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US Army Corps of Engineers®
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Flood and Coastal Storm Damage Reduction

Improved Levee Resilience Through Soil Application of a Natural Organic Polymer

Field Study: Kaufman Levee No. 1

Steven L. Larson, Maureen K. Corcoran, David B. Gent, Afrachanna D. Butler, and Catherine C. Nestler

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Final Report

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Abstract

The Kaufman Levee No. 1 rehabilitation project is under the jurisdiction of the U.S. Army Corps of Engineers (USACE) Fort Worth District. Three areas along the levee, from river mile 445 to river mile 452, were damaged and experienced slope failure as the result of high energy flows in September 2009 and January 2010. In order to provide protection, set-back levees were designed, constructed, and vegetated in 2015. Methods currently used to maintain levees (geotextiles, mulch, riprap, and vegetation) are based on reducing transport of suspended solids from the slope and preventing erosion. Biopolymer was first evaluated at pilot scale for enhanced establishment of grass sod. It was established that determination of the root-adhering soil is an accurate prediction of field success in enhancing the root:soil integration essential to reducing soil erosion on slopes. The field study evaluated the revegetation of a levee with Bermuda grass in soil amended with organic polymer. A digital photographic image analysis technique was successfully deployed to reduce manpower and monitoring field costs for grassed levees. In conclusion, under realistic use, biopolymer soil amendment is an effective means to enhance vegetation on levee slopes, leading to greater slope stability and the potential for reduced maintenance costs.

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Preface

This study was conducted for the Flood and Coastal Storm Damage Reduction, Civil Works program, Project Number 448773, Headquarters, U.S. Army Corps of Engineers (USACE).

The work was performed by the Environmental Engineering Branch (EPE) of the Environmental Processing and Engineering Division (EP), U.S. Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). At the time of publication, Dr. W. Andy Martin was Chief, CEERD-EPE; Mr. Jared Johnson was Acting Chief, CEERD-EP; and Dr. Maureen K. Corcoran, CEERD-EZT was the Associate Technical Director for Water Resources Infrastructure. The Deputy Director of ERDC-EL was Dr. Jack E. Davis, and the Director was Dr. Ilker R. Adiguzel.

The pilot-scale studies were conducted at ERDC-EL, Environmental Engineering Research Facility (EERF). The field demonstration site was the Kaufman Levee No.1, USACE-Fort Worth District, TX. The report was reviewed by Mr. Roy Wade (ERDC-EL) and Ms. Julie Kelley (ERDC-Geotechnical and Structures Laboratory (GSL)). The authors gratefully acknowledge the assistance provided by the Light Detection and Ranging (LiDAR) team from the ERDC-EL Environmental Systems Branch (EEC).

COL Ivan P. Beckman was Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
pints (U.S. liquid)	4.73176 E-04	cubic meters
pints (U.S. liquid)	0.473176	liters
quarts (U.S. liquid)	9.463529 E-04	cubic meters
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

Acronyms and Abbreviations

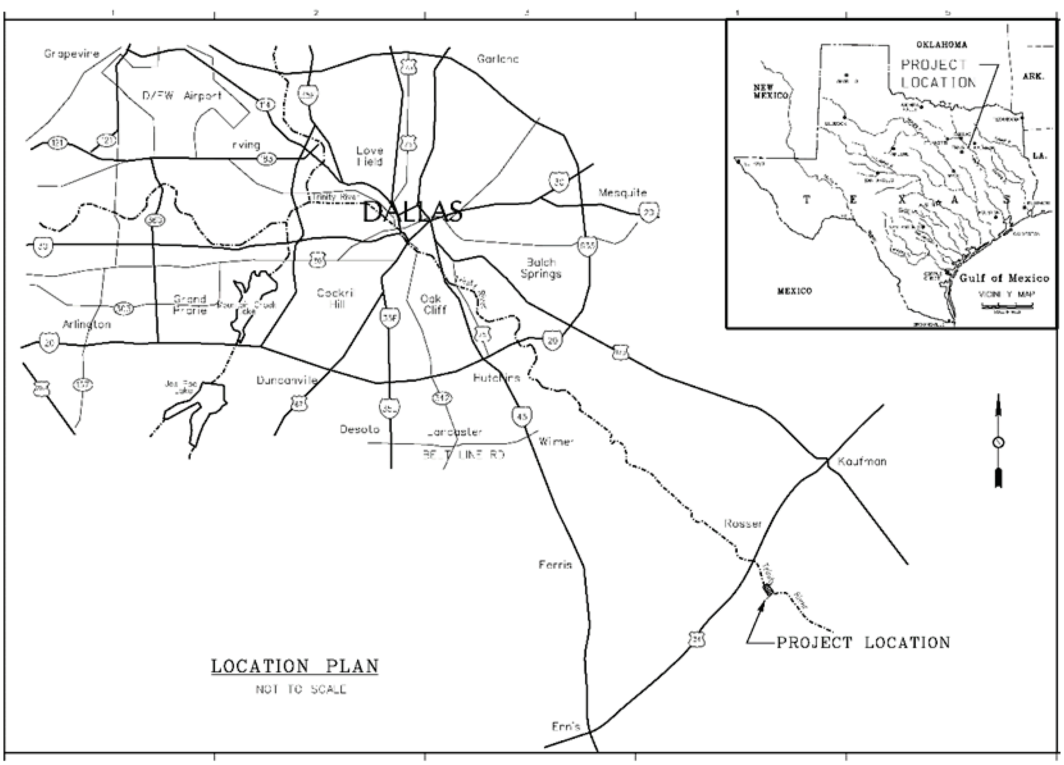
DoD	Department of Defense
EEC	Environmental Systems Branch
EERF	Environmental Engineering Research Facility
EL	Environmental Laboratory
EP	Environmental Processing and Engineering Division
EPE	Environmental Engineering Branch
EPS	Extracellular polymeric substance
ERDC	Engineer Research and Development Center
Foot/Feet	ft
GPS	Global Positioning System
GSL	Geotechnical and Structures Laboratory
LiDAR	Light Detection and Ranging
PVC	Polyvinyl Chloride
RAR	Root Area Ratio
RAS	Root Adhering Soil
RGB	Red/Green/Blue
USACE	United States Army Corps of Engineers
USPTO	United States Patent and Trademark Office

1 Introduction

1.1 Background

The Kaufman Levee No. 1 rehabilitation project is under the jurisdiction of the U.S. Army Corps of Engineers (USACE) Fort Worth District. The levee is located on the east side of the Trinity River, approximately 35 miles southeast of Dallas, TX, and 15 miles northeast of Ennis, TX (Figure 1). Three areas along the levee from river mile 445 to river mile 452 were damaged and experienced slope failure as the result of high energy flows in September 2009 and January 2010. The Kaufman levee protects farmland, pasture, and Trinity Materials, Inc. (Ennis, TX), a sand and gravel mine just to the south of the failed levees. In order to provide protection, set-back levees were designed, constructed, and vegetated in 2015.

Figure 1. Project location of the Kaufman Levee No. 1 emergency rehabilitation project (drawing supplied by Fort Worth District).



The existing levee that experienced failure was constructed from local clay loam soils that have an abundance of expansive clay minerals. Boring logs of the levee and borrow area from 1998 all identified medium-to-high plasticity clays down to a depth of at least 15 feet (ft) (information supplied by Fort Worth District). The high-water flows in 2009 and 2010 undercut the levee bank and resulted in the numerous bank failures that eventually made the levee road narrow and impassable in some places. Local farmers attempted to repair part of the levee in one of the southern-most affected areas during 2013 (Figure 2). The emergency repair plan made by the USACE Fort Worth District defined two new setback levees to be placed behind the existing levee (Figure 2). Materials for this construction project came from the existing levee when it was deconstructed. Additional borrow materials (primarily clays) were provided by Trinity Materials, Inc. located south of the levee construction site. Fort Worth District also completed bank stabilization using two bendway weirs as well as the two setback levees.

In spring 2015, the area was seeded with Bermuda grass to provide erosion control using a hydroseed application method. This provided an opportunity to perform a field scale demonstration using biopolymer as a soil amendment to provide enhanced revegetation of a newly constructed levee.

Figure 2. Overview of the levee setback placement and new borrow site (drawing provided by Fort Worth District).

1.2 Objectives

1. Demonstrate at pilot scale the establishment of grass sod placed on soils amended with organic polymer.
2. Demonstrate at field scale the revegetation of a levee with Bermuda grass in soil amended with organic polymer.
3. Demonstrate at field scale the use of photographic digital image analysis to evaluate establishment of vegetation as a means of reducing manpower/labor costs of levee maintenance.

1.3 Approach

A biopolymer soil amendment was evaluated during pilot-scale studies in support of the Kaufman Levee rehabilitation project by the Fort Worth District. The biopolymer is a product of *Rhizobium tropici* ATCC® 49672, a catalogued symbiotic nodulator of leguminous plants (Martinez-Romero et al. 1991). *R. tropici* is also known for its prolific production of a gel-like, extracellular polymeric substance (EPS), or biopolymer (Gil-Serrano et al. 1990). The natural functions of the EPS in the rhizosphere include surface adhesion, self-adhesion of cells into biofilms, formation of protective barriers, water retention around roots, and nutrient accumulation (Laspidou and Rittmann 2002). The secretion of EPS by bacteria is recognized as a cohesive force in promoting resistance to surface erosion in sediment (Droppo 2009; Gerbersdorf et al. 2008a and b; Perkins et al. 2004; Stone et al. 2011). The function of bacterial EPS in promoting soil adhesion has also been reported for several cyanobacteria (Hu et al. 2003) as well as for EPS in clay soil (Nugent et al. 2009). Soil resistance to erosion may be accomplished through binding soil particles within the biopolymer matrix as well as by the increased root production that holds and armors the soil against water and wind erosion. Bermuda grass is the preferred grass on levees in the Fort Worth District because it grows through rhizomes as well as seeds. The thick rhizome mat tends to discourage growth of undesired plants on the levee.

A technique has been developed through which *R. tropici*-derived biopolymer can be produced in an aerobic bioreactor. The polymer is separated from the bacteria and the growth media, then derivatized in order to produce a non-reactive (non-cross linking) material that can be transported for use (Newman et al. 2010; Patent number 7,824,569).

The use of the biopolymer as a soil modifier for erosion control and sediment transport has been evaluated through slope stability and surface soil durability studies at bench- and meso-scale as well as through economic studies (Larson et al. 2012; Muller and Farr 2015). The biopolymer performed effectively when used with soils at high risk for erosion. Larson et al. (2012) concluded that application of the biopolymer to soil at economically feasible loading rates could effectively maintain the slope stability of a simulated berm. In addition, the biopolymer was able to reduce the transport of soil particulates in runoff water from the slope. The performance of the biopolymer and its ability to stabilize slopes over the long-term (i.e., in three years has now been evaluated) (Larson et al. 2016). This study also examined vegetative growth as a means of rapidly stabilizing disturbed soils.

1.4 Scope

Methods currently used to maintain levees are based on reducing the transport of suspended solids from the slope. These methods include the placement of geotextiles, mulch, riprap, and adding vegetation for erosion control. Standard operating procedure for levee revegetation is to hydroseed (spring growing season) or place sod on the slope (fall growing season). The biopolymer was evaluated as a means to improve establishment of both grass seed and sod in order to stabilize the levee bank and provide rapid revegetation on the slope.

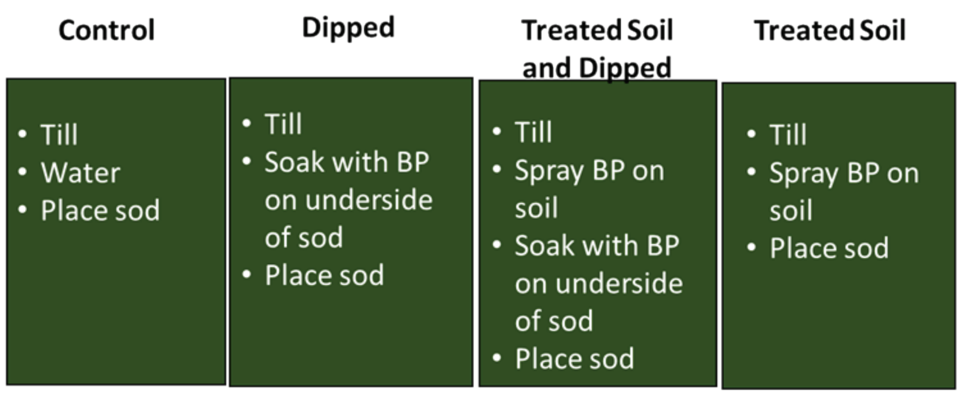
2 Materials and Methods

2.1 Pilot-scale studies

A site was selected at the Environmental Laboratory (EL) Environmental Engineering Research Facility (EERF) large enough to ensure all sod test areas had a similarly flat slope and consistent exposure to sunlight throughout the day. All treatment areas were prepared by chemically killing pre-existing grass/weeds. Two weeks of weathering allowed dissipation of the chemical treatment. All areas were then tilled and raked to provide a level surface for sod placement.

Two soil types prone to erosion were studied; a sand soil and a clay soil. Clay soil types are representative of soils used in levee construction. Bermuda grass sod was purchased locally and used in both sand and clay soil plots. In November 2014, biopolymer from *R. tropici* was applied to the soil and/or the root area of the sod in concordance with the experimental design for each plot (Figure 3).

Figure 3. Experimental design for pilot-scale studies of biopolymer effects on establishment of sod. Test plots were used for both sand and clay soil types.



The *R. tropici*-derived biopolymer was applied to the soil at a rate of 1.0 gallons per square meter in the two plots where soil was treated with biopolymer prior to sod placement. For plots where the underside of the sod was treated with biopolymer, a tray was filled with the biopolymer solution to a depth of 2 in. Sections of sod were placed in the tray prior to placement in the plot. Biopolymer solution was added to the tray to maintain the solution depth between 2 and 3 in. The approximate biopolymer application rate by this method was 0.5 gallons per square meter. A control area received water only, with no biopolymer.

Initially, the site was watered until the soil was consistently wet to a depth of four in. Due to lack of rain in the following weeks, the sod was watered as specified in the Kaufman Levee Emergency Repair Contract until the sod grass was established. A mid-winter sampling of the sod plots was performed at week 10 when all Bermuda grass was senescent.

A sod “pull-box” system was designed and constructed to evaluate the degree to which sod grass expanded roots and became integrated into the underlayer of soil (Figure 4). Each pull-box held one section of sod. The pull-boxes were placed under randomly selected pieces of sod in each soil plot (three sod units x four treatments). The bottom of the box was composed of stiff plastic netting to allow unimpaired root growth from the sod into the soil.

Figure 4. Pull box designed and placed in the field under sod.

A “pull system” was designed with a center tensiometer to measure the pressure required for a direct lift of the sod (Figure 5). The system’s design was based on the hypothesis that as the sod roots grew into the soil, the amount of tension required to lift the sod would increase. The soil removed with the sod was used to determine the mass of root-adhered soil (RAS) using the method of Alami et al. (2000). The RAS, being an integral part of the rhizosphere, is considered a functional soil unit. The RAS contains the greatest number of rhizosphere microorganisms and the associated enzymes and root exudates (Angle et al. 1996).

Figure 5. Field tensiometer designed and constructed to evaluate root establishment of sod in soils treated with an organic polymer. Note the flexible webbing that allowed root growth from the sod to the soil.

2.2 Field study

The setback levees, referred to as Kaufman Levee No.1, were constructed using material from the original, failed levee along with fill material purchased from Trinity Materials, Inc. The ERDC-EL worked with the contractor and USACE Fort Worth District to perform the field demonstration seeding on Kaufman Levee No.1. Three test areas and a control area (not treated with biopolymer) were selected along the levee, identified by their Global Positioning System (GPS) coordinates, and physically marked with stakes at the corners (Figure 6). Seeding was performed during the spring of 2014, using a standard hydroseeding mixture with the addition of a hydromulch (Figure 7).

Figure 6. Satellite image of Kaufman Levee No.1 showing GPS coordinates and upper and lower boundaries of test and control areas: C=Control, N=North, M=Middle, S=South.

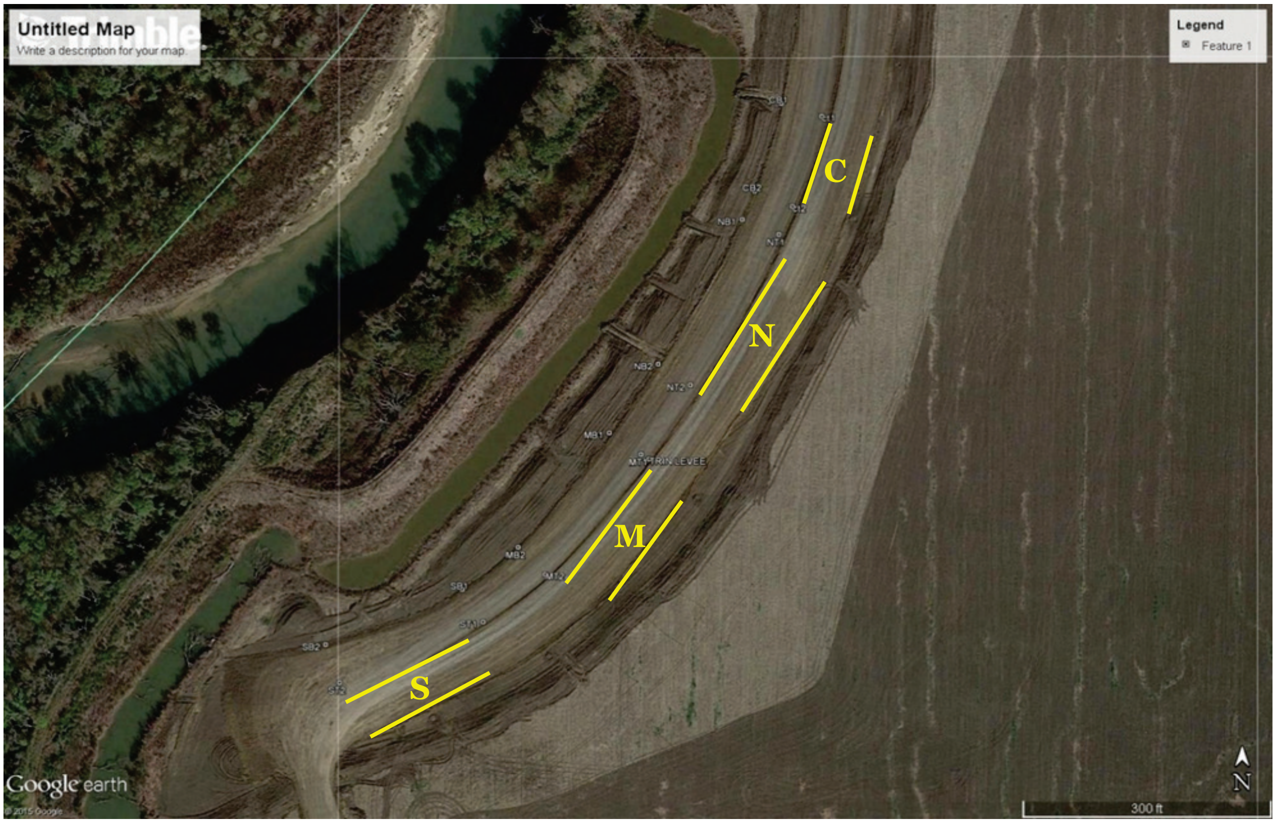


Figure 7. Addition of hydromulch, grass seed and biopolymer to soil on Kaufman Levee, spring, 2014.

Table 1 outlines the experimental design for the Kaufman Levee study area. The control area received only Bermuda grass seed, water, and mulch. The test areas each received Bermuda grass seed, water, mulch, and biopolymer. Biopolymer was added to the hydroseeder at the concentration specified for each test area and was applied along with the water, seed, and mulch. All seed/liquid combinations, control and experimental, were delivered by hydroseeder.

Table 1. Experimental design for biopolymer application at Kaufman Levee No.1.

Test Area	Size (m^2)	Biopolymer Addition	Concentration (gal/m^2)
Control	634	0	0
North	966	25 gal	0.03
Middle	826	50 gal	0.06
South	872	100 gal	0.11

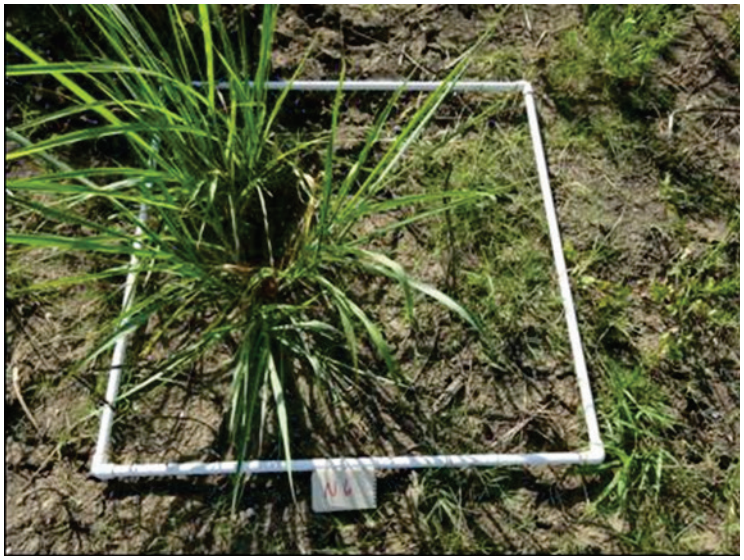
As seen in Table 1, the three areas receiving biopolymer were nearly the same area, ranging in size from 826 m^2 to 966 m^2. These corresponded to one hydroseeder tank application. The experiment was simplified by the ease at which biopolymer application worked with the hydromulch seeding technique used for the entire seeded region. For the three biopolymer-amended sections of the levee, a specific volume of biopolymer solution was used in place of water for the hydromulch seeder's 600 gallon tank. The rest of the volume was made up of the standard hydromulch liquid (i.e., water). The four corners of each study area (shown in Figure 6) were marked with fence posts.

The site area was evaluated after one year to determine what effect, and how much of an effect, biopolymer addition to hydromulch levee vegetation practices might have on establishing desired vegetative cover, in this case, on establishing Bermuda grass.

2.3 Year one post-application: summer 2015

Several techniques were used in order to evaluate establishment of Bermuda grass on the one-year-old levee repair. Sampling for plant density and species diversity was accomplished using a 1 m x 1 m polyvinyl chloride (PVC) grid (Figure 8). Six points were selected randomly from within each section for grid sampling. Visual identification of species and estimates of species coverage were made by walking the area immediately above the water line.

Figure 8. The sampling grid employed to establish plant density and species diversity in the treatment areas on Kaufman Levee.



Digital photographs were taken of each of the sampled grids for image analysis of plant cover. Differences in species diversity were determined using Easy Leaf Area, v2 (Easlon and Bloom 2014), an image analysis software, on each of the photographs. Easy Leaf Area is free, open source, software that rapidly measures leaf area in digital images (photographs or scanner images). The software uses the Red/Green/Blue (RGB) value of each pixel to identify leaf regions in each image.

2.4 Root development

Root architecture, based on washed roots, was analyzed and quantified using WinRHIZO™ (Regent Instruments Inc., CA). WinRHIZO™ is an image analysis system specifically designed for topological, architectural, and color analysis of roots. Root length, diameter, surface area, and volume, were calculated.

3 Results and Discussion

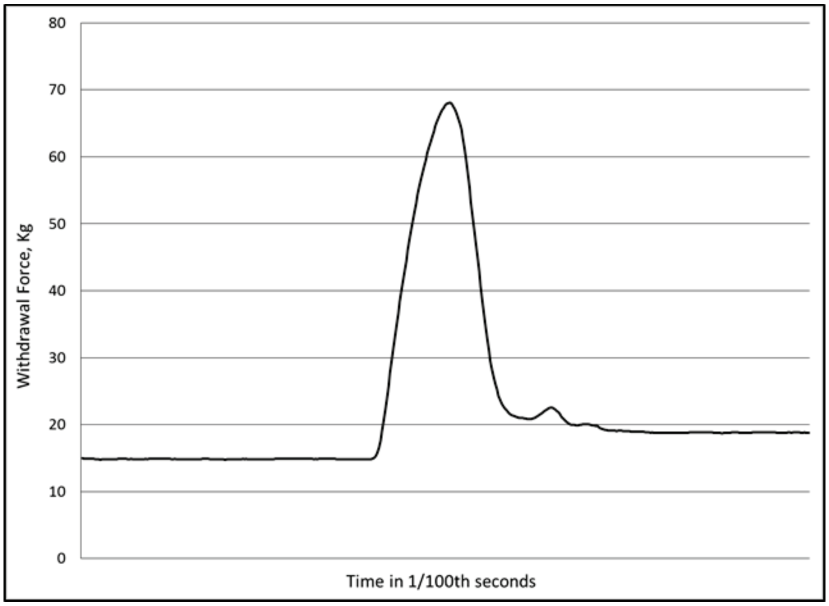
3.1 Pilot-scale studies

After ten weeks in the pilot-scale field plots, the pull-box sod squares, placed during week one, were removed. The pull system designed to remove them was a battery-operated electric lift system, which incorporated a tensiometer capable of measuring the forces required to remove the sod from the soil. An image of the system in the field is shown in Figure 9. Removal of the one square foot sod section allowed evaluation of both the withdrawal force required to remove the section of sod as well as a means of collection of soil/root samples for measurement of root adhering soil (RAS) masses.

Figure 9. Sod pull-box system with tensiometer in use in the pilot demonstration.

An example of tensiometer data obtained from the soil pulls is shown in Figure 10. The data are reported as the average withdrawal force in kg. Three replicates were pulled from each experimental plot of the two soil types. The withdrawal force was exerted on the soil square over a short time (approximately ¼ of a second), and maximum withdrawal forces ranged from 60 to 120 kg. In the example below, the large, initial pull force can be seen as the large peak. Two, much smaller "bounces" can be observed, represented by small peaks visible following the main peak.

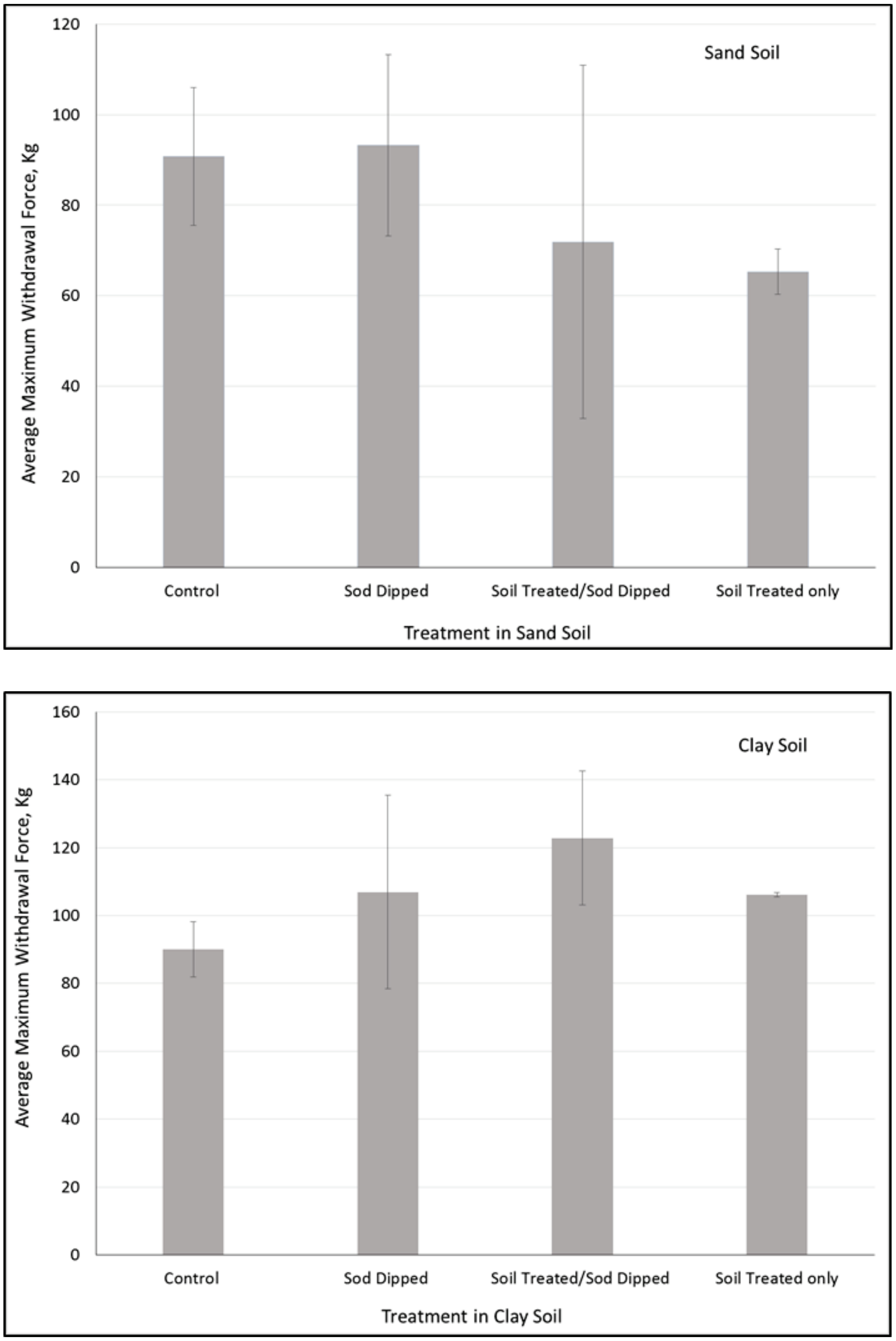
Figure 10. Example of tensiometer data from sod "pulls," measured as withdrawal force vs. time.



The development of a field instrument that exerted reliable upward force, coupled with a tensiometer system for recording the force over time, was thought to be a means of evaluating plant/soil strength. The hypothesis was that a greater withdrawal force would be indicative of sod-root integration into the soil and greater mass, and implied strength, of the biogeotextile.

Figure 11 shows the large variabilities associated with measurement of the force required to pull a piece of sod from the Sand (top) and Clay soil (bottom), by treatment. Unfortunately, the high variability in maximum withdrawal force as measured by this system did not allow a clear comparisons between the treatments.

Figure 11. Average maximum withdrawal force (kg) required to remove sod section from the surrounding soil in control and biopolymer-treated experimental plots after 10 weeks. Top. Sand-soil type. Bottom. Clay-soil type.



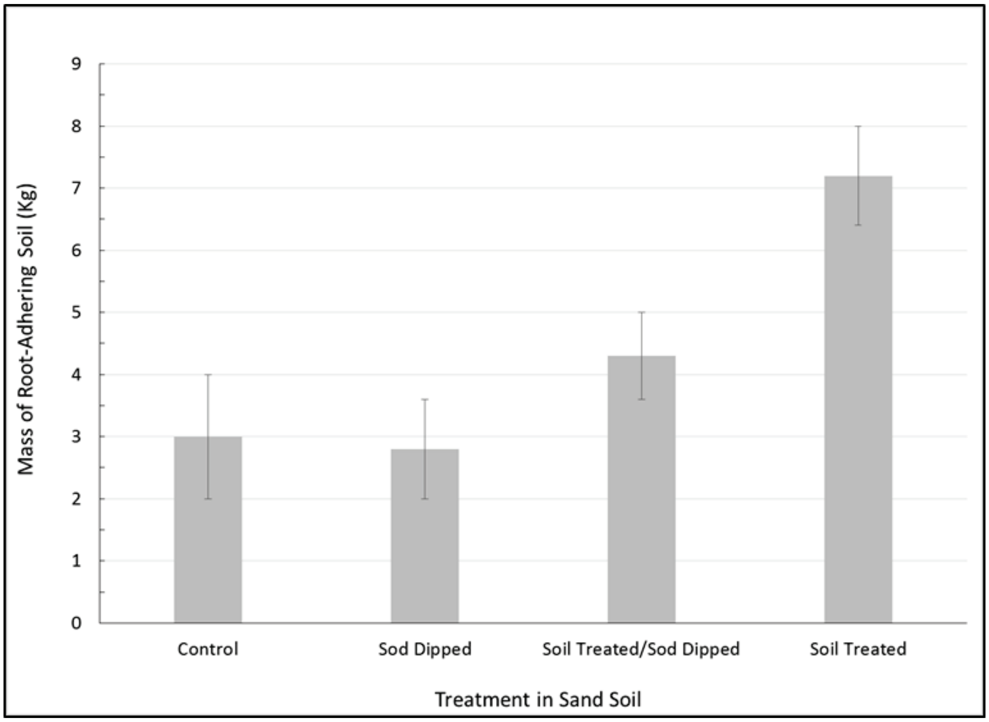
As can be seen in Figure 11, the large error bars extending beyond the average maximum withdrawal force in both the sand and the clay overlap sufficiently that no clear trend is noted. This high degree of variability is most likely a result of uncontrolled environmental factors, such as localized soil moisture content, inability to achieve perfect levelling of the device, or a less-than-vertical orientation of the pull box.

While the withdrawal force results were not beneficial with regards to understanding the integration of sod roots into the soil, the measurement of the mass of soil retained when the pull boxes were removed was beneficial. Differences in the mass of soil adhering to the roots following removal was noted during the pulls. Figure 12 is a photographic comparison of the difference in root mass between the untreated sod and a section of sod grown with biopolymer treatment in the Sand plots.

Figure 12. Comparison of root development in overwintered Bermuda grass sod when left untreated (Control – left) or treated with biopolymer (right).

Masses were obtained for the RAS from the Sand-soil experimental treatments. These are shown in Figure 13. The averages and standard deviations of the RAS results indicate a clear trend with regard to the effect of biopolymer soil amendment on production of a biogeotextile. RAS determination proved to be a more accurate determinant of root/soil integration than the tensiometer.

Figure 13. Root-adhering soil mass (kg) of sod pulls by experimental treatment in Sand soil.



In the Clay-soil experimental plots, the density of the Clay soil was so great, the roots broke rather than be removed with soil. The tensiometer data was fairly homogeneous and no treatment proved statistically different than the control. For the same reason, no mass was obtained for RAS from the Clay-soil experimental treatments.

3.2 Field demonstration

After one year post-application of the biopolymer treatments, there were significant differences in the overall appearance of the vegetation on the levee (Figure 14). The lower extent of the flood and its effect on plant growth on the levee is shown in Figure 15. Note the soil disturbance on the levee (photograph lower right) marking the flood rise.

Figure 14. Vegetation on the slopes of the Kaufman Levee experimental areas.

Amendments

Control
Hydromulch
Seed
No biopolymer

North Site
Hydromulch
Seed
Biopolymer: 0.03 gal/m^2

Middle Site
Hydromulch
Seed
Biopolymer: 0.06 gal/m^2

South Site
Hydromulch
Seed
Biopolymer: 0.1 gal/m^2

Figure 15. Effect of flooding on vegetation growth on the lower Kaufman Levee.

3.2.1 Species diversity and plant density

The following two methods were used to establish differences in species diversity and density in the different treatment areas: visual inspection/counting and photographic digital image analysis. Both used the same randomly-selected m^2 grids. Both visual and digital estimates of Bermuda grass coverage by treatment area are provided in Table 2.

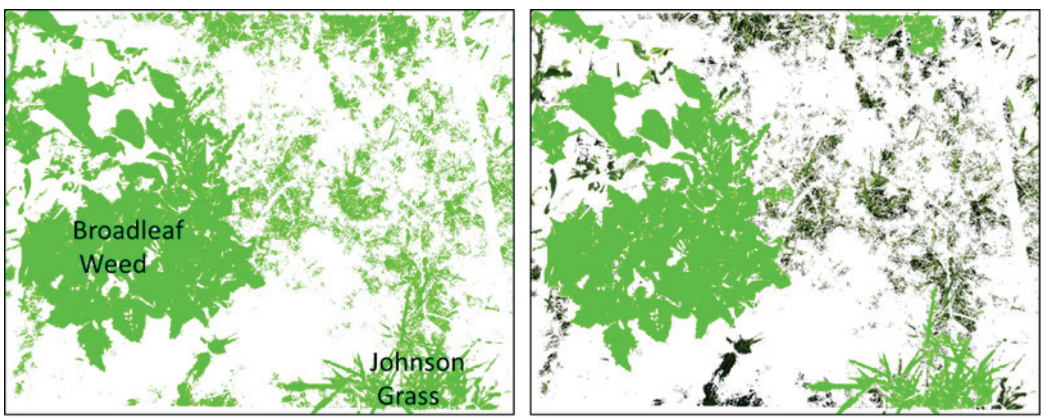
Table 2. Digital image estimate of Bermuda grass coverage on Kaufman Levee No.1 by treatment area.

Estimation Method	Bermuda grass, % cover			
	Control (untreated)	North (25 gal biopolymer)	Middle (50 gal biopolymer)	South (100 gal biopolymer)
Digital	27	32	43	62
Visual	35	30	40	80

The Easy Leaf Area image analysis software uses pixel color and connectivity analysis to evaluate vegetation and calculate species diversity and plant density. As an example, Figure 16 is a digital photograph of one of the m^2 sampling plots. The edges of the white plastic square are just visible. Figure 17 illustrates the vegetation in the same plot as Figure 16 separated from the background by the Easy Leaf Area image analysis. The Leaf Area filter then identifies Bermuda grass leaves in black and shows the unwanted plants in green, providing coverage areas for both selections.

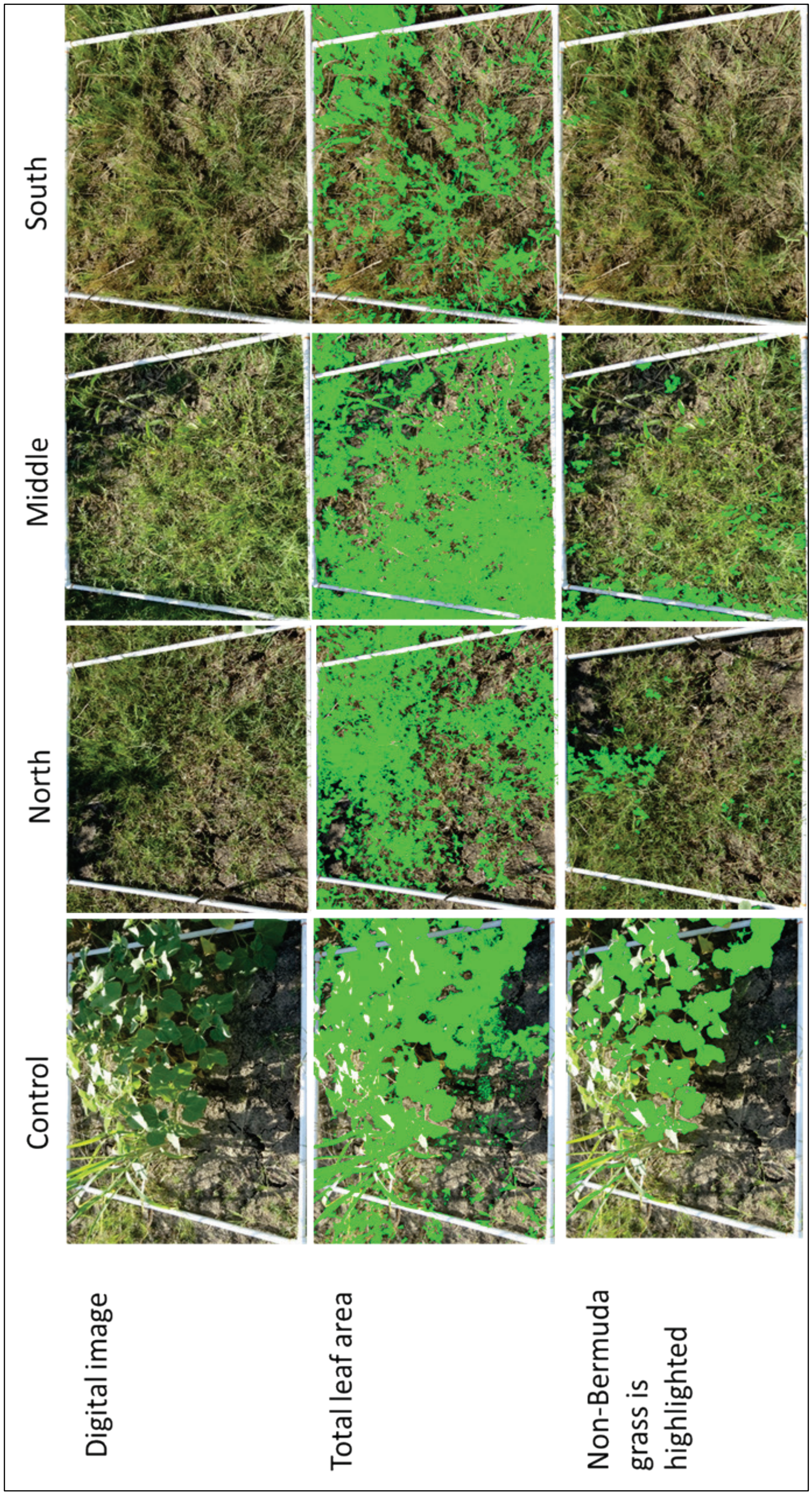
Figure 16. Digital image of one m² sampling plot from Kaufman levee.

Figure 17. Easy Leaf Area digital image of the sample plot shown in Figure 16, with filters applied, allowing separation of plants from background and selection of specific plants. Black in the image on the right indicates Bermuda grass.



There were four treatment areas, including the Control, on the levee (see Figure 7). Six randomly selected areas were used for plant analysis within each area for a total of 24 digital photographs. Figure 18 shows how this software application was used to analyze species density and diversity on the Kaufman levee. The entire collection of digital data can be found in Appendix A.

Figure 18. Set of photographic data from all biopolymer treatment areas and the control area of the Kaufman levee.



Still digital photography and image analysis software are now employed in many types of environmental monitoring studies (Bock et al. 2010; Lapresta-Fernández and Capitán-Vallvey 2011). Photography can replace the labor-intensive, and sometimes costly, manual field work involved in plant species/diversity studies. It also maintains a permanent record of the research. Two arguments against the use of unenhanced photographic analysis are the following:

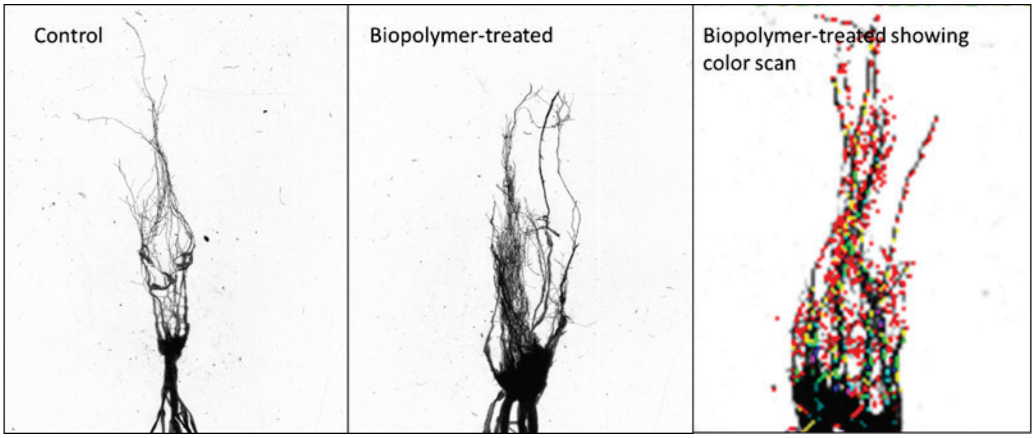
- it can underestimate the object of study (i.e., plant flowers or diseased sections of leaves), as compared to visual identification (van Dongen et al. 2017), and
- labor and cost are simply shifted from the field to the laboratory (van Dongen et al. 2017).

However, image analysis software designed for plant diversity studies has largely negated these arguments by allowing small teams, or even a single researcher, to collect and rapidly analyze large amounts of data (Easlon and Bloom 2014).

3.2.2 Root characteristics

An example of a WinRHIZO™ root scan used to compare growth and development in the control and treated soils is shown in Figure 19. The root from the control soil has less biomass, overall. Analysis revealed there were fewer secondary roots and fine root hairs compared to roots grown in biopolymer-amended soil. Secondary roots and fine root hairs are often an indicator of plant health (Iverson 2014) and are important to the structural integrity of the soil and for erosion prevention Burak et al. 2017). Root hair structures are generally located behind the root tip. Root hairs are the primary point of water and nutrient absorption for the plant (Iverson 2014). As the root tip grows, the root hairs die and are replaced closer to the root tip. The root system on the right in Figure 19 illustrates the color scan of the root produced by the WinRhizo™ software. The colors are indicative of fine root hairs and root branching. This particular scan is of root volume from grass grown in the South treatment Area compared to a root grown in the untreated (control) soil.

Figure 19. Example of root scans performed by WinRHIZO™ image analysis software: in this case, scans of roots grown with and without biopolymer addition to the soil.



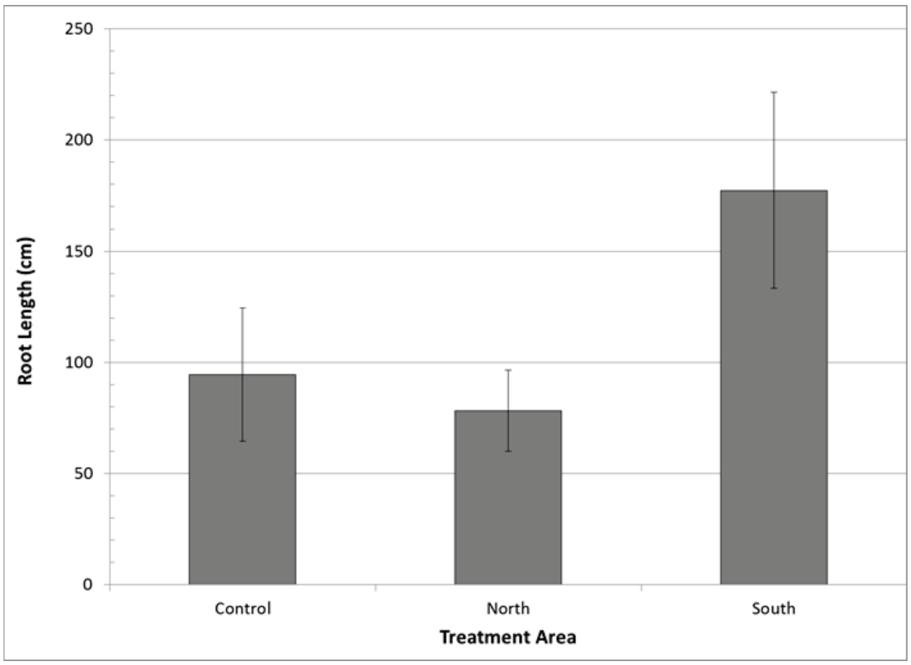
A comparison of root development in the treatment areas of the Kaufman Levee obtained through WinRHIZO™ image analysis is detailed in Table 3. This information is presented graphically in Figure 20 through Figure 24 for root length, root diameter, total area, surface area, and root volume, respectively. Comparisons were made between plant roots from the Control Area, the North Area (lowest biopolymer amendment), and the South Area (highest biopolymer amendment). Images of the Middle treatment Area (medium biopolymer treatment concentration) are available in Appendix A. These values fell between the high and low biopolymer concentrations and were deleted from Table 3 to clarify differences from the control treatment. According to Judd et al. (2015), it is the interrelationship of root measurement with root function that determines the importance of these root parameters.

Table 3. Comparison of the parameters of root growth and development between soil treatments at Kaufman Levee No.1.

Parameter	Control	North	South
Total length (cm)	94.09 ± 33.80	102.67 ± 38.55	120.58 ± 50.22
Root diameter (mm)	0.6 ± 0.13	0.65 ± 0.053	0.8 ± 0.12
Total area (cm^2)	8.20 ± 1.16	8.68 ± 2.24	8.89 ± 1.77
Total surface area (cm^2)	11.26 ± 2.41	11.93 ± 3.46	13.14 ± 3.55
Root volume (cm^3)	0.27 ± 0.13	0.23 ± 0.11	0.89 ± 0.52

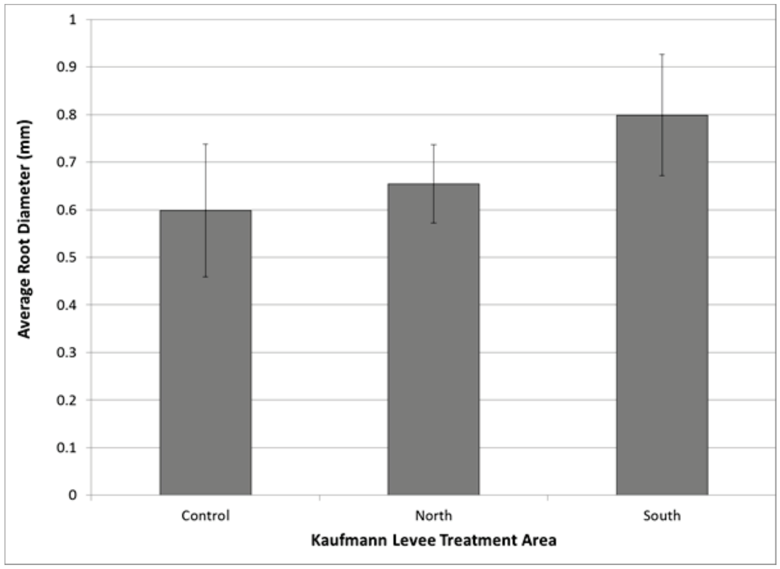
Image analysis, performed as it is with clean roots in water, often underestimates root length due to damage during cleaning and root overlap in the image area (Judd et al. 2015). However, the average total root length (Figure 20) observed in plants grown in the field demonstration areas was greatest in soil amended with the highest concentration of biopolymer (South). The root length from the Control area and the lowest biopolymer amendment (North) are statistically similar.

Figure 20. Comparison of average root length between plants grown with no biopolymer to those grown in biopolymer-treated soil (North and South Treatment Areas).



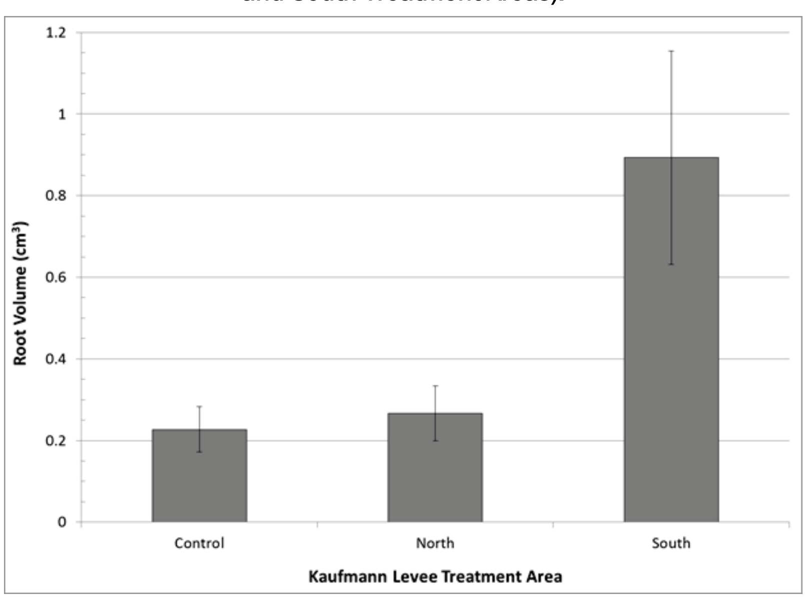
Root diameter can be used to assess what the root and the plant experience in the surrounding environment (Judd et al. 2015). Root diameter affects the length of the root that the plant can produce for resource input to the whole plant system (Fitter 1996). Root diameter also seems to be a good predictor of the effect of mechanical impedance and soil/substrate pore size (Goss 1997, Gregory 2006). Root diameter of plants analyzed from the field demonstration site (Figure 21) show a trend of increased diameter with biopolymer concentration. This may be a preliminary indication of the presence of additional nutrient bioavailability or the decrease in mechanical impedance for roots grown in biopolymer-treated soils.

Figure 21. Comparison of average root diameter between plants grown with no biopolymer to those grown in biopolymer-treated soil (North and South Treatment Areas).



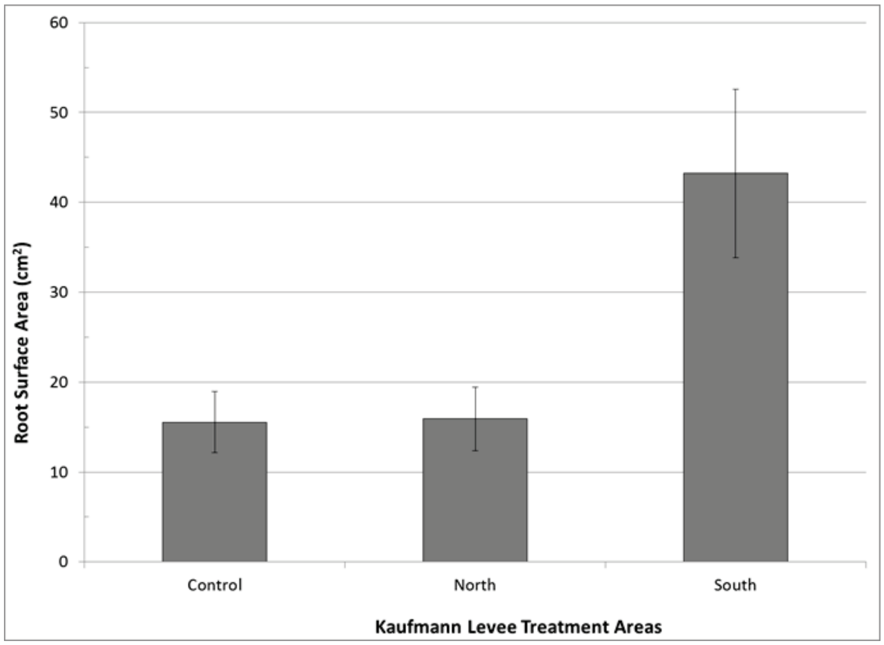
The positive effect of biopolymer soil amendment is clear in the significantly greater value for root volume occurring with the highest level of biopolymer amendment (Figure 22). Volume, being dependent on the radius of the roots examined and their length, is a secondary index of growth and development. It demonstrates the combined effect of greater diameter and greater root length that was not as apparent with the other measurements.

Figure 22. Comparison of root volume (cm^3) between plants grown with no biopolymer to those grown in biopolymer-treated soil (North and South Treatment Areas).



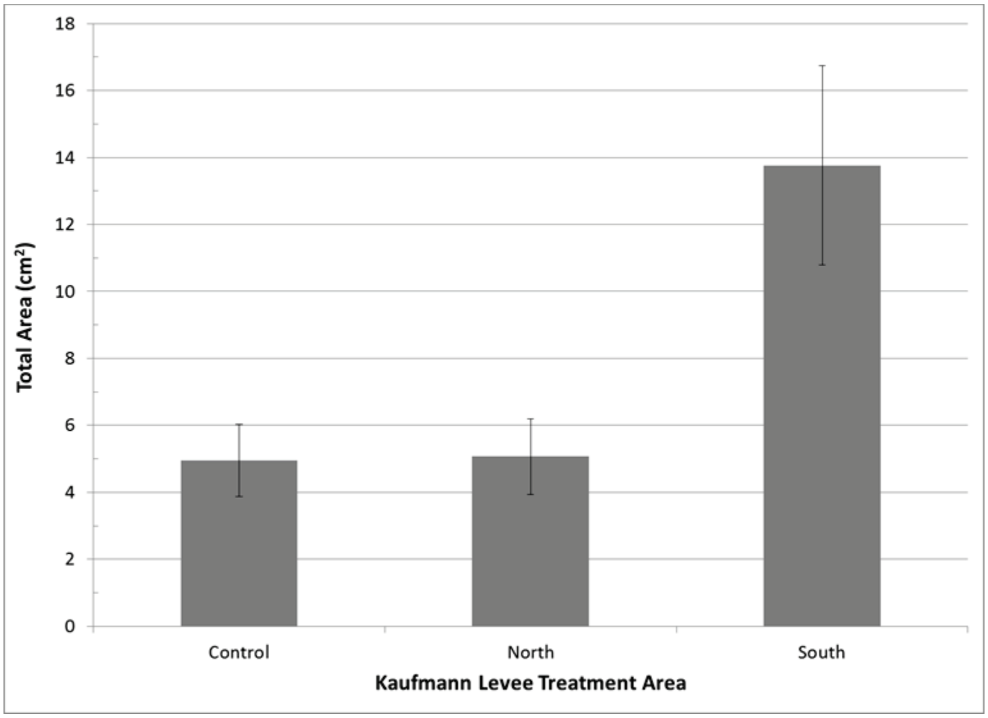
Root surface area includes the fine root hairs (Figure 23). At the highest level of biopolymer soil amendment, the observed plants demonstrated the highest root surface area.

Figure 23. Comparison of root surface area (cm^2) between plants grown with no biopolymer to those grown in biopolymer-treated soil (North and South Treatment Areas).



Root area, on the other hand (Figure 24), does not include the fine root hairs, and is considered an environmental morphological index reflective of soil conditions, not plant growth (Lõhmus et al. 1989). Small, flexible roots increase the soil-fiber strength (Gray and Leiser 1982). Larger roots that intersect the shear plane of the slope act as individual anchors (Coppin and Richards 2007). Root area, therefore, has a direct influence on soil slope stability, which can be quantified as the root area ratio (RAR) (Bischetti et al. 2005). The RAR is the ratio between the area occupied by the roots in a unit area of soil, which will vary by depth. Although the unit area of soil was not calculated for plants observed during the field demonstration, the greater total root area, observed in plants grown with the highest level of biopolymer amendment, would seem to indicate a higher RAR and therefore a higher tensile strength of the soil. The higher tensile strength would contribute to decreased soil erodibility and an increase in soil stability.

Figure 24. Comparison of total root area (cm^2) between plants grown with no biopolymer to those grown in biopolymer-treated soil (North and South Treatment Areas).



The results of WinRHIZO™ analysis of the field scale soil treatments, presented here, are supported by the RAS data obtained from the pilot studies discussed in Section 3.1 (Figure 13) of this report. Soil amendment with the biopolymer is enough to stimulate plant root growth above what would normally occur. However, the concentration of amendment appears to be important. The amendment concentration of the North site was too low to produce discernable root changes from the control roots. Overall, the field results indicate formation of a biogeotextile on the soil surface of the Kaufman Levee that was aided by biopolymer soil amendment.

4 Conclusions

The methods currently used to maintain artificial slopes, by reducing the transport of suspended solids from the slope, include the placement of geotextiles, mulch, riprap or the addition of vegetated areas for erosion control. Artificial petroleum-based soil strengthening and stabilizing additives are currently used for this purpose. These petroleum-derived polymers are based on an increasingly expensive and scarce natural resource. In addition, they are often difficult to transport and apply. The use of petroleum-based polymers also has an increasingly negative public perception due to their limited biodegradability and petrochemical nature.

Previous field demonstrations at military facilities indicated that the biopolymer was a cost-effective means of stabilizing slopes over the long-term, with minimal maintenance costs (Larson et al. 2016) and should be considered for levee stabilization. The pilot demonstration for the Kaufman Levee established that determination of the RAS is an accurate prediction of field success in enhancing the root:soil integration essential to reducing soil erosion on slopes. The field demonstration on the Kaufman Levee successfully transferred a technology developed for military use into a civilian environment. The study employed a digital photographic image analysis technique to reduce manpower and monitoring field costs for grassed levees. In conclusion, under realistic use, biopolymer soil amendment is an effective means of enhancing vegetation on levee slopes, leading to greater slope stability and the potential for reduced maintenance costs.

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Appendix A: Easy Leaf Area

A.1 Control Area

Figure A1. Control Area, sample 1 (digital image).

Figure A2. Control Area, sample 1 (total leaf area).

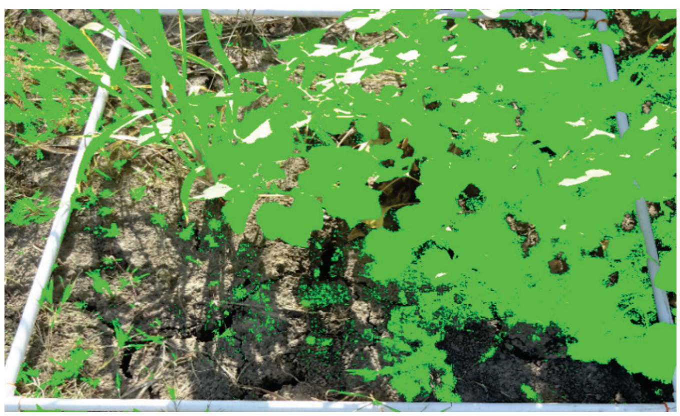


Figure A3. Control Area, sample 1 (Non-Bermuda grass leaf area).

Figure A4. Control Area, sample 2 (digital image).

Figure A5. Control Area, sample 2 (total leaf area).

Figure A6. Control Area, sample 2 (Non-Bermuda grass leaf area).

Figure A7. Control area, sample 3 (digital image).

Figure A8. Control area, sample 3 (total leaf area).

Figure A9. Control Area, sample 3 (Non-Bermuda grass leaf area).

Figure A10. Control Area, sample 4 (digital image).

Figure A11. Control Area, sample 4 (total leaf area).

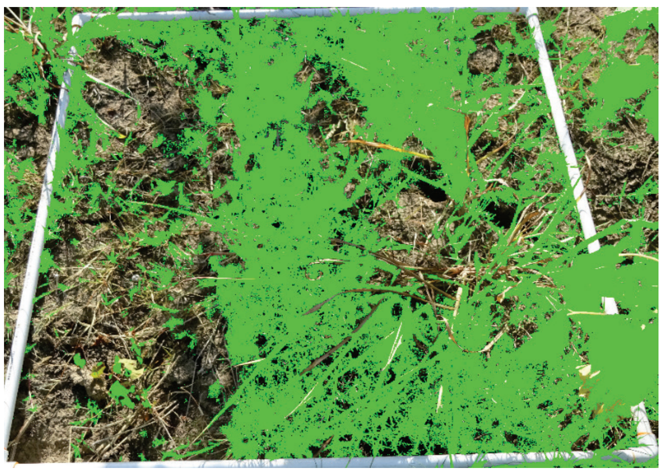


Figure A12. Control Area, sample 4 (Non-Bermuda grass leaf area).

Figure A13. Control Area, sample 5 (digital image).

Figure A14. Control Area, sample 5 (total leaf area).

Figure A15. Control Area, sample 5 (Non-Bermuda grass leaf area).

Figure A16. Control Area, sample 6 (digital image).

Figure A17. Control Area, sample 6 (total leaf area).

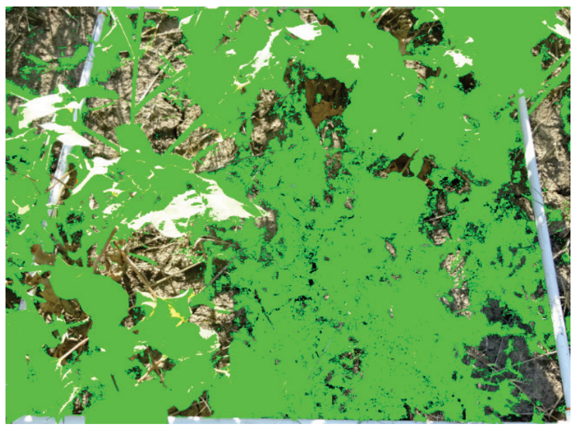


Figure A18. Control Area, sample 6 (Non-Bermuda grass leaf area).

A.2 North Treatment Area (low biopolymer concentration)

Figure A19. North Treatment Area, sample 1 (digital image).

Figure A20. North Treatment Area, sample 1 (total leaf area).

Figure A21. North Treatment Area, sample 1 (Non-Bermuda grass leaf area).

Figure A22. North Treatment Area, sample 2 (digital image).

Figure A23. North Treatment Area, sample 2 (total leaf area).

Figure A24. North Treatment Area, sample 2 (Non-Bermuda grass leaf area).

Figure A25. North Treatment Area, sample 3 (digital image).

Figure A26. North Treatment Area, sample 3 (total leaf area).

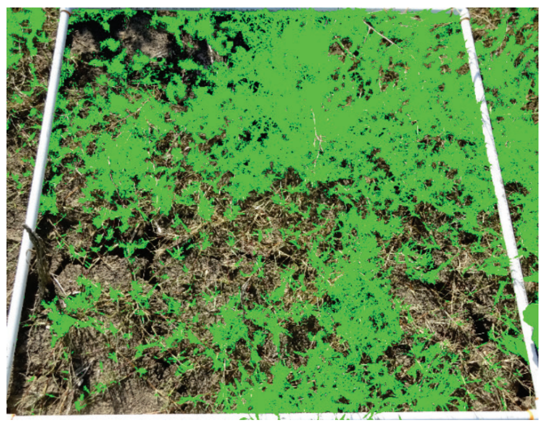


Figure A27. North Treatment Area, sample 3 (Non-Bermuda grass leaf area).

Figure A28. North Treatment Area, sample 4 (digital image).

Figure A29. North Treatment Area, sample 4 (total leaf area).

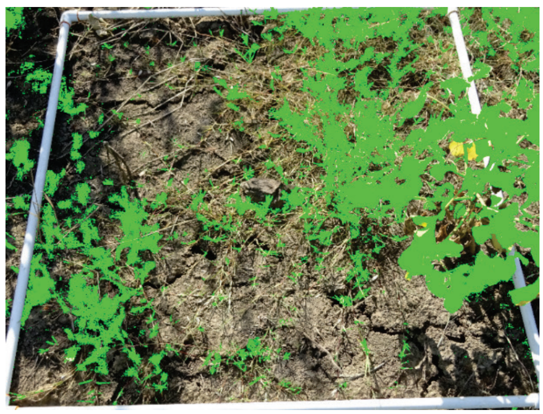


Figure A30. North Treatment Area, sample 4 (Non-Bermuda grass leaf area).

Figure A31. North Treatment Area, sample 5 (digital image).

Figure A32. North Treatment Area, sample 5 (total leaf area).

Figure A33. North Treatment Area, sample 5 (Non-Bermuda grass leaf area).

Figure A34. North Treatment Area, sample 6 (digital image).

Figure A35. North Treatment Area, sample 6 (total leaf area).

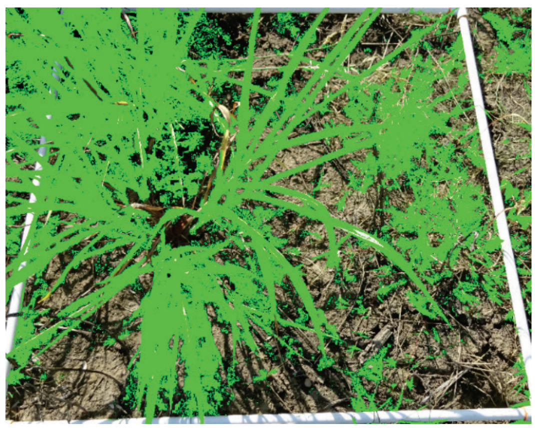


Figure A36. North Treatment Area, sample 6 (Non-Bermuda grass leaf area).

A.3 Middle Treatment Area (medium biopolymer concentration)

Figure A37. Middle Treatment Area, sample 1 (digital image).

Figure A38. Middle Treatment Area, sample 1 (total leaf area).

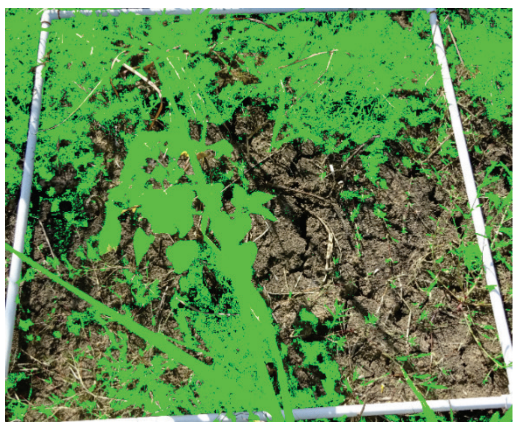


Figure A39. Middle Treatment Area, sample 1 (non-Bermuda grass leaf area).

Figure A40. Middle Treatment Area, sample 2 (digital image).

Figure A41. Middle Treatment Area, sample 2 (total leaf area).

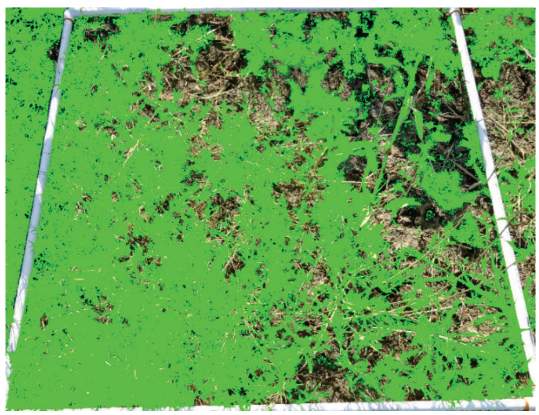


Figure A42. Middle Treatment Area, sample 2 (non-Bermuda grass leaf area).

Figure A43. Middle Treatment Area, sample 3 (digital image).

Figure A44. Middle Treatment Area, sample 3 (total leaf area).

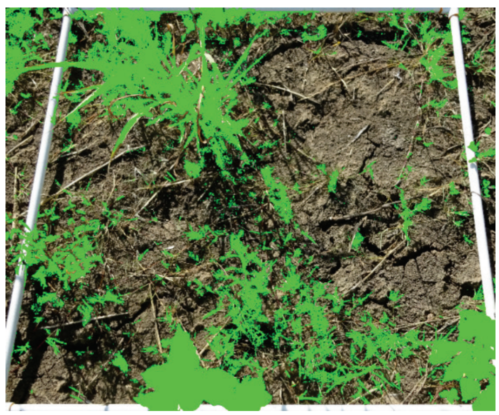


Figure A45. Middle Treatment Area, sample 3 (non-Bermuda grass leaf area).

Figure A46. Middle Treatment Area, sample 4 (digital image).

Figure A47. Middle Treatment Area, sample 4 (total leaf area).

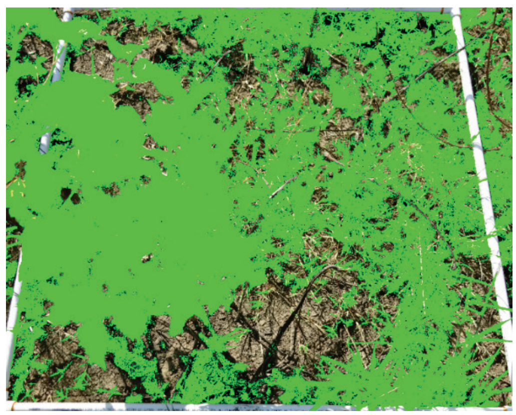


Figure A48. Middle Treatment Area, sample 4 (Non-Bermuda grass leaf area).

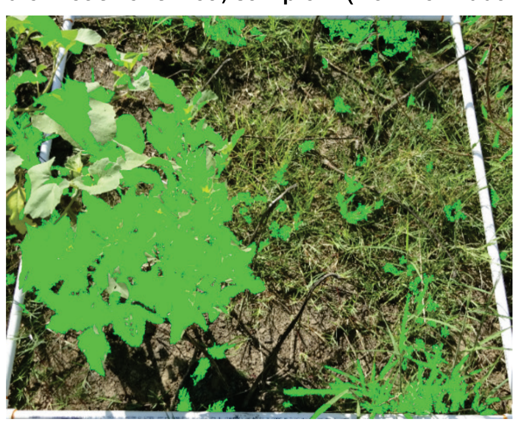


Figure A49. Middle Treatment Area, sample 5 (digital image).

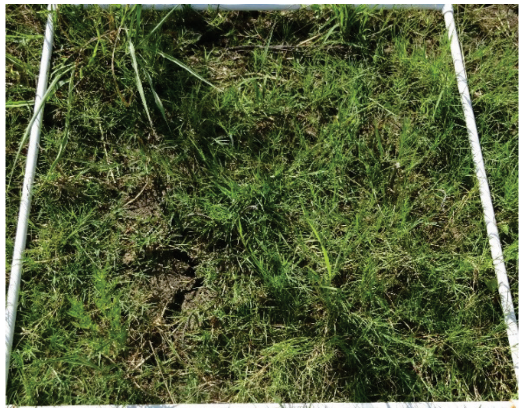


Figure A50. Middle Treatment Area, sample 5 (total leaf area).

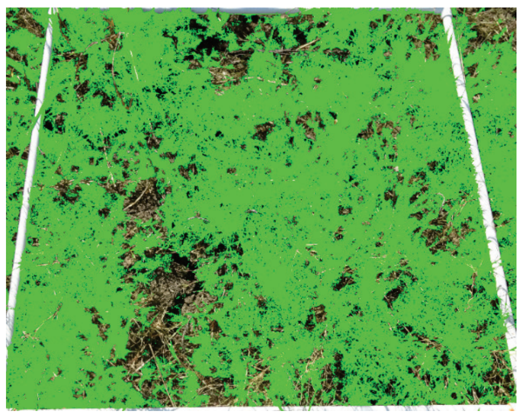


Figure A51. Middle Treatment Area, sample 5 (Non-Bermuda grass leaf area).

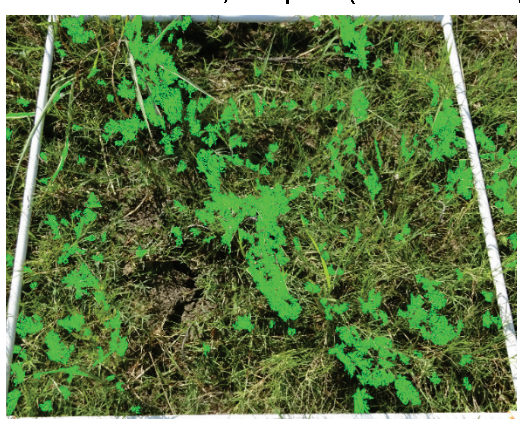


Figure A52. Middle Treatment Area, sample 6 (digital image).

Figure A53. Middle Treatment Area, sample 6 (total leaf area).

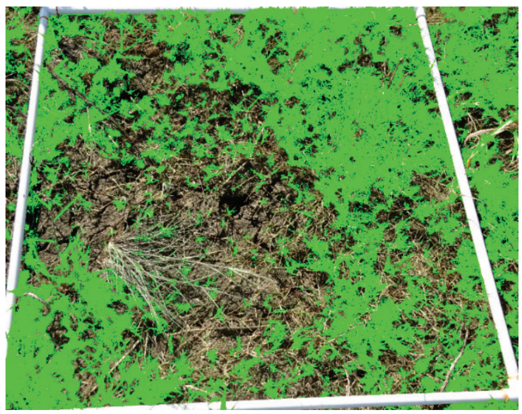


Figure A54. Middle Treatment Area, sample 6 (Non-Bermuda grass leaf area).

A.4 South Treatment Area (high biopolymer concentration)

Figure A55. South Treatment Area, sample 1 (digital image).

Figure A56. South Treatment Area, sample 1 (total leaf area).

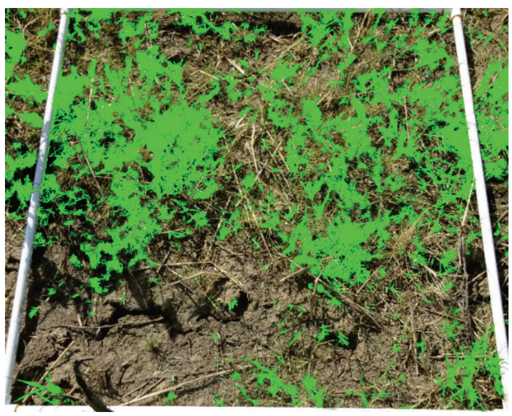


Figure A57. South Treatment Area, sample 1 (non-Bermuda grass leaf area).

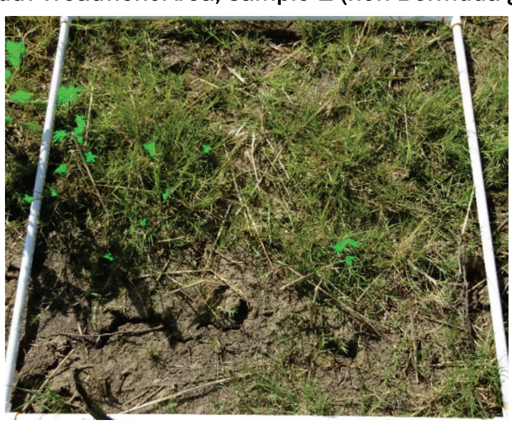


Figure A57. South Treatment Area, Sample 2 (digital image).

Figure A58. South Treatment Area, sample 2 (total leaf area).

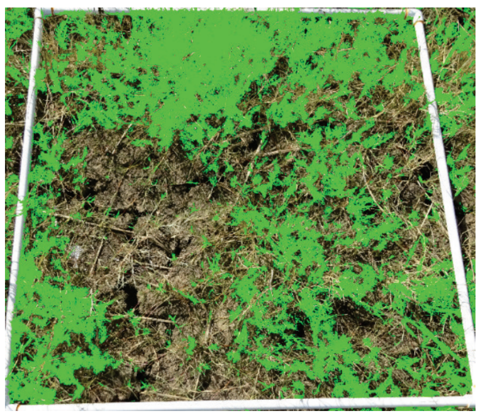


Figure A59. South Treatment Area, sample 2 (Non-Bermuda grass leaf area).

Figure A60. South Treatment Area, sample 3 (digital image).

Figure A61. South Treatment Area, sample 3 (total leaf area).

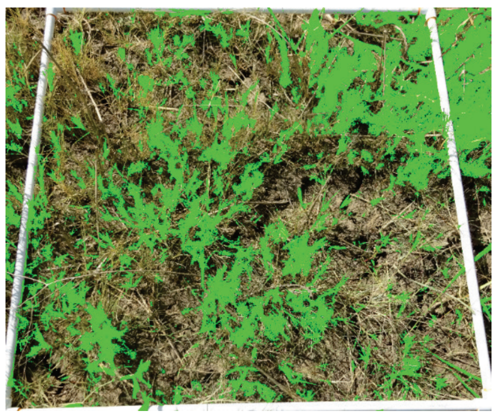


Figure A62. South Treatment Area, sample 3 (non-Bermuda grass-leaf area).

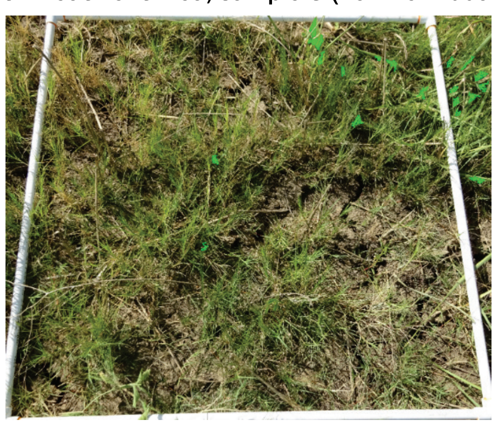


Figure A63. South Treatment Area, sample 4 (digital image).

Figure A64. South Treatment Area, sample 4 (total leaf area).

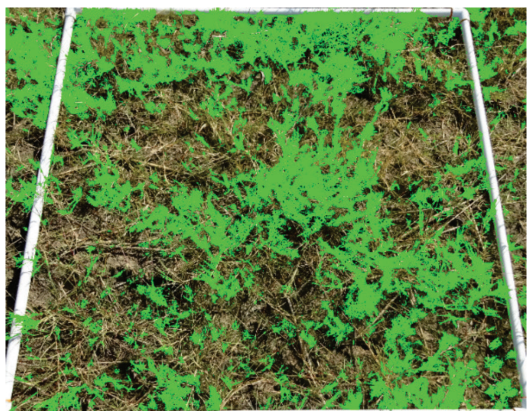


Figure A65. South Treatment Area, sample 4 (non-Bermuda grass leaf area).

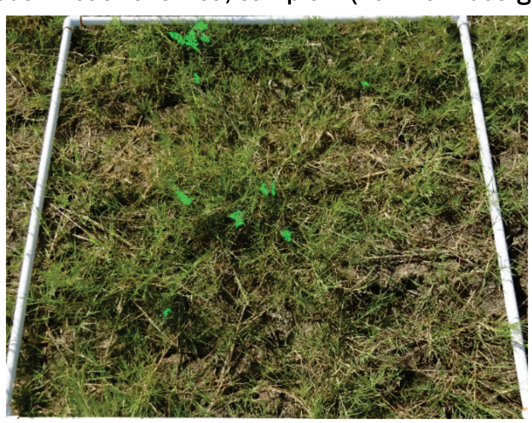


Figure A66. South Treatment Area, Sample 5 (digital image).

Figure A67. South Treatment Area, sample 5 (total leaf area).

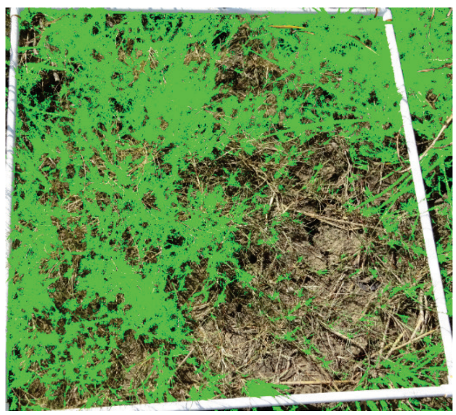
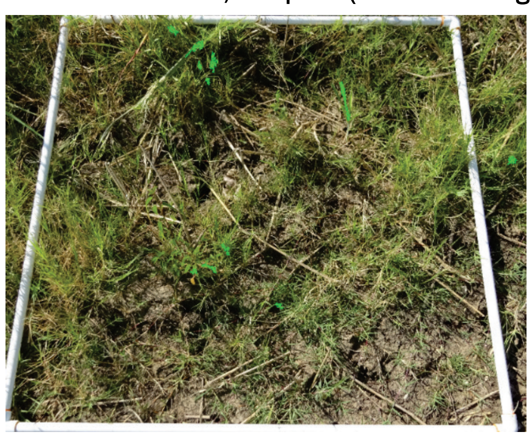


Figure A68. South Treatment Area, sample 5 (non-Bermuda grass leaf area).

Figure A69. South Treatment Area, sample 6 (digital image).

Figure A70. South Treatment Area, sample 6 (total leaf area).

Figure A71. South Treatment Area, sample 6 (non-Bermuda grass leaf area).



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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Kaufman Levee No.1 rehabilitation project is under the jurisdiction of the U.S. Army Corps of Engineers (USACE) Fort Worth District. Three areas along the levee, from river mile 445 to river mile 452, were damaged and experienced slope failure as the result of high energy flows in September 2009 and January 2010. In order to provide protection, set-back levees were designed, constructed, and vegetated in 2015. Methods currently used to maintain levees (geotextiles, mulch, riprap, and vegetation) are based on reducing transport of suspended solids from the slope and preventing erosion. Biopolymer was first evaluated at pilot scale for enhanced establishment of grass sod. It was established that determination of the root-adhering soil is an accurate prediction of field success in enhancing the root:soil integration essential to reducing soil erosion on slopes. The field study evaluated the revegetation of a levee with Bermuda grass in soil amended with organic polymer. A digital photographic image analysis technique was successfully deployed to reduce manpower and monitoring field costs for grassed levees. In conclusion, under realistic use, biopolymer soil amendment is an effective means to enhance vegetation on levee slopes, leading to greater slope stability and the potential for reduced maintenance costs.

15. SUBJECT TERMS
Biopolymer, Erosion control, Extracellular polymeric substance (EPS), field demonstration, Image analysis, Levee maintenance, Re-vegetation, Slope stability, Soil, Soil additive
Please provide at least seven terms, alphabetical order, and first letter upper case.

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