania schottiana* plant and the pulled out root system (D)Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

2.3.7 Excavation of the plants

In order to gather the biomass of the root system, an excavation method was applied after the second series of pull out tests had been executed. The roots of eight plants per species, which had remained in the soil, were excavated. Therefore, in an area of 1 m² and as deep as 50 cm, the soil was stripped in five sections of a depth of 10 cm each. The stripped earth of each section was sieved and the roots of the plants were taken. After being dried in a stove, the roots were weighed. The roots which remained on the stem (< 1.5 mm) were analyzed in respect to their orientation by using a template. Additionally, the diameter at base, the diameter at breaking point and the distance from the stem to the breaking point were taken. Moreover, the pattern of the roots was analyzed and described by the classification of (DUPUY et al.2005). The roots which had remained on the stem were cut in 10 cm sections as well and put together with the appending excavated roots.

Figure 15: (A) Sieving the stripped earth in order to extract the roots that had remained in soil (B) Soil was excavated in an area of 1 m² and deep as 50 cm. Campus, UFSM – CESNORS, Frederico Wesphalen, 10.12.2012.

2.3.8 Statistical analyses

The data generated during the pull out test were subjected to variance tests of normality and homogeneity by applying the Shapiro-Wilk and the White test. The regression analysis was performed using the package “Statistical Analysis System (SAS)”, Version 9.2. All regression calculations were done at an error probability of 5%. This means that the model and regression analysis are highly significant and can be accurately used to extract information. The analyses of variance were calculated using Microsoft excel 2007. They follow a normal trend and are homoscedastic. Therefore, regression analysis can be performed without the need for numerical processing.

2.4 Theoretical principles of root morpho- physiological properties

2.4.1 Orientation of roots

According to ABDULLAH et al. (2011) and ALI (2010), strongest soil anchorage is developed by lateral roots. Hence, plants with an extensive number of lateral roots perform greater pull out resistance. Tap- and stilt roots anchor the plant in a central position while the lateral roots act like guy ropes (STOKES, 1999). The size and number of lateral root axes are determinant for the root's ability to bear a large amount of soil and the area of soil mobilized during pull out (DUPUY et al. 2005). This is affirmed by CUI et al. (2011) who found out in a pull out test that with the increase of pull out resistance, there is an increase in the broken surface area, which indicates that the area affected by soil reinforcement increases along with the pull out resistance.

2.4.2 Spatial Distribution of roots

The effectiveness of coarse, as opposed to fine roots, highly depends upon spatial density and depth. If the spatial density is not sufficient, the soil can easily move around the root and the strengthening effect of the root becomes negligible. In general, soil reinforcement is provided effectively by fine roots, but for shallow slope stability the advantage of fine roots is less obvious (DANJON et al. 2007). Larger infiltration capacity and a higher surface roughness are caused by root particles at the ground surface (GREENWAY, 1987). The soil adjacent to the roots is affected both mechanically and hydrologically, in terms of aggregate stability, infiltration capacity, soil bulk density, soil texture, organic plus chemical content and shear strength; all of these being important determinants for soil erodibility (AMEZKETA, 1999). The most effective soil reinforcement is provided by a combination of both fine and coarse roots. A large density of fine roots in the upper layers of the soil stratum aids in resisting tension and is more resistant in cases of concentrated flow erosion (BOCHET et al. 2005). Coarse roots are extending deep into the soil whereby they are crossing numerous shear planes. In this way, they provide stability against bending and shearing forces (JEROME, 2011). In Figure 16 different grow patterns of root systems are shown by means of visualizing the plant development of some selected species.

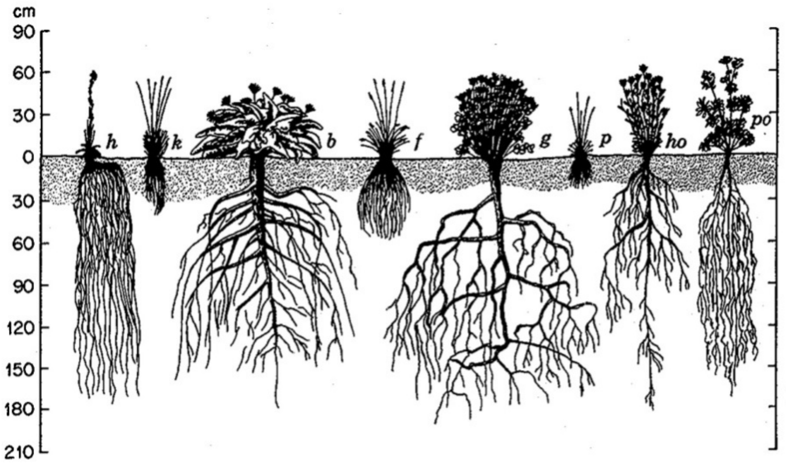

Figure 16: Different grow patterns of root systems, demonstrated by selected species: h *Hieracium scouleri*; k, *Koeleria cristata*; b, *Balsamina sagittata*; f, *Festucata ovina ingrate*;g, *Geranium viscosissimum*; p, *Poa sandbergii*; ho, *Hoorebekia racemosa*; po, *Potentilla blaschkeana* (WEAVER, 1919).

2.4.3 Morphological diversity of roots

Several mechanisms in the development of roots involve growth and result in the geometrical pattern of a root system. To explore the morphological diversity of the root systems, the branching patterns were classified according to the system of (DUPUY et al. 2005). There are two options; to branch or not to branch are the alternatives of an elongation zone. In case of non-branching, the root system will result from longitudinal elongation and directional changes in root growth. This growth pattern was classified as “non-branching structure”. It appears that this phenomenon is strongly determined by the local soil environment. Two categories of branching can be distinguished. Either the apex continues to grow straight and produces second-order lateral branches resulting in herringbone-like systems (classification class “herringbone-like systems”), or two terminal apices appear and replace the former single apex at the tip of the root, as is found in dichotomous-like systems (classification class “dichotomous-like systems”) (DUPUY et al. 2005). The branching pattern can affect the resistance of a plant against uprooting. For an equal root volume, dichotomous systems are significantly better anchored than herringbone systems if roots are rigid. This change in anchorage happens because the total amount of soil mobilized during uprooting increases as it is carried upwards on the forks of lateral root branches (BALL et al. 1996; DUPUY et al. 2005). Properties of roots with a “non-branching structure” pattern are; no branches, axes with thicker diameters than the other elements and an orientation mainly in the longitudinal direction. The stresses during uprooting never reach the yield value in roots, whereas the pulling resistance is limited mainly by the friction of the faces in contact and by the shearing of the soil surrounding the root. In this category, roots are commonly short and thick, causing failure in the soil rather than slipping out, which would require an initial deformation of the root. Dichotomous-like branching structures are significantly the most resistant against uprooting (DUPUY et al. 2005). Tangential friction is the most significant factor contributing to shear stress. The shear resistance increases with greater friction because the roots can rather stretch than slip. Pull out strength is not only influenced by tensile strength at breakages, but also by root characteristics which cause a higher friction, like bend ability, degree of bifurcation (branching), diameter and root hairs (ABE, ZIEMER 1991).

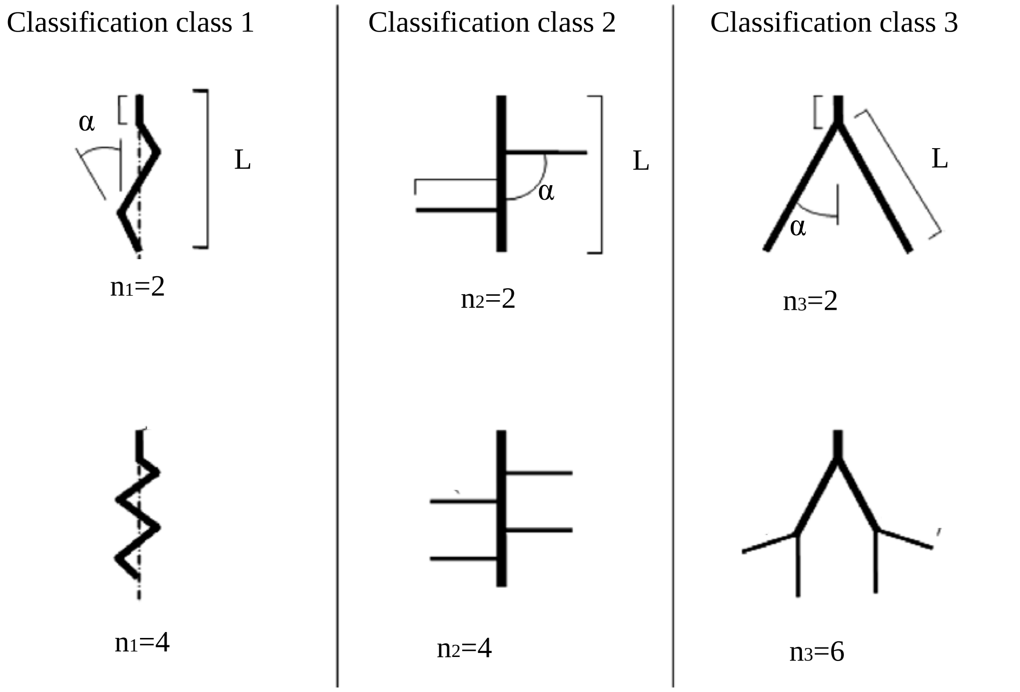

Figure 17: The three classification classes of root patterns by DUPUY et al. (2005). Classification class 1 consists of non-branching structures, classification class 2 of herringbone-like root systems and classification class 3 of dichotomous-like root systems. The quantity n represents the number of secondary segments, L is a reference distance of the secondary segments, and α is the angle between a segment and its bearing axis.

2.4.4 Structure of roots

Although thicker roots require more force to be pulled out of the soil, thinner roots are significantly more durable than thick roots due to changes in cellulose content (cellulose is highly resistant in tension) (GENET et al. 2005). As tensile strength increases with decreasing root diameter, (GENET et al. 2005) a larger number of fine roots would fix the soil more effectively than a small number of course roots (DANJON et al. 2007). During slope failure, fine roots tend to break but stay in position relative to the adjacent soil particles, while coarse roots can slip out of the soil (ENNOS, 1990). However, coarse roots, e.g. sinker roots or tap roots, penetrate the soil in the same way concrete is reinforced by steel rods. As a consequence, deep penetrating roots are able to fix shallow soil layers. The spatial position of these thick roots also has an additional indirect effect on soil fixation in that the location of thin and fine roots will depend on the arrangement of thick roots (ATGER, 2009). In conclusion, a combination of a dense rooting pattern of fine roots in the top layer, where resistance in tension is most important, and coarse, deeply penetrating roots, crossing the potential shear surface and hence more submitted to bending and shearing, is most effective (DANJON et al. 2007).

ATGER et al. (2009) compiled three classes of root thickness depending on their diameter in order to better understand the different processes governing soil fixation by roots. In this research work, the classes were subdivided based on ATGER et al. (2009) and adjusted to the properties of investigated species. However, as the plants examined in this work had a maximum root diameter of 10 mm, the division of the classes was adapted to suit the present situation.

(0 – 2 mm) Taking up water and nutrients are a major function of these roots. If roots are in young state and not yet woody, root hairs, which aid uptake, may be present. The turnover of fine roots to course roots happens quite rapidly.

(2 – 5 mm) In woody species most roots will be lignified in this class. Turnover is not known as further thickening of the roots depends on a certain number of external and internal processes.

(5 – 10 mm) R**oots which are most important for anchoring the plants on the soil.** These roots play a major role in anchoring the plant to the soil and might develop even stronger and surpass the diameter of 10 mm.

According to DUPUY et al. (2005), the resistance of a root element, regardless of the group type, is well predicted by the basal diameter and the number of branches in the rooting pattern. As it will be presented in the chapters 3.2 and 3.3 this has been observed also in the present study

2.5 Results pull out test

2.5.1 Descriptive Statistics

Descriptive statistic was used in order to get a better understanding of the uprooting resistance data. For that purpose, the gathered data from the pull out test plus the most correlating variable of the plants' morphological properties and the maximum uprooting resistance were summarized. In Table 1, the respective data is shown.

			Sebastiania schottiana	
Variable	**Minimum**	**Maximum**	**Average**	**Standard deviation**
Maximum force applied (N)	148.00	1562.00	626.11	332.70
Maximum displacement (cm)	35.92	109.70	54.65	13.54
Displacement at pull out(cm)	4.45	47.61	12.24	7.58
CSA shoots (mm²)	28.60	577.80	202.69	111.47
			Phyllanthus sellowianus	
Variable	**Minimum**	**Maximum**	**Average**	**Standard deviation**
Maximum force applied (N)	1003.00	2795.00	1767.20	504.01
Maximum displacement (cm)	32.85	126.13	76.30	22.91
Displacement at pull out (cm)	10.86	36.75	23.22	6.55
CSA shoots (mm²)	259.2	935.3	519.98	183.20

Table 1: Descriptive statistics for the data, gathered in the uprooting process, and the variables correlating most with the uprooting resistance.Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

In Figure 18, representative graphs, illustrating the average characteristics of species, are shown. Although no further elaborated statistical analysis (apart from the descriptive analyses) was carried out, they can be considered as representative, as they are supported by the morphological characteristic (cross-sectional area shoots), which showed very strong linear correlation to the pull out resistance.

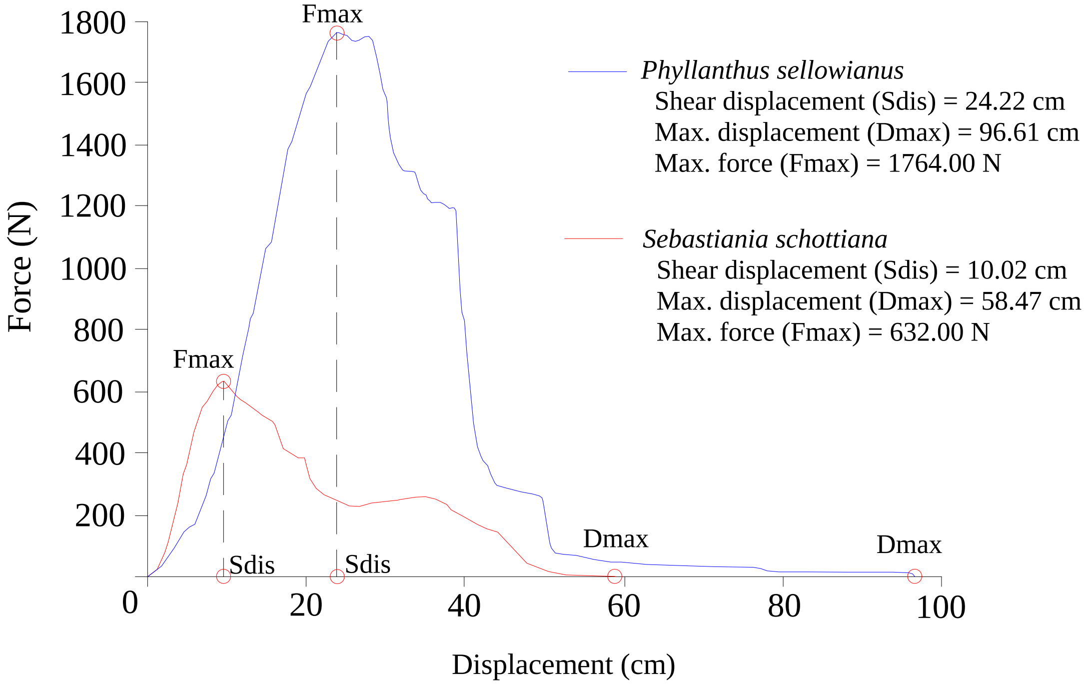

Figure 18: Graphs based on the average test results of *Phyllanthus sellowianus* and *Sebastiania schottiana*.Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

In order to present the obtained results in more detail, the graphs of the plant individuals which performed the maximum, medium, and minimum uprooting resistance are shown;

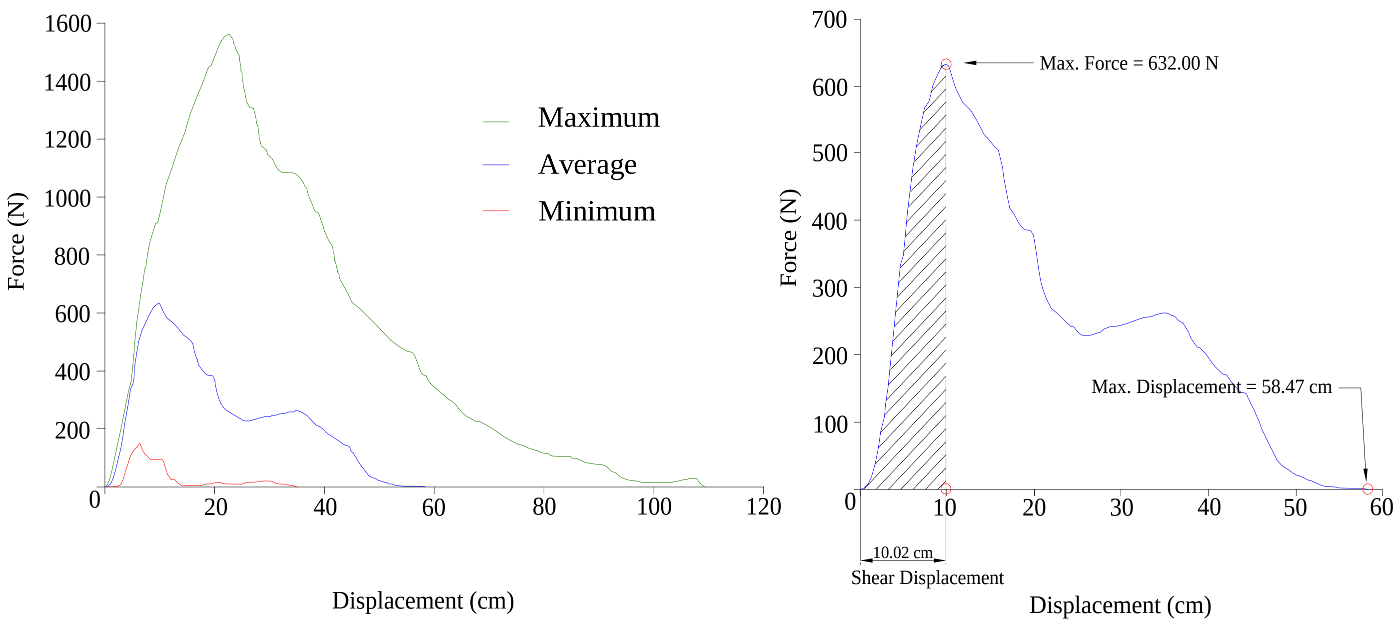

Figure 19: On the left, characteristic graphs, presenting the plant individuals of *Sebastiania schottiana*, which performed the maximum, average (in more detail on the right) and minimum uprooting resistance. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

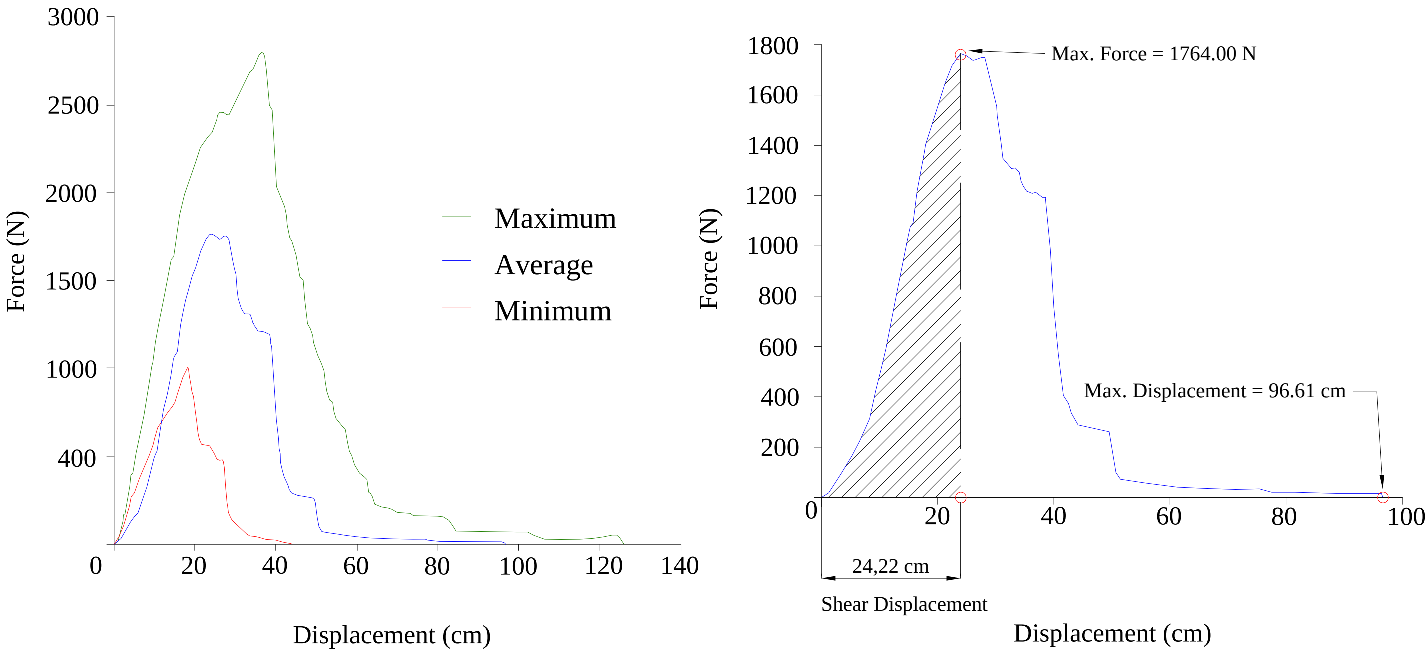

Figure 20: On the left, characteristic graphs, presenting the plant individuals of *Phyllanthus sellowianus*, which performed the maximum, medium (in more detail on the right) and minimum uprooting resistance. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

2.5.2 Analysis of the gathered graphs

The first break in the graphs and consequently the first movement of the plants eventuates with the increase of the force applied; implying that with the first impulsions the plants did not show any movement. However, the highest peak and respectively the maximum pull out resistance, was reached at a very different level by the species. The graph of *Phyllanthus sellowianus* shows a steep gradient until reaching the peak and further significant high points in the declining curve. *Sebastiania schottiana* shows a different pattern, either with the peak after another lower high point, or only one peak and total absence of further significant high points. In each case, however, it does not reach even close to the level of *Phyllanthus sellowianus*. ABDULLAH et al. (2005) assessed the first breakage in a pull out test as a result of failure of the lateral root system. Only then the tap- and stilt roots become tense and break. Both species do develop lateral as well as tap and sinker roots, but of different quantity, as the next chapter will explain in more detail. Thus, the lower first high point of the tested plants of *Sebastiania schottiana* can be explained through the absence, or significantly lower amount of lateral roots. The mean maximum resistance was reached at 12 cm of displacement among *Sebastiania schottiana and* 23 cm among *Phyllanthus sellowianus*. This additionally reflects the more diverse root system and slope reinforce quality of *Phyllanthus sellowianus.* In Figure 21 and 22, representative displacement versus force graphs are shown for each species. The pattern of these two graphs conforms to the majority of the other generated graphs and therefore they can be used to describe the results.

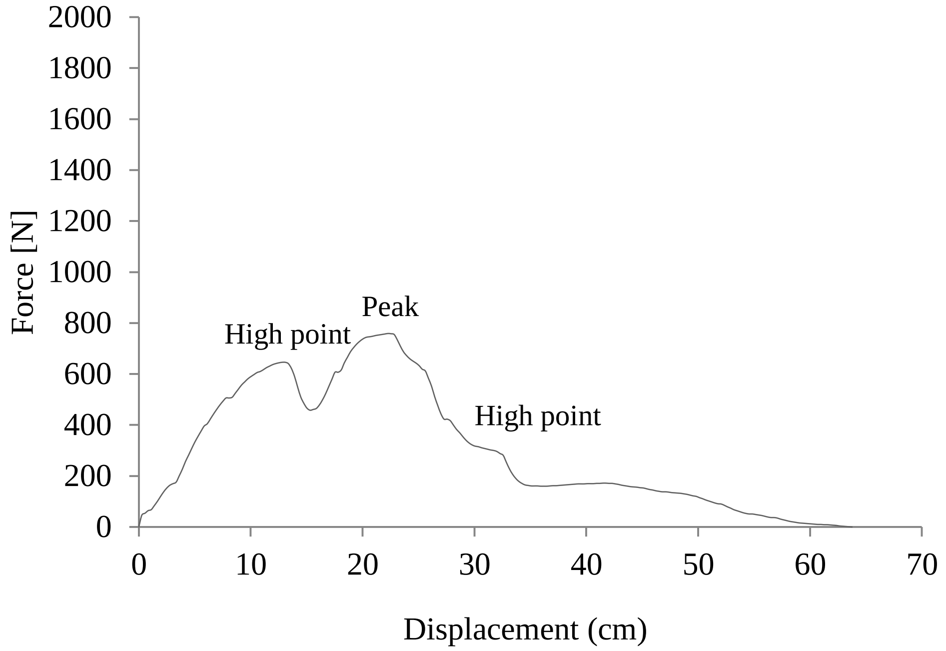

Figure 21: Typical pattern of uprooting - displacement curve for *Sebastiania schottiana*. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

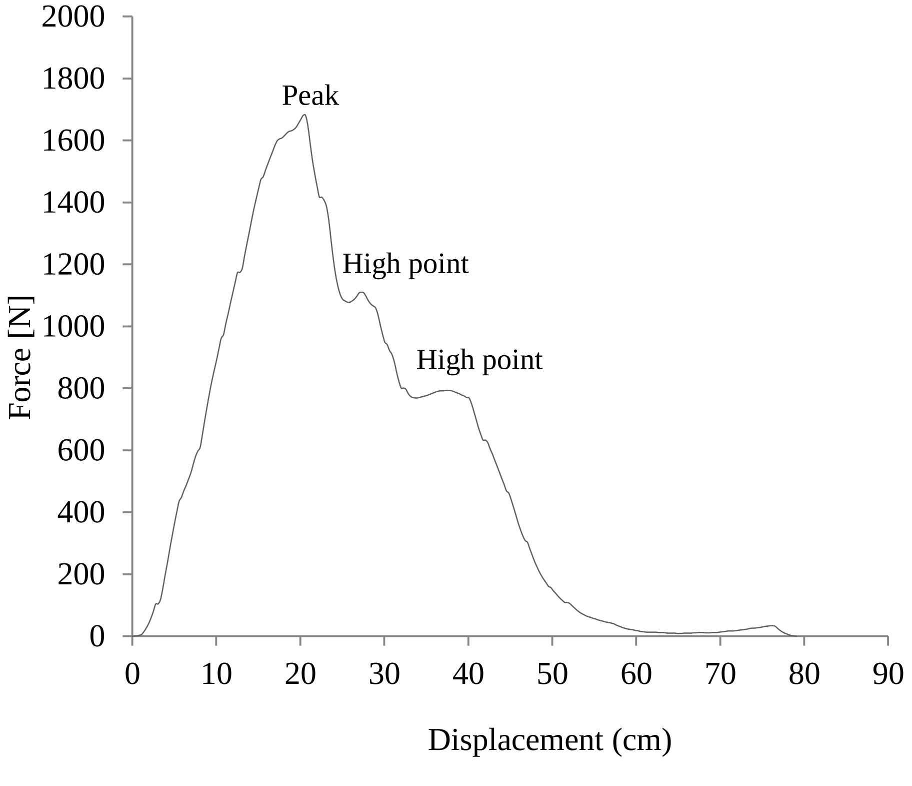

Figure 22: Typical pattern of uprooting - displacement curve for *Phyllanthus sellowianus*. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

2.5.3 Plant growth and uprooting resistance

Simultaneously with the growth of the plants, their uprooting resistance increased in the time between both test series. The maximum uprooting resistance of *Sebastiania schottiana* ranged from 148N to 1562N, with an average of 626N in the first performed test series (September) and 834N to 1970N, with an average of 1374N in the second test series (December). The pullout resistance of *Phyllanthus sellowianus* was significantly higher, ranging between 1003N and 2795N, with an average of 1767N in September and from 1287N to 3269N with an average of 2018N in December. The significant increase of the uprooting resistance, simultaneous with the growth and increase of biomass clearly shows the correlation of plant growth and uprooting resistance.

2.6 Results of analyses of root characteristics

The results obtained through the analysis of the roots characteristics provide important information on how the anchorage of the plants is affected by its root system. Different composition in root distribution, branching and orientation were observed. Also, the structure of the roots showed distinctions between the investigated species.

2.6.1 Orientation of roots

In *Phyllanthus sellowianus*, laterally oriented roots were dominant with an average of 8, compared to 3.1 vertically and 4.9 obliquely oriented roots, while *Sebastiania schottiana* showed, on average, 4.5 horizontally, 3.1 vertically and 3.9 obliquely oriented roots. This shows the distinctly more laterally oriented nature of the root system of *Phyllanthus sellowianus*, resulting in stronger uprooting resistance. Figure 23 and 24 display the root system of the investigated species. The sketches show the root systems of the plants after uprooting. Due to the different distribution and quantity of roots, the amount of fixed soil and hence the effectiveness of soil reinforcement was significantly higher in *Phyllanthus sellowianus*. This was not examined in more detail, except for the observations during the pull out tests. The profundity reached by both species was approximately the same.

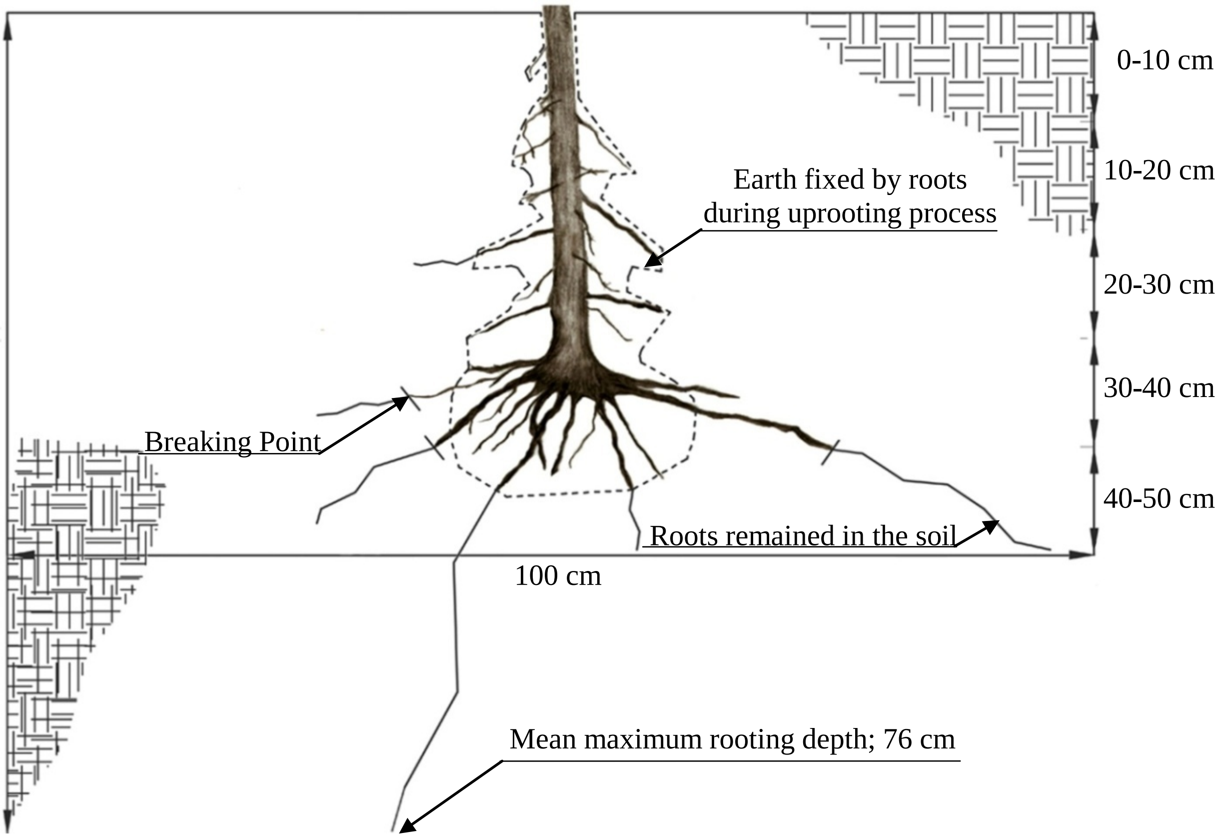

Figure 23: Sketch, illustrating the root system of a *Sebastiania schottiana* plant individual after uprooting, the roots remained in the soil, the soil fixed by the root system, the deepest point reached on average by this species and the divisions for the excavation method. Campus, UFSM – CESNORS, Frederico Wesphalen, 10.12.2012.

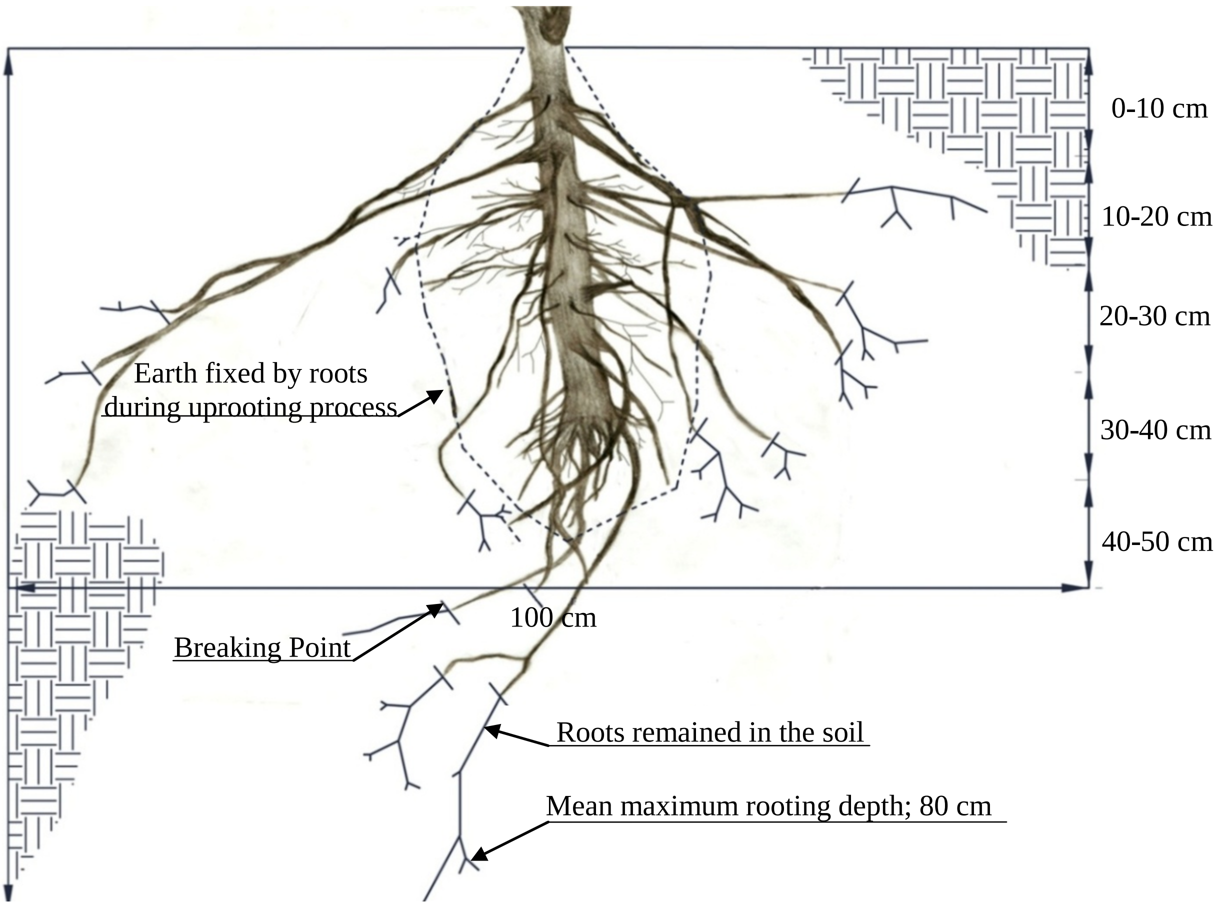

Figure 24: Sketch, illustrating the root system of a *Phyllanthus sellowianus* plant individual after uprooting, the roots remained in the soil, the soil fixed by the root system, the deepest point reached on average by this species and the divisions for the excavation method. Campus, UFSM – CESNORS, Frederico Wesphalen, 10.12.2012.

2.6.2 Distribution of roots

Considering that *Phyllanthus sellowianus* showed both deep penetrating and shallow fine roots, it can be assumed that it contributes effectively to slope reinforcement. *Sebastiania schottiana* showed strong root growth in depth and sparse root growth near the surface. STOKES (1999) stated that for a landslide engineer, it is important to remember that a slope is stabilized by the whole community of plants, and not by individual root systems in isolation. This means that, even if the near-surface soil is hardly reinforced by *Sebastiania schottiana*, for example in combination with herbaceous species, which typically perform strong reinforcement of the upper soil layers, it can be an important contributor to soil stabilization. Figure 25 shows the distribution of the root biomass.

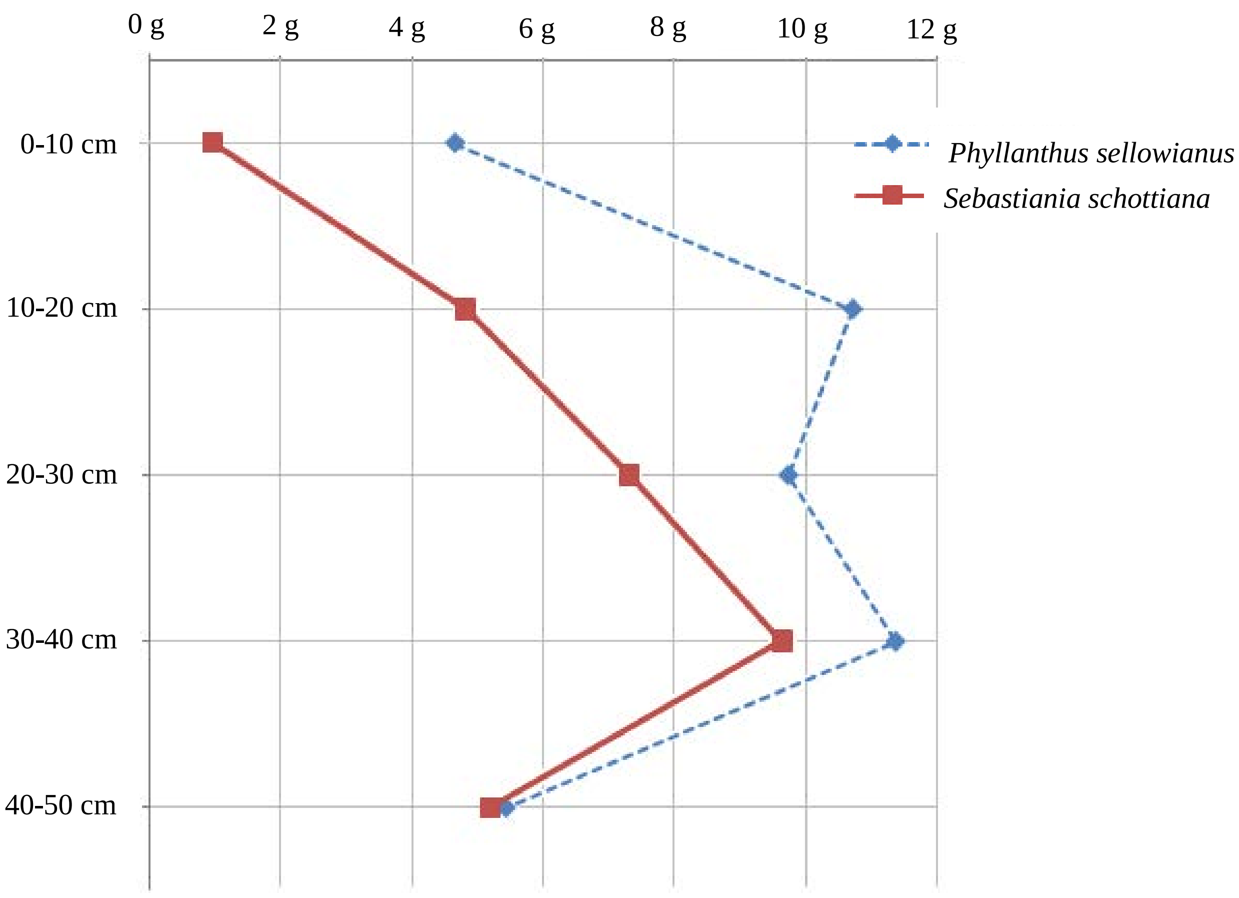

Figure 25: Distribution of root biomass for one year old life-stakes of *Phyllanthus sellowianus* and *Sebastiania schottiana*. Campus, UFSM – CESNORS, Frederico Wesphalen, 10.01.2013.

The following pictures were taken after the roots had been cut off the stems. They show the distribution of the roots in depth. Moreover, the different root patterns of the investigated species are visualized.

Figure 26: Pictures, showing the distribution of the roots in depth and the root pattern of a *Sebastiania schottiana* plant individual. Divided in following sections; (A) 0-10 cm (B) 10–20 cm, (C) 20-30 cm, (D) 30-40 cm in depth. This plant individual showed no roots deeper than 40 cm. Campus, UFSM – CESNORS, Frederico Wesphalen, 10.12.2013.

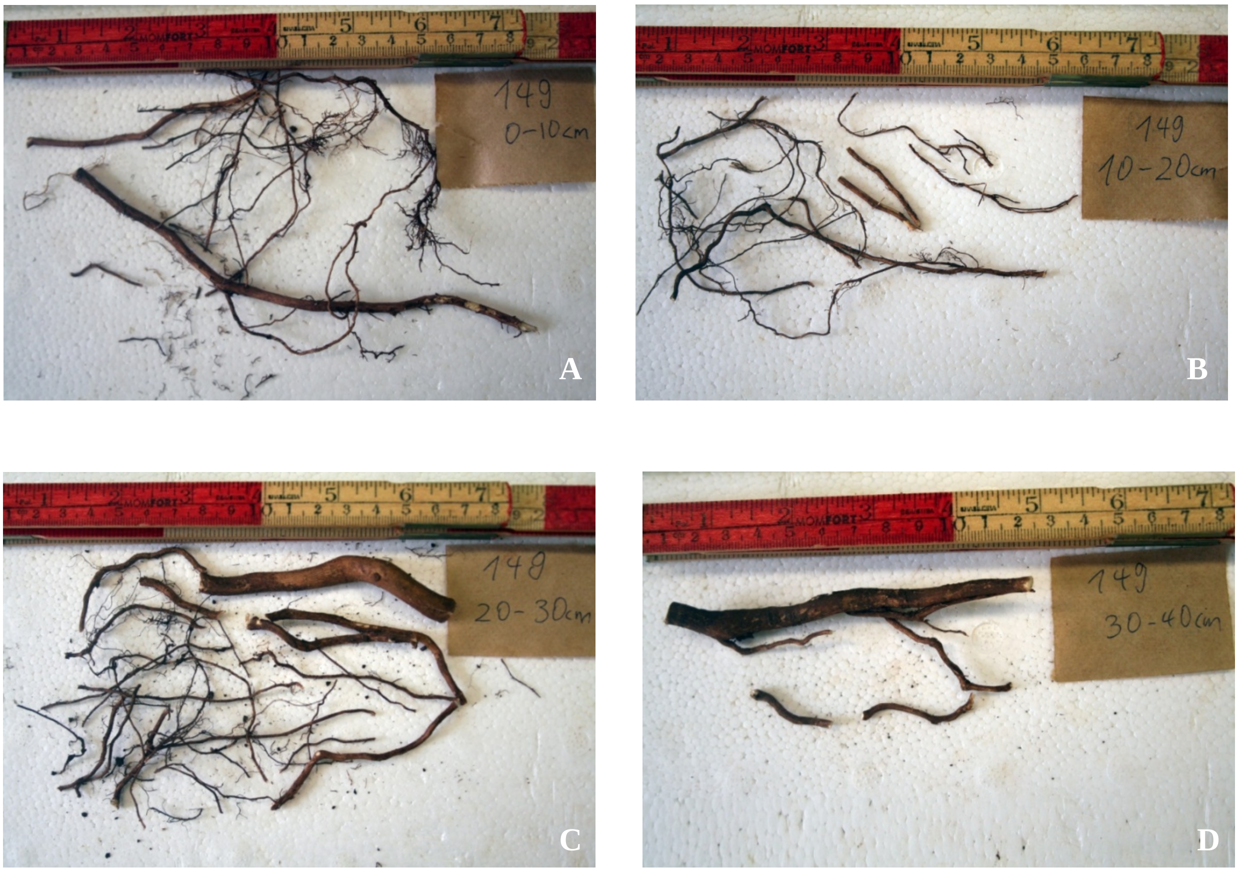

Figure 27: Pictures, showing the distribution of the roots in depth and the root pattern of a *Phyllanthus sellowianus* plant individual. Divided in following sections; (A) 0-10 cm (B) 10–20 cm, (C) 20-30 cm, (D) 30-40 cm in depth. This plant individual showed no roots deeper than 40 cm.Campus, UFSM – CESNORS, Frederico Wesphalen, 10.12.2012.

2.6.3 Morphological diversity of the root systems

The root characteristics of both investigated species showed structures of non-branching and dichotomous like structures. Whereas in *Sebastiania schottiana* dichotomous-like patterns were nearly absent, they were the dominant pattern in *Phyllanthus sellowianus* and the amount of root hair was significantly higher in this species.

2.6.4 Structure of roots

Thickness of roots

The proportion of fine roots was significantly higher in *Phyllanthus sellowianus.* This is also visible on the pictures of the excavated roots (Figure 26, 27). The roots beyond a diameter of about 1.5 mm were measured and serve as a representative for the proportion of fine roots.

	Sebastiania schottiana	***Phyllanthus sellowianus***
Classification class	**Proportion in %**	**Proportion in %**
(1.5 – 2 mm)	11%	28%
(2 – 5 mm)	68%	55%
(5 – 10 mm)	21%	17%

Table 2: Proportion of roots of Sebastiania schottiana and Phyllanthus sellowianus in the three classification classes (1.5 – 2mm), (2 -5 mm) and (5 -10mm) in diameter. Campus, UFSM – CESNORS, Frederico Wesphalen, 10.01.2013.

The results show that *Sebastiania schottiana* produced a higher proportion of thicker roots after having grown for one year. During the experiment, *Sebastiania schottiana* could just sparsely develop fine roots. It should be further investigated how the species develops under different growing conditions. However, the results indicate that *Sebastiania schottiana* potentially performs good soil anchorage abilities under distinct circumstances, like over a longer growth period.

Wooden structures of roots

To investigate the strength of the wooden structures of the roots, the diameter of the broken roots at base and at the breaking point as well as the distance from the stem up to the breaking point were measured. The total cross-sectional area (CSA) at the breaking point, summed over all roots with a diameter bigger than 1.5 mm was calculated and divided by the maximum uprooting resistance. The results showed that, on average, a root of *Sebastiania schottiana* performs an uprooting resistance of 36.7N per mm² whereas a root of *Phyllanthus sellowianus* performs a resistance of 29.9N per mm². This indicates that the wooden structures of the roots *of Sebastiania schottiana* are stronger and that few roots can indeed perform a high uprooting resistance.

2.7 Interrelating results of pull out test and results of analyses of morpho-physiological properties

2.7.1 Plant traits and their relationship with resistance to uprooting

In order to investigate the statistical relation between the plant traits and the uprooting resistance, the coefficient of determination (R^2) was calculated. To do this, the morphological characteristics of 38 plants (data achieved in the first test series) of each species, were set in relation with the respective maximum uprooting resistance of the plant individuals. In Table 1, the most correlating plant traits are listed. Additionally, the number of shoots, the mean length of shoots, the mean diameter of shoots at base and the number of roots were examined in terms of their correlation to the maximum pull out resistance. However, these plant properties did not show a statistically significant correlation. The strongest correlation to uprooting resistance was shown by the cross-sectional area (CAS) of shoots at base. The dry mass of shoots showed the second highest significant statistical correlation. As a result, it can be assumed that bigger plants show a higher pull out resistance.

	Sebastiania schottiana		***Phyllanthus sellowianus***	
Morphological Characteristics	**Reg. Equation**	**R^2**	**Reg. Equation**	**R^2**
Stem dia. At base (mm)	F= -847,5+95,64	0.51	F= 371,5+116,7	0.54
Sum dia. Of shoots at base	F=-208,7+29,25	0.67	F=246,6+50,27	0.69
Sum length of Shoots (cm)	F=-94,02+3,67	0.79	F=575,4+4,11	0.54
CSA of shoots at base (mm^2)	F=93,8+5,061	0.85	F=508,7+4,967	0.83
Dry mass of shoots (g)	F=284,9+20,75	0.83	F=757,9+12,52	0.72
Dry mass of roots (g)	F=-163,4+21,57	0.61	F=699,7+17,76	0.43
CSA of roots at base (mm^2)	F=391,8+8,5	0.65	F=943,7+8,32	0.73

Table 3: Morphological characteristics of 38 uprooted plant individuals, each investigated species and the regression equations between maximal uprooting force (F) and plant morphological characteristics .Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

Below the graphs of the coefficient of determination of the most correlating above ground, the cross sectional area of shoots at base, and the most correlating below ground, the cross sectional area of roots at base, plant traits are shown.

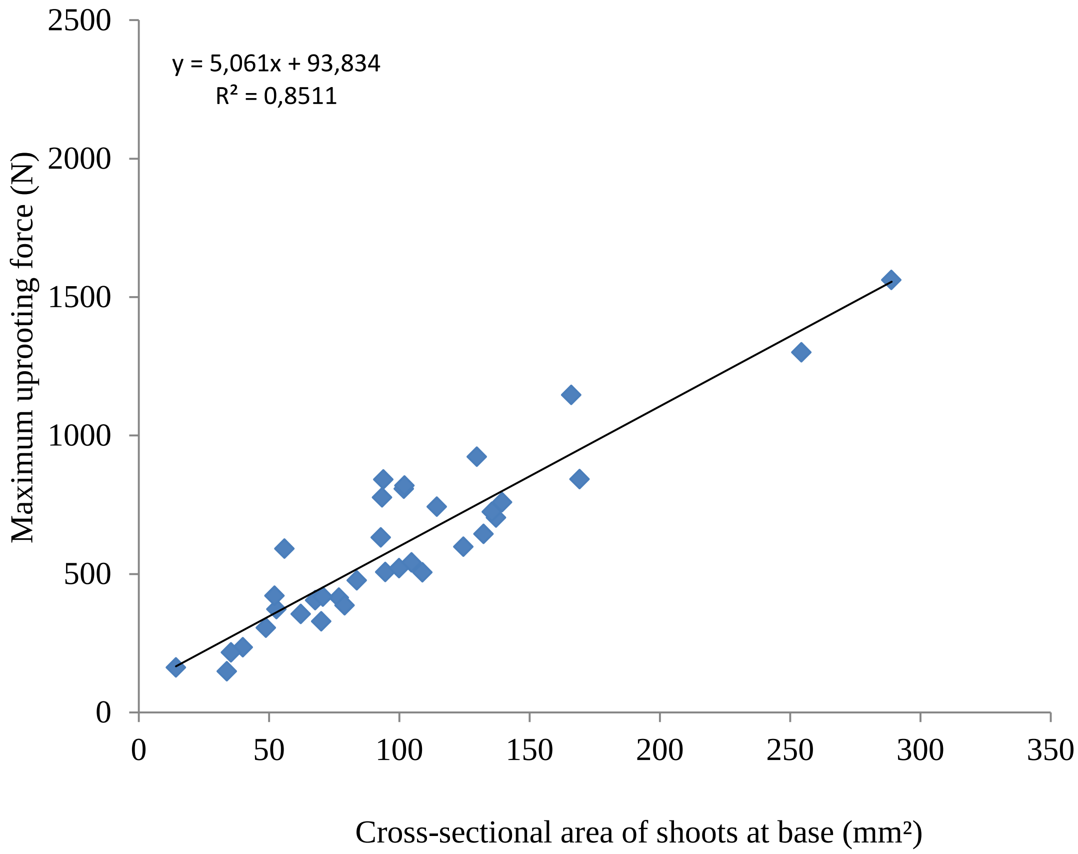

Figure 28: The relation between the maximum uprooting force and the cross sectional area of the shoots at base of *Sebastiania schottiana*. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

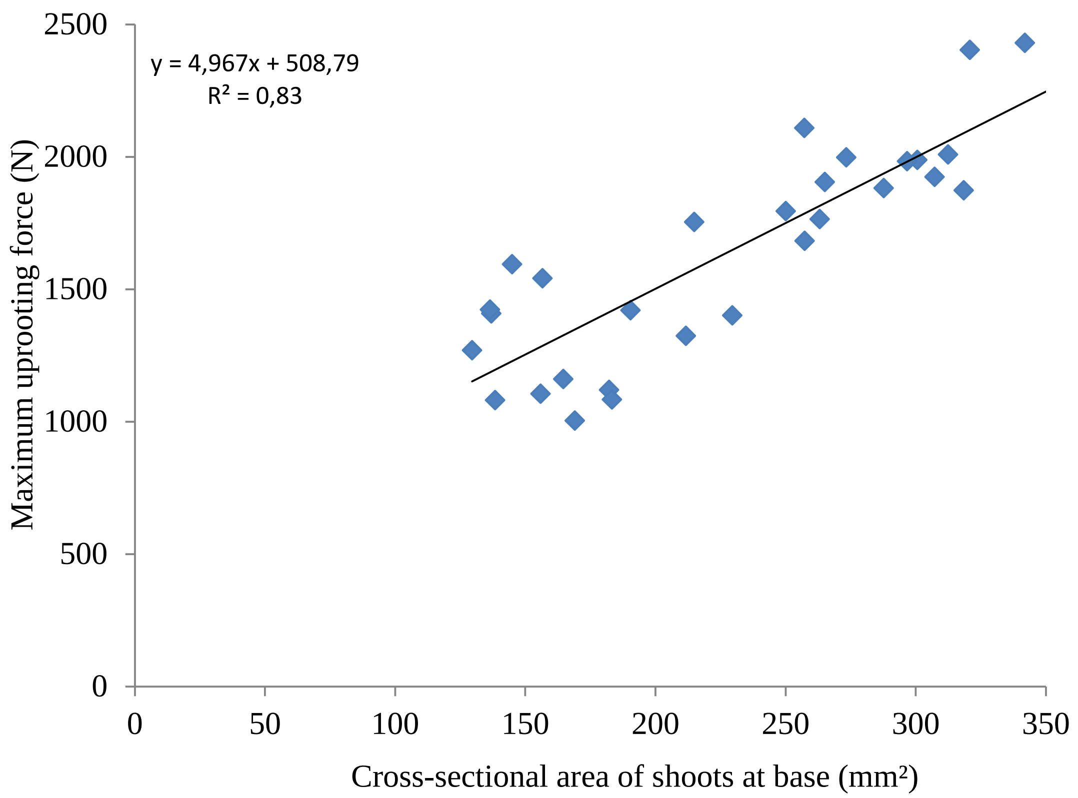

Figure 29: The relation between the maximum uprooting force and the cross sectional area of the shoots at base of *Phyllanthus sellowianus*. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

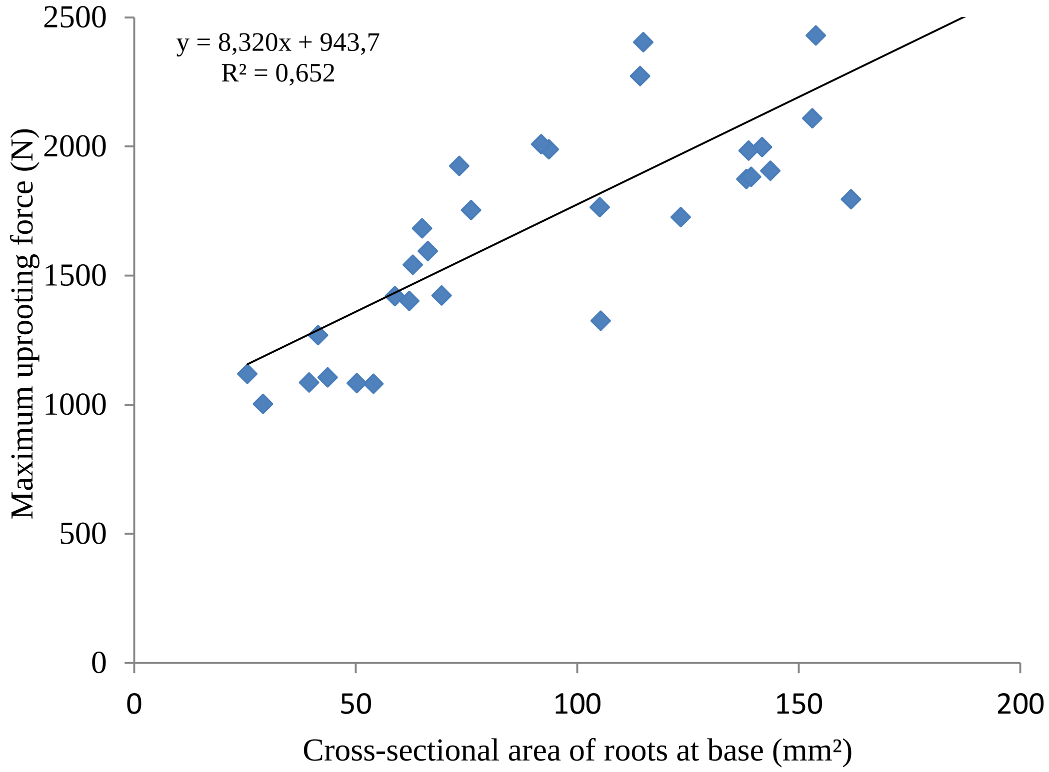

Figure 30: The relation between the maximum uprooting force and the cross sectional area of the roots at base of *Sebastiania schottiana*. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

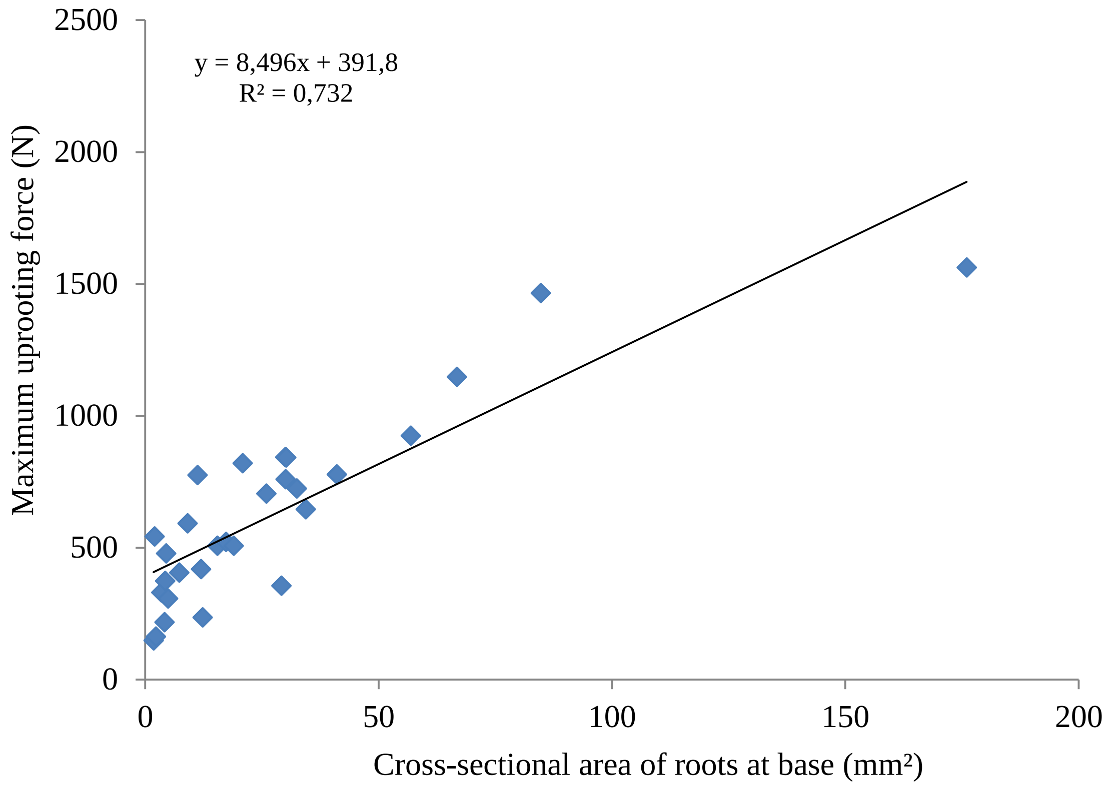

Figure 31: The relation between the maximum uprooting force and the cross sectional area of the roots at base of *Phyllanthus sellowianus*. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

2.7.2 Correlation between morphological characteristics and maximum uprooting resistance, using the Pearson Correlation test.

The results achieved by using the Pearson test of correlation corroborated the output of the calculations of the coefficient of determination (R^2). Again, the CSA of the shoots at base showed the strongest correlation with uprooting resistance in both species.

Interpretation of results:

r = correlation coefficient.

If;

$0.00 < r < 0.30$ → weak linear correlation

$0.30 < r < 0.60$ → moderate linear correlation

$0.60 < r < 0.90$ → strong linear correlation

$0.90 < r < 1.0$ → very strong linear correlation

Morphological characteristic	***Sebastiania schottiana***	***Phyllanthus sellowianus***
Cross-Sectional Area Shoots	**0.92**	**0.91**
Dry Mass Shoots	**0.91**	**0.85**
Sum diameter Shoots	0.82	0.83
Cross-Sectional Area Roots	0.86	0.81
Sum length Shoots	0.89	0.74
Diameter Stem	0.72	0.74
Dry Mass Stem	0.78	0.66
Mean length of Shoots	0.38	0.63
Nr. of Roots	0.62	0.62
Mean diameter of Shoots	0.30	0.57
Nr. of Shoots	0.09	0.18

Table 4: Plant traits correlated to the maximum uprooting resistance by using the Pearson test of correlation. Campus, UFSM – CESNORS, Frederico Wesphalen, 15.10.2012.

2.8 Conclusion

Besides the results concerning uprooting resistance and analysis of the root system, important information on how the species react on dry periods was gained during the study. *Sebastiania schottiana* showed a high mortality rate and weak growth until the first performed test series but a very strong growth in the following spring, resulting in a stronger resistance against uprooting in the second test series. *Phyllanthus sellowianus* manifested itself as a drought-resistant species with a consistent growth rate and a strong plant development. Since the investigated plants have already shown good morpho-physiological attributes, like bending resistance and easy propagation by hard wood cuttings (SUTILI, 2007) in previous studies, both seem to have great potentials to be used in soil bioengineering. Further tests concerning the pull out resistance should be performed in order to investigate the potentials of *Sebastiania schottiana* on moderate site conditions.

Both shoot and root profiles were observed to affect the pull out resistance. The regression analyses showed that the best predictor of pull out resistance is the cross sectional area at the base of the shoots. This value can easily be used as an indicator in field work for estimations concerning uprooting resistance of plant individuals. The analysis of the root system showed that *Phyllanthus sellowianus* has a great morphological diversity with both fine and course roots and shallow as well as deeply penetrating roots. Thus the study suggests that *Phyllanthus sellowianus* has an added value as a plant for slope stabilization work such as in preventing erosion and possesses high resistance towards torrential runoff as it exhibits outstanding root mechanical properties.

3 A Case study: Restoration of an eroded river embankment in Southern Brazil

3.1 Introduction and objectives

One of the main fields of application of biological engineering constructions in running waters is the protection of embankments from the impacting forces of water. Compared to protection by solid banks, the great advantage is, apart from the customarily lower construction costs, an obtainment of ecological plus aesthetical enhancement of the river and the surrounding landscape. Immediately after completion, the living components alone are not able to resist the erosive forces of water because young plants, similarly to humans, need time to develop. Therefore, plants must be protected in their early years (2 to 5 years), to enable a sufficient forming of roots and shoots. Prospectively, they are able to firm the embankment by themselves. The principle of biological engineering constructions is based on the combination of dead and living materials and the emerging positive synergistic effects. The dead auxiliaries (stone, wood, etc.) protect the living plants until they have developed strong enough. After several years, a part of the auxiliary material rots and the stabilization of the bank is secured by the plants (GERSTGASSER, 2000). Since persistent surface erosion is the first barrier to succession and restoration of landslides, physical efforts to reshape a slope are often necessary before ecological restoration can begin (SHIELS, WALKER, 2008).

This case study presents an intervention applied in the end of the year 2010, at the river Pardinho in the state of Rio Grande do Sul. The riverbank restoration became necessary because of a combination of hydraulic-induced erosion at the toe of the slope and bank mass failure. Bank mass failure resulted from fluvial erosion at the toe of the bank with a continuous removal of bank material, affecting a change in the bank slope by over deepening the bank and altering its angle. Before the fielding of the plant material could be accomplished, a physical correction of the slope was performed. Additionally to the forces of the running water, surcharge due to the weight of trees on the top of the slope accelerated the erosion process. Surcharge and near-surface moisture are, according to (SIMON, COLLISON, 2002), destabilization effects that can affect slope stability. However, the positive impacts of a close vegetation cover are a reduction of soil moisture content because of canopy interception and evapotranspiration plus the reinforcement by roots. For this reason, a comprehensive vegetation survey in combination with an assessment of the slope stability was one of the main purposes of the work in hand, examining the long term effect and functionality of dense vegetation on slope reinforcement. It is of high interest to analyze the vegetation after a certain period and evaluate the used species because the investigated intervention was one of the first constructions realized in a biological engineering modality in Brazil.

In course of the elaboration of the issue, following research questions were drafted;

- Which of the applied species proved themselves as appropriate for further usage in embankment restoration works?
- Which composition of species is present after a certain time after the installation of the interventions?

-To which extent did spontaneous species spread in the plant stand?

-What is the coverage rate of each species in the different transects of the embankment?

3.2 Study area

The river Pardinho, a tributary to the river Jacuí, is located in the watershed of the river Pardo, in the central region of the state of Rio Grande do Sul. The section where the intervention was realized is situated downstream of a reservoir dam which provides the water supply for the municipality of Santa Cruz do Sul with 119.057 inhabitants (HEUSER, 2013).The Pardo River Basin comprises of areas with a difference in altitude of up to 500 m. Approximately 40% of its total area appertains to the middle portion of the basin, where the municipal seat of Sinimbu is located, with altitudes ranging from 200 m to 500 m. The downstream (lower part) of the Basin, where Santa Cruz do Sulis located, is characterized through flat areas with a slightly undulating relief (COMMITÊ PARDO, 2011).

Conforming with the classification of “Köppen” (MORENO, 1961), the local climate is subtropical of the Cfa 2 type, with humid climatical conditions, hot summers and rainfall during all seasons. However, in months of high temperatures, hydrological deficits can occur and during the rainy season the area is sometimes prone to extremely flashy flow conditions.

Figure 32: (A) The course of the river Pardinho from its origin in the upland down to its estuary into the river Pardo. (B) The location where the intervention was realized. Santa Maria/RS, Brazil.

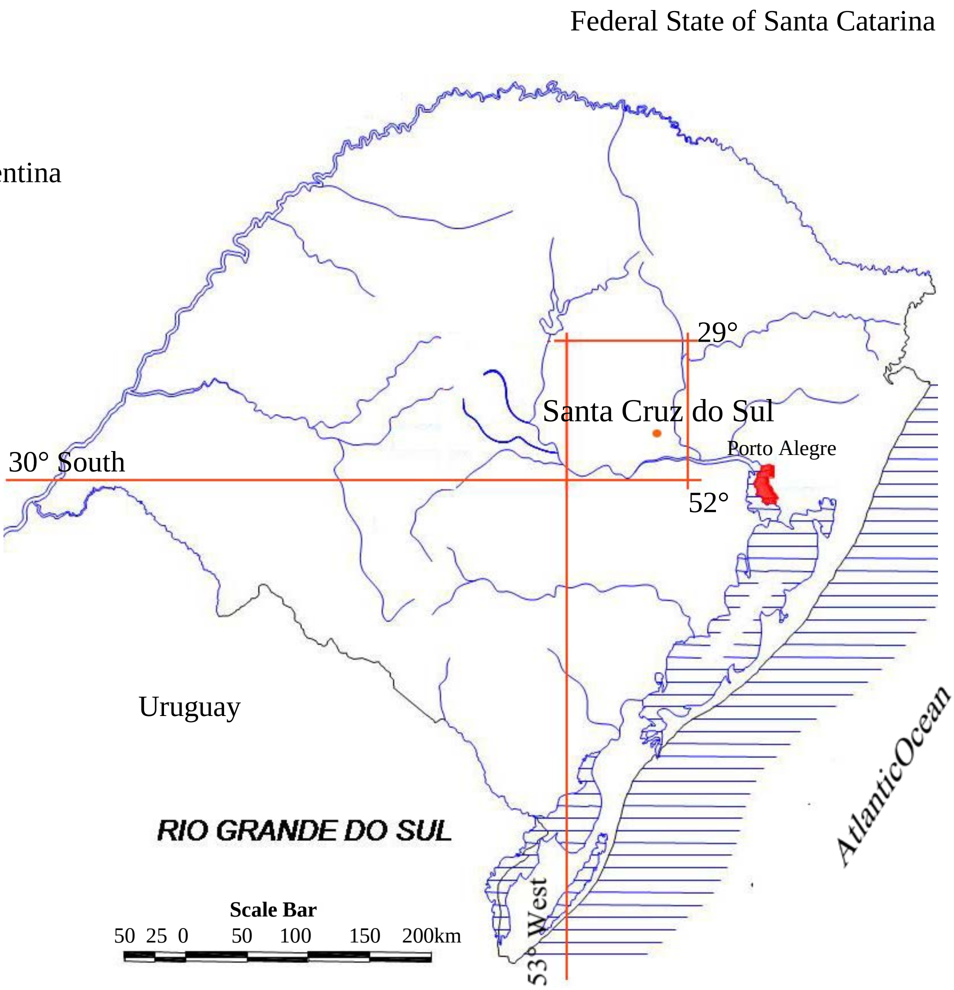

Figure 33:.The state of Rio Grande do Sul and the location of Santa Cruz do Sul, Brazil.

3.3 The causing of the eroding process

The presented work was implemented at an actively eroding bank section at the left side of the river with more than 80 m in length. The instability of the bank resulted from a continuous process of erosion, landslide, collapse and removal of material due to the action of the watercourse. The latter has shifted its axes outwards on this slightly curving river section. The instability of the embankment was exacerbated by the steep angle of the embankment, preventing the vegetation from spontaneous establishment. Additionally, the vegetation that occupied the top of the margin (trees of *Enterolobium contortisiliquum*) did not have any stabilization effect on the site. Quite the reverse, this vegetation formed an overhead in the vertical axes, shifting its center of gravity in a less stable position. It captures and transmits wind power to the slope, creating a lever that certainly amplifies the dynamics of landslides, triggered by the current of the stream (DURLO, SUTILI, 2012).

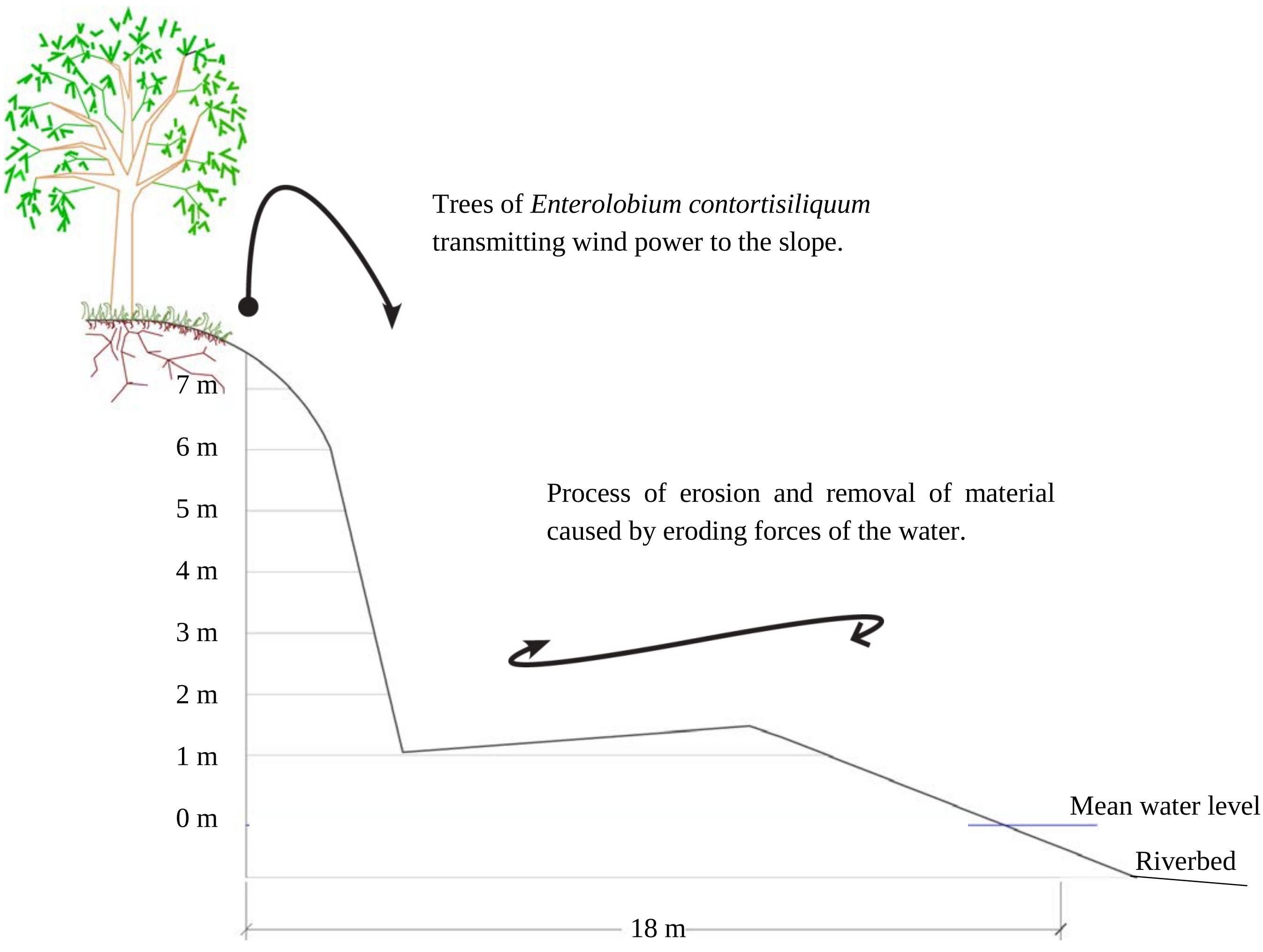

Figure 34: Sectional view, illustrating the eroding process. Rio Pardinho, 08.2010.

The following pictures show the initial situation in the embankment and a similar condition, found in the year 2013 downstream of the intervention. The downstream erosive section is not part of the present study but can be shown as a reference section.

Figure 35: (A) Embankment before implementation of reinforcement works (SUTILI, 2010). (B, C) Erosive process, downstream of the intervention, observed in the year 2013. (D) Intervention and the eroding embankment downstream, in the year 2013, at the rio Pardinho. Santa Cruz do Sul (A) 08.2010 (B,C,D) 01.2013.

3.4 Execution of interventions

3.4.1 Some of the species used

3.4.1.1 Callandria brevipes Benth.

Family: Fabacae –Mimosoidae, Leguminosae

Popular names: Esponjinha, Angiquinho

Figure 36: Shrub of *Calliandra brevipes.*

Botanic description

Calliandra brevipes is an arborescent, evergreen shrub (PENTEADO-DIASE, CAVALHO,2008), strongly ramified and reaching 1-2 m in height. It has fine, green colored, split leaves, red powder-filled flowers and small fruits with tiny seeds (SAMPAIO et al. 2005).

Site requirements, Distribution and Usage

Figure 37: Intense pink flowering and its ecological value.

It is native to South America but has been introduced into many subtropical and tropical places around the world (LORENZI, SOUZA, 1995). According to MARCHIORI (2007), it is a reophil species, the natural habitat is humid, e.g. on riverbanks, and it is capable of supporting the force of floodwaters and temporary submersion. Although it produces very hard wood, it is hardly used due to its small size of stem. As it is a very ornamental plant, strongly ramified and forming a dense canopy, it is often used for hedges and. The dense, beautiful, green colored foliage acquires gorgeous appearance during its intense pink flowering. It is propagated by cutting of twigs or by seed.

3.4.1.2 Schinus terebentifolia Raddi

Family: Anacardiaceae

Popular names: aroeira-mansa, aroeira-vermelha, aroeira-do-sertão

Figure 38: Small tree of *Schinus terbentifolia.*

Botanic description

Schinus terebentifolia can be characterized as an evergreen, small tree reaching a height of 5 to 10 m. The trunk is up to 60 cm in diameter and coated with a thick bark. Its leaves are unevenly pinnate, usually with seven leaflets, strongly aromatic and measure 3 to 7 cm in length and 2 to 3 cm in width. The flowers are small and whitish in color (LORENZI, 2008).

Figure 39: Ornamental, fruit bearing branch of *Schinus terbentifolia.*

Site requirements, Distribution and Usage

It is a heliophile, pioneering species, common in river banks, secondary floodplain forests and on dry, nutrient poor terrains. Its natural distribution encompasses from Pernambuco down to Mato Grosso do Sul and Rio Grande do Sul in various types of plant formations. The wood is moderately heavy, soft, very durable and long lasting. It is a very ornamental tree, especially while it is bearing fruits (LORENZI, 2008).

3.4.1.3 Schinus molle L.

Figure 40: Habitus of a young tree of *Schinus molle.*

Family: Anacardiaceae

Popular names: Brazilian peppertree, Peruvian peppertree, California peppertree, aroeira, aroeira salsa, escobilla, Mastic-tree, American pepper, aguaribay, anacahuita, castilla, false pepper, gualeguay, Jesuit's balsam, molle del Peru, mulli, pepper tree, pimentero, pimientillo, pirul (TAYLOR, 2002).

Botanic description

Schinus molle is a long-lived and drought-tolerant, evergreen, deciduous tree which produces flowers and fruits the whole year (HUGHES et al. 2010). It grows up to 8 m in height, with a trunk of up to 35 cm in diameter. The trunk is coated with a scaly rhytidome. Its linear-lanceolate to linear leaves are pinnate, without stipules, pendulous, glabrous, subcoriaceous, with serrate margins and measure 3 to 8 cm in length. The wood is hard, inelastic and of excellent durability (LORENZI, 2008).

Site requirements, Distribution and Usage

The distribution encompasses from Minas Gerais to Rio Grande do Sul, being most common in the three southern states Santa Catarina, Paraná and Rio Grande do Sul as well as more elevated locations. It is heliophile, tolerates half-shade, mostly occurs in dry soils and adapts easily to infertile and stony land (LORENZI, 2008). According to HUGHES et al. (2010) and VAN DRIESCHE et al. (2002), it is one of the main invasive species in South Africa and Florida with partly severe impacts on the local ecosystems.

3.4.1.4 *Enterolobium contortisiliquum (Vell.) Morong*

Family: Leguminosae, Subfamily, Mimosicae

There is a great variety of **popular names**. To list some of them; Brown Ear tree, tamboril, tambauvá branca, araribá, cambanambi, pau de sabão, timbó, orelha de macaco.

Figure 41: Tree of Enterolobium contortisiliquum.

Botanic description

It is a tree species, ranging between 20 and 30 m in height, with a trunk of 80 to 160 cm in diameter (SANTOS, SILVA, 2009), with a big deciduous tree crown and rugged surface rooting (MARCHIORI, 2007). The outer bark is grayish-brown, smooth on young individuals but fissures with age. The leaves are alternate and bipinate with 3 to 7 pairs of opposite pinnae and glabrous petioles (LORENZI, 2008).

Ecology, Distribution and Usage:

Figure 42: Habitus of a young tree of Enterolobium contortisiliquum.

It spreads widely in South America, with its spreading area reaching from Pará to Maranhão, Piauí, Mato Grosso do Sul and Rio Grande do Sul in Brazil (Silva et al 2009) and extending further to Uruguay and Argentina (LORENZI, 2008). It is heliophil and an initial invader in secondary forests. It is most abundant in seasonal forests. Due to its rapid initial growth, it is applicable for reforestation in mixed plantations in terms of permanent preservation of degraded areas. The wood is light, soft and used in the manufacture of boats, toys and furniture. Its fruits contain saponin (LORENZI, 2008).

3.4.1.5 *Salix humboldtiana Willd.*

Family: Salicaceae

Popular names: salgueiro, salseiro, oeirana (Brazil), sarandi, yvyrapuku (Paraguay), sauce criollo (Argentina), sausechilleno ,saucaamargo (Chile), sauce llóron (Central America), sauz, mixicaxtac (Mexico), sauce colorado, mimbre (Columbia), sauce real (Bolivia).

Figure 43: Tree of *Salix humboldtiana.*

Botanic description:

Salix humboldtiana can be described as a medium size tree, reaching 15 to 25 m in height, with a trunk of up to 80 cm in diameter and branching in the upper 70% of the plant. Its conical crown is triangularly stretched and the trunk is straight with pendant branches. The bark is hard, thick, deeply fissured and brown-gray. Its leaves are simple, linear-lanceolate, glabrous, with a prominent midrib, have serrate margins, reach from 6 to 15 cm in length and measure 1.5 cm in width. Its color varies throughout the growing season: bright green in early spring, dark green in summer and yellow in autumn, before losing the foliage. The terminal inflorescences grow in 4 to 10 cm long catkins and the fruit is formed as ovoid capsules (SALAZAR-FIGUEROA, 1999).

Figure 44: Simple, linear-lanceolate leaves of *Salix humboldtiana.*

Ecology, Distribution and Usage

Distribution encompasses from 23° North in Mexico to 45° South in Argentina. The altitudinal distribution ranges from 10 up to 3300 m a.s.l in the Andes, in areas with an annual precipitations of between 800 and 3300 mm, a maximum dry period of 2 months and annual average temperatures between 16 and 28 C°. It is a pioneer species heliophile, selectively hygrophytic and common in secondary forests. Common habitats are in valleys, lowland floodplains, estuaries and along rivers. It is typically encountered in isolation or associated with other typical riparian shrubs and prefers humid, sandy soils. Propagation by cutting is easy (SALAZAR-FIGUEROA, 1999). The peculiarity of the species is its ability to survive in flooded areas throughout several months if the water is running. It is applicable in erosion control and can be used for reforestation on river banks, dams or reservoirs (MOURA, 2002).

Figure 45: *Salix humboldtiana*, planted along a river channel.

3.4.2 Gathering information for the intervention

For the dimensioning of the planned interventions it was necessary to collect some topographical information about the site. For the georeferencing, UTM coordinates were taken at a local point - E358480m, N6716320m / SIRGAS 2000. Additionally, the local distribution of potentially useful species was investigated. In Table 5, the species found on site are listed.

Botanical name	Popular Name (Brazil)
Enterolobium contortisiliquum	Timbaúva
Phyllanthus sellowianus	Sarandi-branco
Pouteria salicifolia	Sarandi-mata-olho
Terminalia australis	Satandi-amarelo
Salix humboldtiana	Salso
Schinus molle	Aroeira - salso
Schinus terebentifolia	Aroeira - mansa

Table 5: Native species, found along the embankment of the river Pardinho, Santa Cruz do Sul (SUTILI, 2010).

3.4.3 Execution of the interventions in detail

The intervention onsite was composed of two complementary and inseparable parts; the physical actions and the implementation of vegetation. The physical constructions and first vegetative interventions were realized from January to February 2010. As predicted, in the end of October 2010 (spring), a second vegetative intervention was performed which aimed to increase the vegetative cover in the middle and upper section of the embankment. The intervention was executed in the following sequence: Firstly, the vegetated riprap was realized by using basalt blocks, combined with planting of seedlings of *Calliandra brevipes* and hardwood cuttings of *Salix humboldtiana*. Above, hedge brush layers of the species *Terminalia australis, Schinus molle, Schinus terebentifolia* and *Pouteria salicifolia* were installed. In the upper portion, trees of *Salix humboldtiana* were anchored to the slope, using wooden poles and steel wires. Even further up, in the same way, trees of *Enterolobium contortisiliquum* were anchored to the slope but without expectation of sprouting. As a final measure, the top angle of the slope was corrected and seedlings and hardwood cuttings of *Phyllanthus sellowianus* were fielded on its middle portion and. In the following section of the work in hand, the installed interventions will be described in detail.

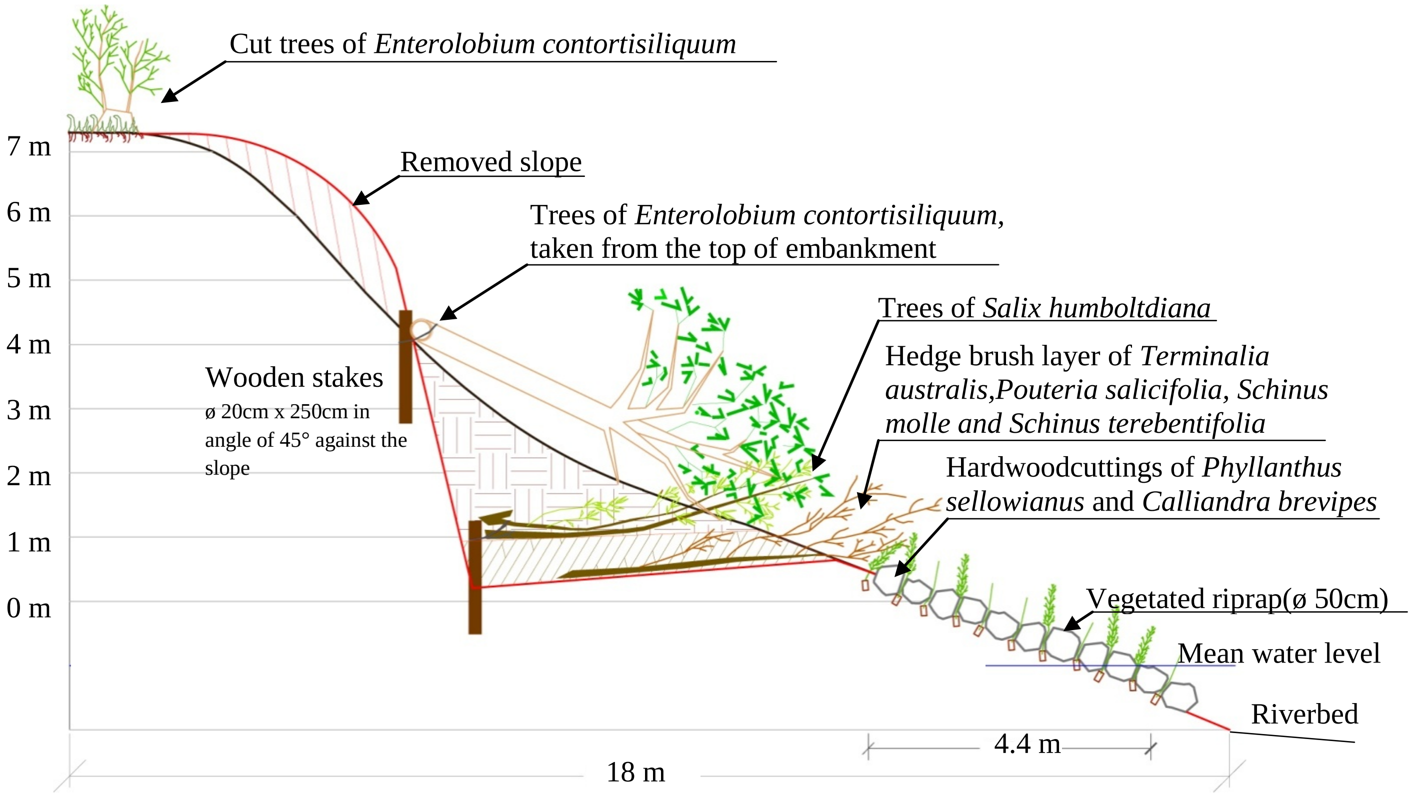

Figure 46: Sectional view, illustrating the first interventions. Rio Pardinho 05.2010.Traced by an original of (SUTILI, 2010).

3.4.3.1 Vegetated riprap

As a first step, the lower portion of the slope was made accessible. With the aid of a backhoe crawler, a ramp was built with a width of 5 to 6 m, which enabled the arrival of the machines and materials to the lower portion of the slope. Since the steep slope was one of the key factors for the extensive erosions, the first action taken was a reduction of the slope angel to 20 -25° at the base of the embankment. Starting slightly beneath the medium water level, riprap with an extension of 1.7 to 2 m in height and 5 to 6 m in wide was raised. Approximately 140m ³ of basalt blocks with a diameter of 20 to 85 cm were used to cover an area of 450 m².

Figure 47: (A, B) Installation of riprap. Rio Pardinho, 04.2010. Picture, SUTILI.

Above the mean water level, the riprap was planted with seedlings and hardwood cuttings of *Calliandra brevipes* and *Salix humboldtiana*. About 900 seedlings of *Calliandra brevipes*, with a stem diameter at base of 3 – 4 cm and around 1 m in height were used. The seedlings were planted through seeds and were reared in plastic bags of 15 x 18 cm for about one year before being fielded. Approximately 500 seedlings of *Salix humboldtiana* were taken by hardwood cuttings and were reared in the same bags as *Calliandra brevipes*. Subsequently they were sliced in half in order to obtain bigger amount of life stakes. Those plants had a diameter of between 2 and 4 cm and a height of 1 to 2 m.

Figure 48: (A) Seedlings of *Calliandra brevipes.* (B) Seedlings of *Salix humboldtiana.* Rio Pardinho, 04.2010. Picture, SUTILI.

Figure 49: (A) Bisected seedlings of Salix *humboldtiana.* (B) And the same being planted with the bigger side up Rio Pardinho, 04.2010. Picture, SUTILI.

Figure 50: (A) Fielding the seedlings using a hand shovel. (B) Seedlings planted along the water line. Rio Pardinho, 04.2010. Picture, SUTILI.

As soon as the riprap was installed, the planting was done by using hand shovels and digging sticks. To facilitate planting, blocks were removed and replaced in order to fix and protect the seedlings. The hardwood cuttings were planted in a manner to facilitate their alignment with the streaming line. In each square meter of the riprap three to four seedlings were fielded. Whenever necessary, the plants were irrigated by using buckets or a water bowser.

3.4.3.2 Hedge brush layer

Above the vegetated riprap and along the whole construction, a hedge brush layer of *Pouteria salicifolia*, *Schinus molle, Schinus terebentifolia* and *Terminalia australis* with 5 m in width, was installed. Subsequently, the shrubs were covered with a soil layer, with the expectation of vegetative propagation.

Figure 51: Installation of the hedge brush layer above the vegetated riprap. (B) After the shrubs are mounted, they are covered with a soil layer. Rio Pardinho, 04.2010. Picture, SUTILI.

3.4.3.3 Anchored willows

Above the hedge brush layer another section, applying solely *Salix humboldtiana*, was installed. To that end, 22 wooden poles (Eucalyptus), with a length of 2.5 m and 17 cm in diameter were buried with the aid of an excavator. The poles were installed along the slope in a depth of 1.5 m and an angle of 45° towards the soil. After that, they were interconnected with a steel wire of 11 mm in diameter. The willows were collected at the embankment along the river Pardinho itself. Conforming to the law “Licença Ambiental n° 16/2010” of the municipal of Santa Cruz do Sul, only unstable or fallen trees were collected and utilized for the construction.

Figure 52: (A) Interconnecting willows with steel wire. (B) Mounting of a soil layer due to expectation of propagation. Rio Pardinho, 05.2010. Picture, SUTILI.

Figure 53: (A) Wooden poles (Eucalyptus). (B) The same stakes being buried 1.5 m deep and at an angle of 45° towards the slope. Rio Pardinho, 05.2010. Picture, SUTILI.

3.4.3.4 Anchoring trees of Enterolobium contortisiliquum

In the section above the willows, trees of the species *Enterolobium contortisiliquum* (timbaúva) that were taken off the top of the embankment were installed as a soil cover. To affix them in the embankment, the trees were anchored with wooden poles and aligned with the streaming line. Thus, no vegetative propagation could be expected and no further soil layer was mounted. The installation rather aimed at providing protection for the embankment by decreasing the water force and enabling sediment deposition. However, one hundred seedlings of the shoot developing plant *Calliandra brevipes* and one hundred shoots of *Phyllanthus sellowianus* were fielded on site with the expectation of their vegetative propagation.

Figure 54: (A) Cutting trees of Enterolobium contortisiliquum. (B) Anchoring them to the slope.Rio Pardinho, 05.2010. Picture, SUTILI.

3.4.3.5 Correction of the slope angle

After the installations in the embankment had been completed, the bevelling of the top was executed by reducing the top level along the entire length with the help of an excavator.

Figure 55: Anchored trees of Enterolobium contortisiliquum. (B) Shaping the slope angle.Rio Pardinho, 05.2010. Picture, SUTILI.

Figure 56: The embankment shortly after the implementation of the structures. Rio Pardinho, 05.2010. Picture, SUTILI.

3.5 Meteorological conditions and first development of installations

During the construction works, the precipitation remained within the expected monthly average for the region. However, uncommon heavy rainfalls occurred in the month of July and September. Again and again during the winter period, the water exceeded the vegetated riprap and reached the middle portion of the slope. It can be assumed that a heavy rainfall event in September, with precipitation reaching 102 mm in 4 days (according to the data of UNISC – Universidade de Santa Cruz do Sul) caused the anchored trees of *Enterolobium contortisiliquum* to be swept away. At that point, the water exceeded the top of the slope, flooding the work completely. The vegetative installations and the vegetated riprap did not suffer any, or only minor damage and resisted the flooding period well. The few damages that occurred show that despite a certain risk, implementations of vegetative interventions in the beginning of the winter can be successful and guarantee a protection of the embankment, if they are designed to resist the flooding period. At the base of the embankment and in between the hedge brush layer, an increased roughness was caused by intense sediment deposition. This affirmed an enhanced stability of the slope caused by the reduction of the water velocity and tension on the site of erosion. The budding of the seedlings and hardwood cuttings, which had been fielded in April, 2010, started in late August in the same year. In spite of intensive ant attacks, all species which were reduced to the stem sprouted after the ants were exterminated using ant baits.

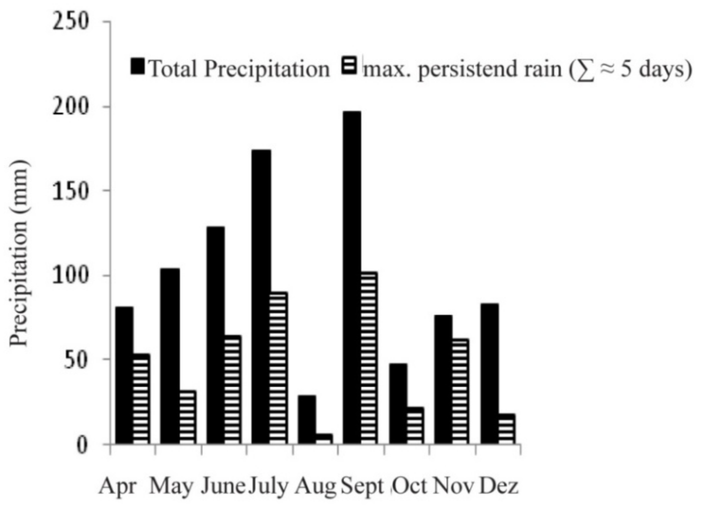

Figure 57: Precipitation during construction works. Rio Pardinho, 2010 (HERPICH, 2011).

3.6 Second vegetative intervention

After the heavy rain falls, a second vegetative intervention was important to ensure the physical integrity of the margin. Its purpose was to support the vegetated riprap, the hedge brush layer and the anchored willows. Particularly as the anchored trees of *Enterolobium contortisiliquum* had been removed, a swift action became necessary. Aiming at an enhancement of the biodiversity on site, a wide range of species was used. The plant material consisted of 1550 seedlings of 32 native species. Fielding was done in the second half of October. In Figure 58, a sectional view of the embankment, after the intervention was performed, is shown.

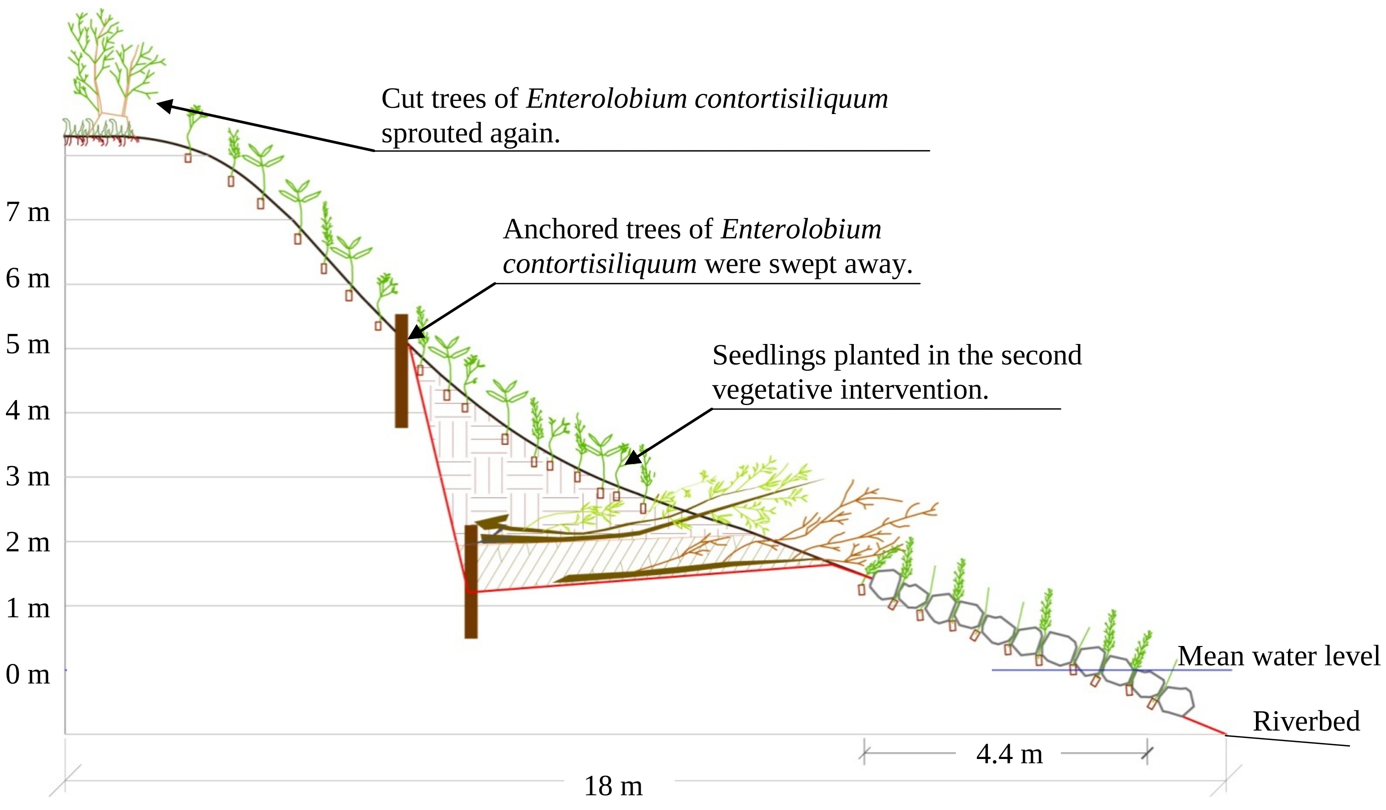

Figure 58: Sectional view of the embankment after the second vegetative intervention. Rio Pardinho, 09.2010.Traced by (SUTILI, 2010).

3.7 Methodology of vegetation survey and evaluation of construction

In the end of November 2010, a vegetation survey was carried out in order to analyze the growth pattern of the plant stand. Therefore, 10 stripe-shaped parcels where staked out along the river bank. Each parcel presented an area of 2 m in width and 15 m in length, extending from the waterline to the highest point of the slope. The data were collected in order to determine the variation of the plant stand along the whole construction. By dividing the parcels into sub-sampled portions of 1 m x 2 m, it was possible to recognize the variation along each parcel (Figure 59). In this way, it was facilitated to interpret the data according to their variation along the gradient of the slope and individualize their analysis in accordance to the construction. Additionally to the classification of the plant individuals, the stem diameter at base and the plant height were measured. At the end of January 2013, a second vegetation survey was carried out in order to examine the long term effects of the riverbank restoration and the development of species and their distribution. For this survey, the same methodology as for the first one was used in order to be able to compare the results of each parcel and sub parcel with the previous data. Supplementary, in the second survey the crown diameter and the number of shoots were measured, the coverage rate of species was estimated and a classification of vitality was performed. In the first compilation of data, only 9 parcels could be surveyed because of a swarm of *Apis mellifera scutellata* in the field. However, the collected data represented 20% of the area and were sufficient in containing all species which were fielded in course of the bank restoration. Thus, 9 parcels were observed in the second performed survey as well in order to get the same amount of data.

Figure 59: (A, B) Materialization of the strips and sub parcels-plots in field. Rio Pardinho, 11.2010. Picture, SUTILI.

3.7.1 Coverage and vitality

During the course of the second vegetation survey, the coverage rate of the plant stand was estimated and the vitality of the plant individuals was gathered. For this purpose, the method of Braun - Blanquet, which is based on estimations, was applied. The species composition, layering and the coverage ratio can be determined by using this method. In order to apply the method on site, the slope was divided into three sections. The chosen transects were inside of the performed construction, to achieve homogenous areas. In this way it was possible to compare the implemented measures and analyze the development of each one. Based on the theory, the area of each transect should not be smaller than 100 m² or bigger than 500 m². Finally, the defined transects had a size of 148 m² at the lower portion (vegetated riprap), 222 m² at the middle portion (hedge brush layer, anchored willows) and 148 m² at the upper portion (planted in the second vegetative intervention). The highest grown species (*Salix humboldtiana*) reached only 2.16 m on average, and in general the plant stand did not show significantly different layering. For that reason, no classification of layering was made. The coverage rate of each species was ascertained in proportion to the area of the previously determined transects. Single individuals were noted separately. Additionally, the vitality of each plant individual was estimated by the following classification:

1. **Exceedingly strong developed;** leaves lush green in color, high leaf mass, strong shoots development and growth in length.

2. **Well developed;** leaves lush green in color, little less leaf mass, weaker shoots development and growth in length.

3. **Poorly developed;** leaves yellow-green in color, little leaf mass, very weak shoots development and growth in length.

4. Plant already **dead or dying.**

3.7.2 Evaluation of the constructions

The implemented constructions were evaluated in terms of their effectiveness on stabilization of the embankment plus their impact on containing the eroding process. Additionally, their condition and durability were assessed by defining two classification classes, as described further on.

Effectiveness classes

Valuation number 1 – good:
The ascribed effect to the respective construction is highly achieved and is clearly visible.

Valuation number 2 – sufficient:
The ascribed effect to the respective construction is largely achieved and is clearly visible, but not quite as remarkable as in the rating "good".

Valuation number 3 – still sufficient but obvious deficiencies:
The ascribed effect to the respective construction is barely achieved but still visible.

Valuation number 4 – insufficient:
The ascribed effect to the respective construction is not achieved.

Status classes

Valuation number 1 – good:
Both the supporting, technical structure (inert materials) as well as the used plant material are in an apparently good state. There is no visible external damage indicating an imminent failure of the structure and the used plants are well established.

Valuation number 2 – slight damage of construction or little dominance of invasive vegetation:

Slight damage in the technical structure (inert materials), or on the plants used, is observable. It is most probable that the living material will be able to compensate for the harmful effect by its growth and mechanical skills and it will not result in failure of the structure. The used plant material is well established and little or no invasive vegetation is present.

Valuation number 3 – severe damage of construction or strong dominance of invasive vegetation:

Both, the technical structure (inert materials) as well as the used plants show external damage or are largely suppressed by invasive plants which became predominant. In the case that the invasive species can not compensate the stability of the used vegetation it can be assumed that an utter failure is imminent

Valuation number 4 – destructed:

The structure is only rudimentarily observable or not existing anymore and is to be classified as ineffective.

3.8 Results and discussion

The following chapter aims at a presentation of the measures taken in respect to their long term functionality, the development of the used plant material as well as the development of the plant stand. It attempts to work out species which have proven to be appropriate for future restoration works.

3.8.1 Presentation of results achieved in the vegetation surveys performed in 2010 and 2013

The following Table is listing the species, which had been fielded in the construction and surveyed in 2010 and 2013. Species which had established particularly well are highlighted green.

Family	Species	Popular Name	Speci-mens fielded	Field. (%)	Speci-mens 2010	2010 (%)	Speci-mens 2013	2013 (%)
Anacardiaceae	Schinus molle	Aroeira-salsa	3	1,1	3	0,59	3	0,9
	Schinus terebenthifolia	Aroeira-vermelha	8	2,9	15	2,95	7	2,2
Anonaceae	Annona cacans	Annona cacans	2	0,7	2	0,39	-	-
Boraginaceae	Cordia ecalyculata	Guaçatumba	1	0,4	1	0,2	-	-
Combretaceae	Terminalia australis	Amarilho	-	-	1	0,2	5	1,6
Erythroxylaceae	Erythroxylum argentinum	Cocão	4	1,5	4	0,79	2	0,6
Fabaceae	Ateleia glazioveana	Timbó	30	11	30	5,89	22	6,9
	Bauhinia forficata	Pata-de-vaca	22	8,1	22	4,32	13	4,1
	Calliandra brevipes	Caliandra-rosa	48	17,6	147	28,88	156	49
	Inga marginata	Ingá-feijão	11	4	11	2,16	13	4
	Inga sessilis	Ingá-macaco	4	1,5	4	0,79	-	-
	Machaerium paraguariense	Farinha-seca	17	8,2	18	3,54	-	-
	Parapiptadenia rigida	Angico vermelho	4	1	4	0,79	1	0,3
Lauraceae	Aiouea saligna	Canela-sebo	2	0,7	2	0,39	-	-
Lythraceae	Lafoensia pacari	Dedaleiro	3	1,1	3	0,59	-	-
Melastomataceae	Tibouchina mutabilis	Manacá	2	1,1	3	0,59	-	-
Meliaceae	Trichilia claussenii	Catiguá-vermelho	4	1,5	4	0,79	-	-
	Trichilia elegans	Catiguá-vermelho	2	0,7	2	0,39	-	-
Moraceae	Morus nigra	Amoreira	-	-	6	1,18	4	1,3
Myrtaceae	Acca sellowiana	Goiaba-serrana	11	4	11	2,16	2	0,6
	Calyptranthes sp.	Guamirim	-	-	1	0,2	1	0,3
	Eugenia involucrata	Cerejeira	5	1,8	5	0,98	-	-
	Eugenia myrcianthes	Pessego-do-mato	14	5,1	14	2,75	-	-
	Eugenia rostrifolia	Batinga	3	1,1	3	0,59	-	-
	Eugenia uniflora	Pitangueira	4	1,5	4	0,79	1	0,3
	Psidium cattleyanum	Aracá	7	2,6	7	1,38	4	1,3
	Myrcianthes pungens	Guabiju	8	2,9	8	1,57	-	-
Phyllantaceae	Phyllanthus sellowianus	Sarandi-branco	4	1,5	15	2,95	20	6,3
Salicaceae	Salix humboldtiana	Salso	12	4,4	123	24,17	24	7,4
	Banara parviflora	Olho-de-pomba	3	1	3	0,59	-	-
Sapindaceae	Allophylus edulis	Chal-chal	12	4,4	12	2,23	3	0,9
	Cupania vernalis	Camboatá-Vermelho	13	4,8	12	2,55	5	1,6
	Matayba elaeagnoides	Camboatá-branco	3	1,1	3	0,59	-	-
Tiliaceae	Luehea divaricata	Açoita-cavalo	5	1,8	5	0,98	7	2,2

Table 6: Family, species, popular name, number of specimens fielded, % of specimens fielded, number of specimens surveyed in 2010, % of specimens surveyed in 2010, number of specimens surveyed in 2013 and % of specimens surveyed in 2013. Species which developed particularly well are highlighted green. Rio Pardinho, 11.2010 and 01.2013

Species which emerged between the first and second plant survey are listed in the Table below.

Family	Species	Popular Name	Speci-mens 2013	2013 (%)
Aquifoliaceae	Ilex paraguariensis	Erva Mate	1	0,3
Asteraceae	Baccharis dracunculifolia	Vassoura	9	2,8
Fabaceae	Enterolobium contor-tisiliquum	Timbaúva	2	0,6
	Lonchocarpus Muehlbergianus	Rabo-de-bugio	4	1,3
Bromeliaceae	Bromelia balansae	Caraguatá	1	0,3
Lauraceae	Nectandra megapotamica	Canela-preta	1	0,3
Rosaceae	Prunus myrtifolia	Pessegueiro-do-mato	8	2,5
Zingiberaceae	Hedychium coronarium	Cardamom	1	0,3

Table 7: Species which emerged between the first and second plant survey. Rio Pardinho 01.2013

3.8.2 Species observed in each section of the construction

Vegetated riprap

In the segment of the vegetated riprap, three kinds of species were observed in the first survey, namely: *Calliandra brevipes* (51% of specimens), *Salix humboldtiana* (43% of specimens) and some plants which had emerged from the cuttings of *Phyllanthus sellowianus* (6% of specimens). These species constituted an average density of 2.6 plants per square meter. Compared to an initial density of 3.5 plants per square meter planted during the first intervention, 28% of seedlings had been lost in the first 8 months. These losses had occurred mainly in the segment closest to the normal water level, caused by long periods of submersion or by the forces of the running water, sweeping them away.

In the second plant survey the presence of the species was as follows; *Calliandra brevipes* (82% of specimens), *Phyllanthus sellowianus* (10% of specimens), *Salix humboldtiana* (5% of specimens) and *Terminalia australis* (5% of specimens). The density, now being 3.3 plants per square meter, had decreased slightly since the previous plant survey. In the lower part of the riprap, the dominating species were *Calliandra brevipes* and *Phyllanthus sellowianus* with some presence of *Salix humboldtiana*. It can be assumed that these species can best support the forces of the water, especially along the mid water line where *Phyllanthus sellowianus* was growing. Spontaneous vegetation was scarcely observed in this part. Indeed, presence of vines was noted but infrequent. In the upper portion of the riprap, a strong dominance of *Calliandra brevipes* was noticeable. Just a few other individuals had been able to emerge in this section. Namely; *Salix humboldtiana, Terminalia australis* and some spontaneous vegetation, like *Penisetum purpureum, Sida sp.* and *Xanthium strumarium.*

Hedge brush layer and anchored willows

In the first vegetative survey following plants were observed in the sections of the hedge brush layer and anchored willows; sprouting of *Salix humboldtiana* was prevalent, accounting for 59%, and concentrated on the central portion. *Phyllanthus sellowianus* was only found in the first section (due to the planting of some hardwood cuttings at this location). *Terminalia australis*, *Morus nigra* (which sprouted from a single specimen used in the hedge brush mattress) and *Schinus terebentifolia* were only found point wise. There was no sprouting of the hedge brush layer or the anchored willows in the parcels 7, 8 and 9. This uneven distribution of species developed from the way the hedge brush layer had been installed. At each portion of the section a few species had been used predominantly. In the portion of the parcels 7, 8 and 9 mainly the shrubs S*chinus molle, Schinus terebentifolia* and *Pouteria salicifolia,* which did not produce any shoots, had been used.

The vegetation survey in 2013 showed the following situation in this section; *Salix humboldtiana* had diminished to a proportion of 31%, still concentrating more in the central portion. *Phyllanthus sellowianus* was only found in the first parcel and had disappeared in the second one. *Terminalia australis* totally had disappeared. *Morus nigra* and *Schinus terebentifolia* still were observed only point wise. *Calliandra brevipes* had been able to spread in each part of the construction. Spontaneous vegetation had emerged over the whole length of the intervention and was partly dominant. Frequently *Poaceae sp.* was found besides *Penisetum purpureum* and constituted the second most prevalent group of spontaneous vegetation.

3.8.3 Second vegetative intervention

The plants fielded in the second vegetative intervention in October 2010 showed mortality rate of only 2.6% two months after the performed survey. In total, 273 plants were observed in the first survey. This number had decreased to 127 plant individuals in 2013. In the upper portion of the embankment the greatest variety of species was found, although it had diminished distinctly from the first to the second survey. The diameter, as well as the plant height, had increased noticeably in this period of time. The vitality analysis showed that most of the species had developed very well. The amount of spontaneous vegetation was very high in this portion. As can be seen in Figure 60 and from the high coverage rate of 41% (Figure 62), *Penisetum purpureum* was dominant in several parts of the section. In Table 8, the development of vegetation in the upper portion is shown.

Species	Specimens 2010	%	Mean ø at base	Mean height	Speci-mens 2013	%	Mean ø at base	Mean height	Mean vitality 2013
Calliandra brevipes	48	17,7	16,3	0,82	24		19	1,14	1,3
Ateleia glazioveana	30	11	10,6	0,80	19		39	2,3	1
Bauhinia forficata	22	8,1	8,5	0,97	9		23	2,2	1
Machaerium paraguariense	17	6,2	7,4	0,62	-		-	-	-
Eugenia myrcianthes	14	5,1	7,8	0,83	7		10,1	0,93	1,3
Cupania vernalis	13	4,8	8,6	0,72	5		19,6	1,48	1,8
Allophylus edulis	12	4,4	10,6	1,03	3!		12,9	1,2	1,5
Salix humboldtiana	12	4,4	9,2	0,78	2		25,7	2,16	1,8
Acca sellowiana	11	4	6,2	0,55	2		13	0,95	2
Inga marginata	11	4	5,9	0,46	12		16,8	0,96	1,1
Myrcianthes pungens	8	2,9	7,7	0,66	-		-	-	-
Schinus terebenthifolia	8	2,9	8,2	0,74	4		15,7	1,28	1,2
Psidium cattleyanum	7	2,6	8,6	0,62	3		12,8	0,78	1,3
Eugenia involucrata	5	1,8	9,3	0,63	-		-	-	-
Luehea divaricata	5	1,8	10,2	0,83	4		17,3	1,5	1,6
Erythroxylum argentinum	4	1,5	8,5	0,67	1		-	-	-
Eugenia uniflora	4	1,5	10	0,55	1		11,1	0,75	2
Inga sessilis	4	1,5	4,9	0,54	0		8,2	0,74	1,2
Parapiptadenia rigida	4	1,5	10,4	1,01	4		11	1,4	1
Phyllanthus sellowianus	4	1,5	7,5	0,57	-		-	-	-
Trichilia claussenii	4	1,5	5,5	0,32	-		-	-	-
Banara parviflora	3	1,1	7,7	0,58	-		-	-	-
Eugenia rostrifolia	3	1,1	5	0,40	-		-	-	-
Lafoensia pacari	3	1,1	7,2	0,70	-		-	-	-
Matayba elaeagnoides	3	1,1	6	0,45	-		-	-	-
Schinus molle	3	1,1	7,1	0,75	3		23,5	1,7	1
Tibouchina mutabilis	3	1,1	8,6	0,67	-		-	-	-
Aiouea saligna	2	0,7	10,8	0,88	-		-	-	-
Annona cacans	2	0,7	5,5	0,05	-		-	-	-
Trichilia elegans	2	0,7	7,3	0,66	-		-	-	-
Calyptranthes grandifolia	1	0,4	7,3	0,63	1		10	1	1
Cordia ecalyculata	1	0,4	9,7	0,7	-		-	-	-
Terminalia australis	-	-	-	-	1		13,9	1	1,6

Table 8: Illustrating the development of the upper portion from the first to the second vegetation survey. Listing; the observed species, specimens of each species in 2010/2013, the percentage of each species in 2010/2013, the diameter at base of each species in 2010/2013, the mean height of each species in 2010/2013 and the mean vitality class of each species in 2013. Rio Pardinho, 11.2010 and 01.2013.

In Table 9, the species which emerged between the first and the second vegetation survey are shown.

Species	Specimens 2013	Mean ø at base	Mean height	Mean vitality 2013
Baccharis dracunculifolia	8	20,85	152	2,4
Prunus myrthifolia	8	10	81,3	1,3
Lonchocarpus Muehlbergianus	3	13,4	132,5	1,25
Enterolobium contortisiliquum	1	18,6	140	1
Nectandra megapotamica	1	8	50	2
Hedychium coronarium	1	-	-	-

Table 9: Listing the species which emerged between the first and the second vegetation survey. Moreover, the mean diameter at base, the mean height and mean vitality are shown. Rio Pardinho, 01.2013.

In Figure 60, a schematic illustration of the distribution of species in the embankment is shown. Through the segmentation into three sections, depending to the respective installation, the presence of vegetation can be allocated to the different implemented constructions. Additionally, the arrangement of the parcels for the vegetation survey is visualized.

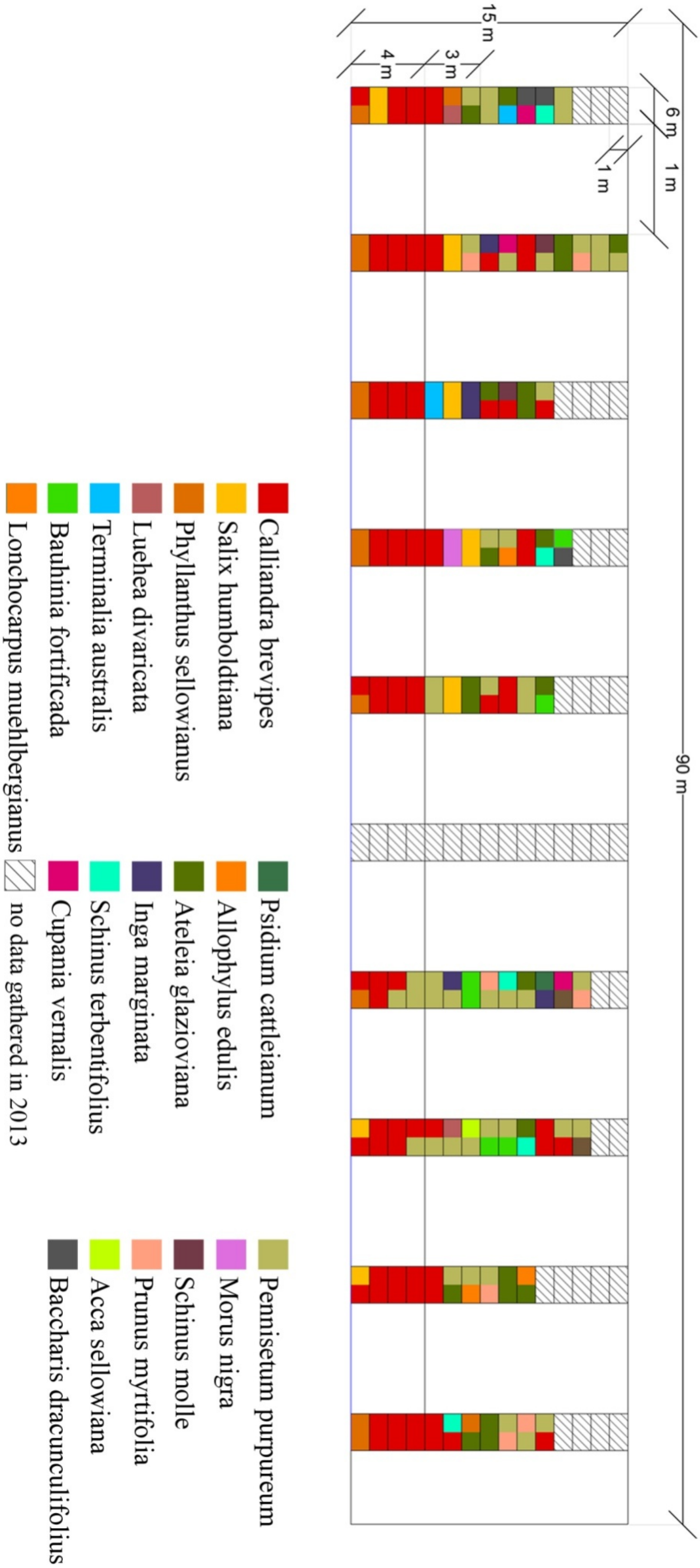

Figure 60: Illustration of the parcels defined for the vegetation survey and the distribution of species in the embankment. Rio Pardinho, 01.2013.

3.8.4 Evaluation of structures

As a whole, the intervention can be assessed as functional and safe. As Figure 61 shows, the effectivenesses of the structures in conjunction with the present vegetation are rated in the classification classes one or two. This means that the embankment is well protected and no imminent failure has to be expected. Analyzing the structures separately showed some infirmities of the intervention. In the portion above the vegetated riprap, the desired development of the constructions was not obtained in some parts. In several spots, the implemented vegetation material did not or just sparsely emerge. In these parts, the spontaneous vegetation took on to protect against erosion. The question arises if the spontaneous vegetation, like *Penisetum purpureum*, with a weaker root system in terms of soil anchorage ability, will provide long term slope reinforcement. Once the established vegetation has reached a certain height, no further pushing back by *Penisetum purpureum* has to be expected. It is, however possible that it will be pushed back again in further succession of the plant stand. This, as well as the long term slope reinforcement effect, should be a task for further surveys on site. In the upper part of the slope it was observed during the second vegetative intervention that many species had diminished or disappeared. Although slope reinforcement was obtained, the high proportion of spontaneous vegetation plus uncovered areas might endanger the stability in the long term. Implemented species which diminished or disappeared completely are not recommendable for further slope reinforcement construction. Since the anchored trees of *Enterolobium contortisiliquum were* swept away shortly after their installation, that intervention was classified with the category “destructed”. In Figure 61, the evaluation of the structures in terms of effectiveness and status is shown.

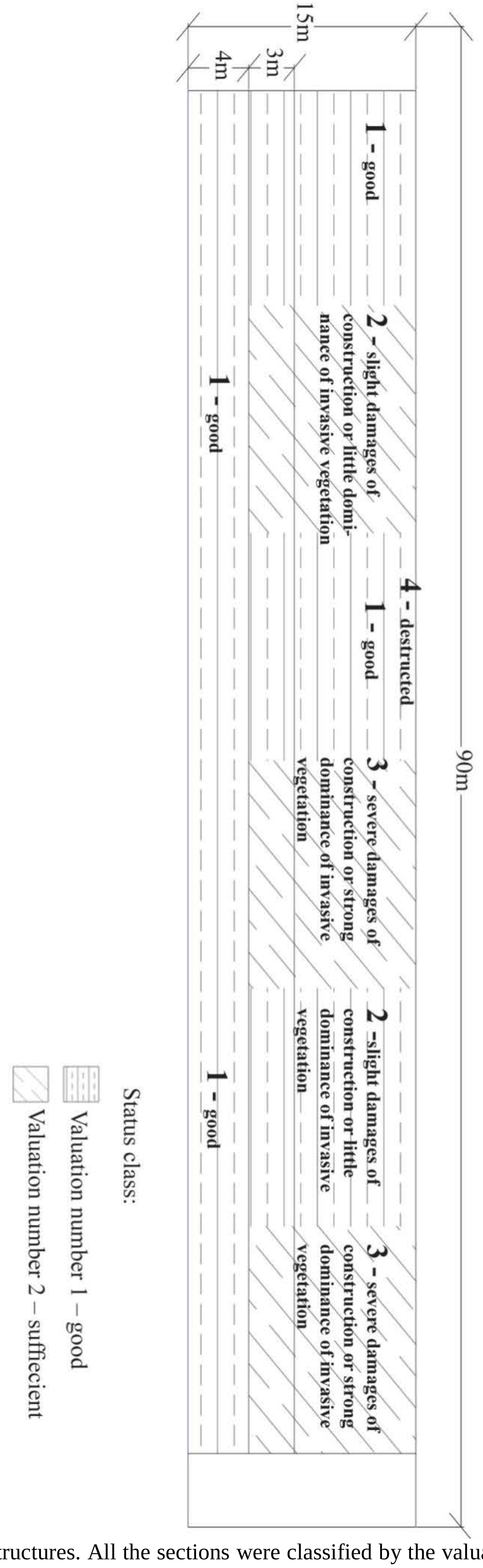

Figure 61: Illustration of the evaluation of structures. All the sections were classified by the valuation number 1 (good) or 2 (sufficient). The classification class for the status of the constructions varied from 1 (good) to 4 (destructed). The intervention using anchored trees of *Enterolobium contortisiliquum* was classified with 4 (destructed) because they were swept away shortly after their installation. Rio Pardinho, 01.2013.

3.8.5 Coverage rate

The results of the coverage analysis provide a clear overview of the distribution and dominance of the species occurring. Additionally, they display the proportion of uncovered areas.

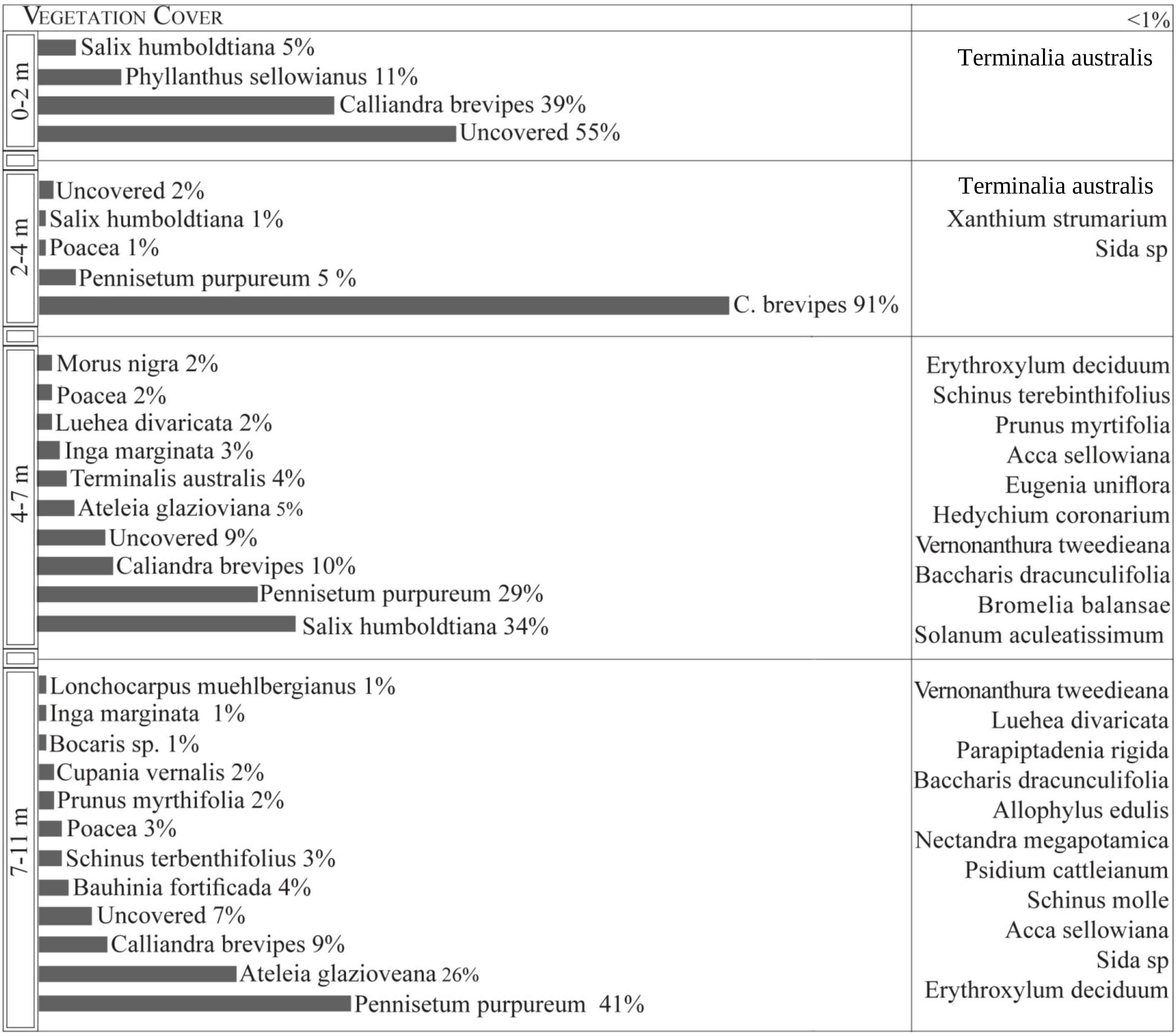

Figure 62: Illustration of the coverage rate of species in the respective section in the embankment.Rio Pardinho, 01.2013.

3.8.6 Graphic illustration of actual state

Figure 63, shows a sectional view of the actual state of the embankment. It displays the course of the restoration works, the corrected slope angel and the actual angle which was formed through the recurrence of erosion processes. Additionally, it gives an overview of the actual plant stand.

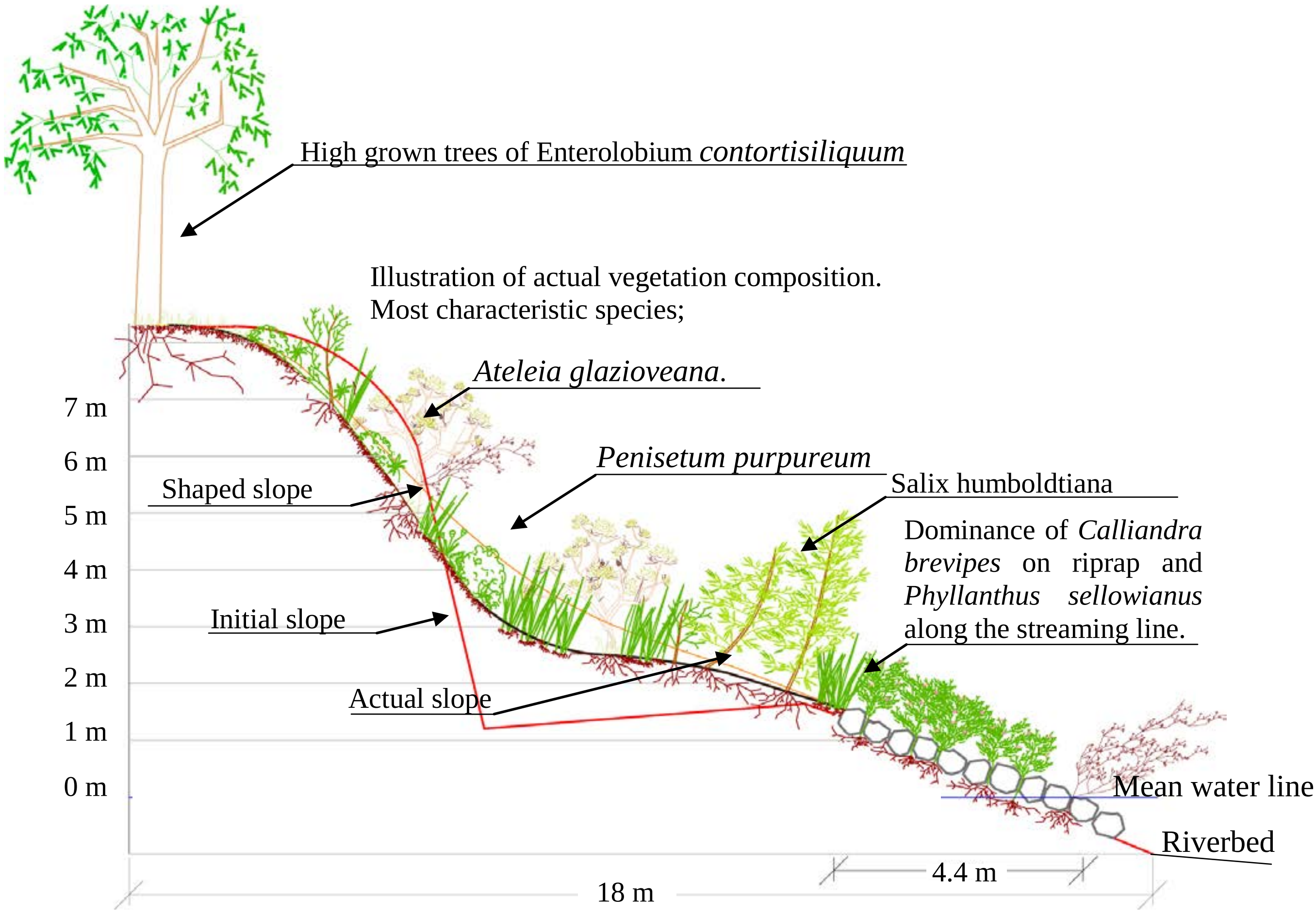

Figure 63: Sectional view of the embankment at the time of the second vegetation survey, in 2013.Rio Pardinho, 01.2013.

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The pictures below are illustrating the situation before the implementation of the reinforcement works and the situation two years after its completion.

Figure 64: (A) Embankment before implementation of reinforcement works (SUTILI, 2010), and (B) two years after its completion – 2013. Rio Pardinho, (A) 03.2010, (B) 01.2013.

3.9 Discussion on the applicability of some species for future restoration works

3.9.1 Calliandra brevipes

The strong dominance of *Calliandra brevipes* shows that it has very good properties to resist the forces of the water and is applicable to locations with extreme growth conditions like ripraps. Through its very dense growth and production of many shoots, its contribution to soil coverage and consequently to erosion protection is very high. But it could also prevail in the upper section of the embankment and is the only species which was present in all portions. Due to its dense growth pattern, no other plants had the chance to develop, which is a major reason for its dominance. It proved to be very appropriate for slope reinforcement interventions, but its dominant characteristics should be considered for further works. As it is both a very ornamental brush and a very robust species, it has great potential to be applied in numerous places such as along inner-city watercourses.

3.9.2 Phyllanthus sellowianus

Phyllanthus sellowianus was the species which established best along the mid waterline. It can be assumed that it is very well applicable along the mid water level as it is compatible with extreme growth conditions, for example temporary submersions. Obviously, it can support the forces of floodwaters and shows very good properties for soil anchorage. It was hardly present above the riprap and it can therefore be assumed that it is a specialist on extreme growth conditions and not very dominating.

3.9.3 Salix humboldtiana

It proved to be very appropriate to be used in embankment restoration works. Like *Phyllanthus sellowianus* and *Calliandra brevipes,* it can be easily propagated by hardwood cutting and showed a good growth on extreme site conditions. It was, along with *Phyllanthus sellowianus,* the only species which established along the mid water level. In the upper portion, where *Salix humboldtiana* could prevail and form shoots, high, vital brushes developed, making a major contribution to slope reinforcement. However, in view of its large application along the whole construction but only partial occurrence, the assertiveness against other species seems to be relatively low. This fact should be considered in further applications of hedge brush layers using *Salix humboldtiana*.

3.9.4 Ateleia glazioveana

In the upper portion of the embankment, *Ateleia glazioveana* was the species which established best. Reaching an average height of 2.19 m and a mean diameter of 39 cm, it developed to be the strongest grown species in the plant stand. In this stage, the plant continues to contribute to the protection of the slope because it is still flexible. However, maintenance works are necessary to prevent an overly strong growth of that species. If maintenance works are neglected, *Ateleia glazioveana* will become a high grown tree and put shade pressure onto other plant individuals. Also it can cause slope instabilities by its own weight.

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5 Register of illustrations

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