7-11-2013

Remediation of Sand Dune Blowouts Along Pipeline Right of Ways.

Knutt Peterson

Recommended Citation

Peterson, Knutt. "Remediation of Sand Dune Blowouts Along Pipeline Right of Ways.." (2013). https://digitalrepository.unm.edu/geog_etds/16

Knutt Peterson
Candidate

Geography
Department

This thesis is approved, and it is acceptable in quality and form for publication:

Approved by the Thesis Committee:

Olen Paul Matthews , Chairperson

Chris S. Duvall

Bradley T. Cullen

REMEDIATION OF SAND DUNE BLOWOUTS ALONG PIPELINE RIGHT OF WAYS.

BY

KNUTT PETERSON
BACHELOR OF SCIENCE
GEOGRAPHY

THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science
Geography

The University of New Mexico

Albuquerque, New Mexico

May, 2013

DEDICATION

For my wife Leslie Rose, thank you for your love and support. I could not have achieved this goal without you.

ACKNOWLEGMENTS

I heartily acknowledge Dr. Olen Paul Matthews, my advisor and thesis chair, for encouraging me through the years of classroom teachings and the long number of years it took me to write these chapters. His guidance and professional style will remain with me as I continue my career.

I also thank my committee members, Dr. Chris S. Duvall, and Dr. Bradley T Cullen, for their valuable recommendations pertaining to this study and assistance in my professional development. Gratitude is extended to the Bureau of Land Management, Roswell Field Office for the funding and time to pursue this research. A special thanks to Chuck Schmidt, Angel Mayes and Janell Desmond.

To Jerry Williams, my first geography professor who inspired me to pursue geography as a profession, you made geography exciting!

To my children Amber, Dillan, and Stuart, who gave me immeasurable support over the years. Your encouragement is greatly appreciated. And finally to my wife, Leslie Rose, your love is the greatest gift of all.

Remediation of Sand Dune Blowouts along Pipeline Right of Ways

By

Knutt Peterson

B.S, Geography, University of New Mexico, 2006
M.S., Geography, University of New Mexico, 2013

ABSTRACT

Blowouts in sand dunes along pipeline right of ways are a problem facing many pipeline maintenance companies, environmentalists, and public land managers. Blowouts form in sandy soils when the ground surface is not protected from seasonal winds. The ground surface becomes unprotected when there is a lack of vegetation covering the pipeline right of way. Most pipeline maintenance companies are using temporary mitigation methods. Results presented in this study demonstrate that there are low cost, long term solutions to the problem of blowouts along pipeline right of ways. Studies were conducted using three low cost mitigation methods. Branch piles showed that a successful depositional environment could be created at the same time protecting the surface from deflation. The net structures studied, were not as successful, but with further development could be a viable solution. Snow fence was studied in a closed cell configuration, with poor results.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

1.1 Background

Geographers have long been concerned with the impact of human activities on the natural environment. In this thesis the human activity is the construction of pipelines and the natural environment is a fragile sand dune area managed by the federal government. The construction of the pipeline and the failure to adequately remediate the surface of the dune area has the potential for catastrophic harm to both this environment and any humans in the vicinity. The ability to remediate such sites and prevent this potential harm is a subject of geographic significance.

Pipeline companies are experiencing deflation problems where their pipelines are buried in loose sediments covered by un-stabilized sandy surfaces. The deflation process removes material that supports and protects the pipelines, placing the pipelines at risk of failure and leakage. This problem is evident in the high plains in southeast New Mexico, amongst other places. Although the area is mostly short grass prairie, a large crescent shaped portion within it is composed of sand dunes stabilized by Shinnery Oak (*Quercus havardii*). Several large oil fields are also found which pump, gather, and transport oil and natural gas to collection points feeding large cross country pipelines. These pipelines require long right of ways (ROWs) over federal, state, and private lands.

The ROWs crossing the crescent shaped sand dune area are particularly susceptible to deflation and blowouts which can lead to pipeline failure. Because a substantial number of pipeline miles cross BLM (Bureau of Land Management) land, federal land managers are concerned about the exposure of these buried pipelines. BLM’s primary concerns are for the safety of the public and any potential environmental impacts.

For the purposes of this thesis, a study area was selected on BLM land within the crescent shaped area of sand dunes 72 kilometers east of Roswell, New Mexico (Figure 2). The crescent shaped area in Figure 2, noted as Dunes Sagebrush Lizard (DSL) habitat, is also coincident with the sand dune Shinnery Oak environment. The sand dunes cover an area of approximately 2230 sq kilometers and are 40 kilometers wide in the latitude of the study area. The study area is located on the pipeline ROW belonging to the El Paso Natural Gas Company (EPNG). The pipeline crosses the sand dunes for 40 kilometers at an azimuth of 295º. The entire ROW was sand dunes covered by Shinnery Oak before pipeline construction. The pipeline company cleared a straight path 30 meters wide during the construction process.

Shinnery Oak grows up to 1 meter above the surface of the sand. Where the oak is thick enough, it effectively reduces the carrying capacity of the wind, and creates a depositional environment. As Shinnery Oak grows the wind deposits sand around the oak and slowly buries it, creating coppice dunes. During the oak’s life, sand is continuously deposited elevating the ground level. The oak may have sprouted when the ground surface was 5 meters below its current location. By removing the Shinnery Oak and not revegetating the ROW, a deflationary environment was created causing pipeline exposure in several places and thus potentially compromising it.

1.2 Problem Statement

Pipelines have been and will continue to be used by industry to transport fluid and gaseous materials over long distances. Often the most cost effective route between the supply end and the demand end of a pipeline is a straight line. Inevitably some of these pipelines will cross through regions with surfaces composed of loose sediments, such as sand dunes.

Without proper stabilization from the onset or perhaps due to surface destabilization after the fact, eolian processes can deflate a surface composed of loose sediments and create a blowout. If this blowout is along the path of a pipeline, the pipeline can become exposed to the elements and or unsupported and thus compromised (Figure 1). Pipeline companies spend many millions of dollars each year mitigating eolian damage in pipeline rights of way.

Figure 1: Pipelines Exposed by Blowout . Blowout on right of way located within the Mescalero sand sheet. Photo: Knutt Peterson

My research question is: Can low cost methods be utilized to inhibit deflation and encourage deposition in order to protect pipeline integrity? The question is limited to areas in which the soil is sandy and blowouts are common.

1.3 Objectives

The goal of this thesis is to evaluate the performance of three low cost sand capturing structures. Two objectives and hypothesis are established to meet the goal of this thesis:

1) The first objective is to compare the sand capturing characteristics of three different structures erected in a pipeline right of way that is susceptible to deflationary wind action. This research hypothesizes that all of these structures will create a depositional environment.

2) The second objective will determine the variability in the performance of the three structures. It is hypothesized the structure mimicking a natural organic form will perform better than structures with straight lines.

The two hypotheses relate to a general hypothesis that any depositional environment created would also be favorable to the establishment of native vegetation.

The rational for conducting this study is three fold. Mitigating blowouts on pipeline ROWs (i) impacts pipeline maintenance companies, (ii) public safety, and (iii) the environment.

Pipeline maintenance companies are in a constant battle with blowouts in sand dunes. They spend millions of dollars filling in blowouts to cover up exposed pipelines and also in preventative measures to avert future blowouts. They need to keep the pipelines covered to prevent external corrosion caused by the elements. The pipe's external protective coating can be degraded by wind driven sand through abrasion, ultraviolet light from the sun, and precipitation. Finding a cost effective, long term and environmentally sound solution to this problem is in their best interests. Disruption of service, environmental cleanup, litigation payouts, and repairs resulting from pipeline failure can be more costly than mitigating a single blowout.

Public safety concerns range from motorized vehicle collisions with the exposed pipeline to someone shooting an exposed high pressure pipeline with a high powered rifle. If a pipeline is compromised by either internal or external corrosion, the additional stress from an impact to the pipeline can cause a rupture. On August 19, 2000, a 30-inch diameter El Paso Natural Gas transmission line ruptured near where the pipeline crosses the Pecos River, about 30 miles southeast of Carlsbad, New Mexico. After the rupture, a natural gas fire started and burned for almost an hour before firefighters brought it under control. The fire killed seven adults, three children and two infants camped 250 meters from the rupture, and destroyed three pickup trucks. The trucks had been driven unwittingly across the buried pipeline to reach the area adjacent to the bridge carrying the pipelines. The subsequent investigation found that the pipeline had failed due to internal corrosion (NTSB, 2003). The dollar amount associated with this rupture was nearly one million dollars in damage repair, and $14 million dollars to the family of one of the victims. Compensation amounts for the other 11 victims are not available. The DOT is seeking a $2.52 million civil penalty from El Paso Natural Gas (Billingsley, 2002).

The environmental impacts from a pipeline rupture can be varied depending on the contents of the pipe. Spills of fluid minerals such as oil or gasoline need to be cleaned up before they come in contact with groundwater. Natural gas pipeline ruptures can cause large explosions resulting in large craters and fire spreading to habitat or homes if it occurs near urban areas. Ranchers in rural areas can loose valuable forage their cows graze to fire. Disruption of service to customers has national security implications. In areas where pipelines cross through the habitat of threatened species like the Lesser Prairie Chicken (LPC) (*Tympanuchus pallidicinctus*) and the Dunes Sagebrush Lizard (DSL) (*Sceloporus arenicolus*), (Figure 2), the BLM and environmentalists are concerned with damage, contamination and or the destruction of habitat. This damage can come in the form of fluid mineral spills (contamination) or fire which can burn habitat.

The BLM has developed a resource management planning area (RMPA), which establishes certain habitat protection measures to limit wholesale destruction of habitat. Within the RMPA, two ACEC's (Areas of Critical Environmental Concern) have been established. The southern ACEC was created to protect two large open sand dune areas. The northern ACEC protects some of the best LPC habitat on federally managed lands (Figure 2).

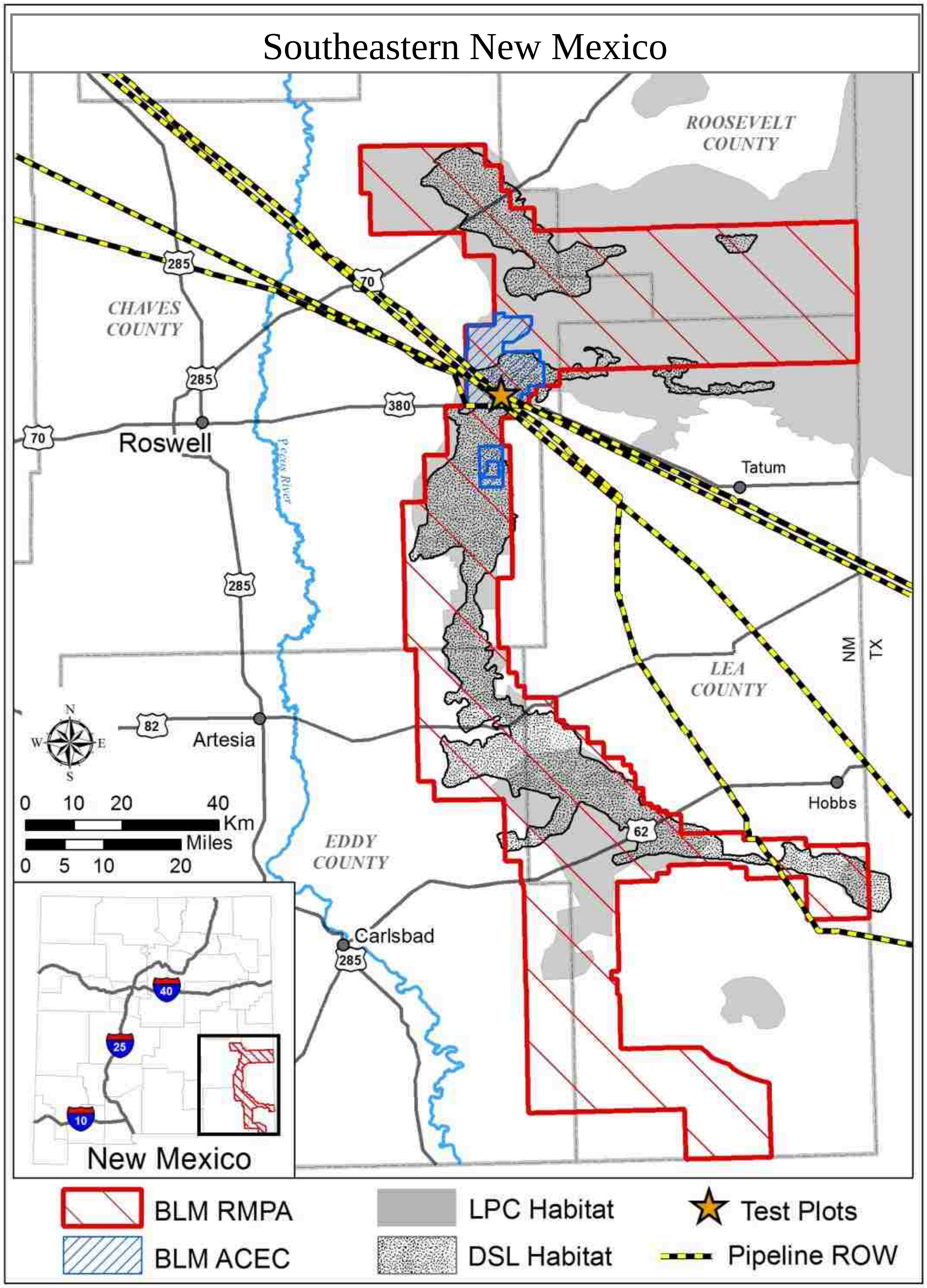


Figure 2: Map showing the area of southeastern New Mexico where the Mescalero sand sheet exists. The sand sheet is coincident with the DSL habitat. The sand sheet is contained within the BLM's Resource Management Planning Area. Habitat of the threatened species LPC and DSL are contained within the RMPA. Map by: Knutt Peterson

2. Literature Review

The literature review is divided into two basic parts. The first deals with the theory behind sand movement and the formation of blowouts. There are three environmental variables which affect eolian sand movement and the formation of blowouts: (i) wind speed, (ii) surface conditions, and (iii) wind direction (Figure 3). As we will see, not all variables are equal under all circumstances and thus can create a wide variety of aeolian features through deposition and deflation. The second concerns different methods used for mitigating sand movement. Some of these methods have been applied to blowouts along pipelines with varied success.

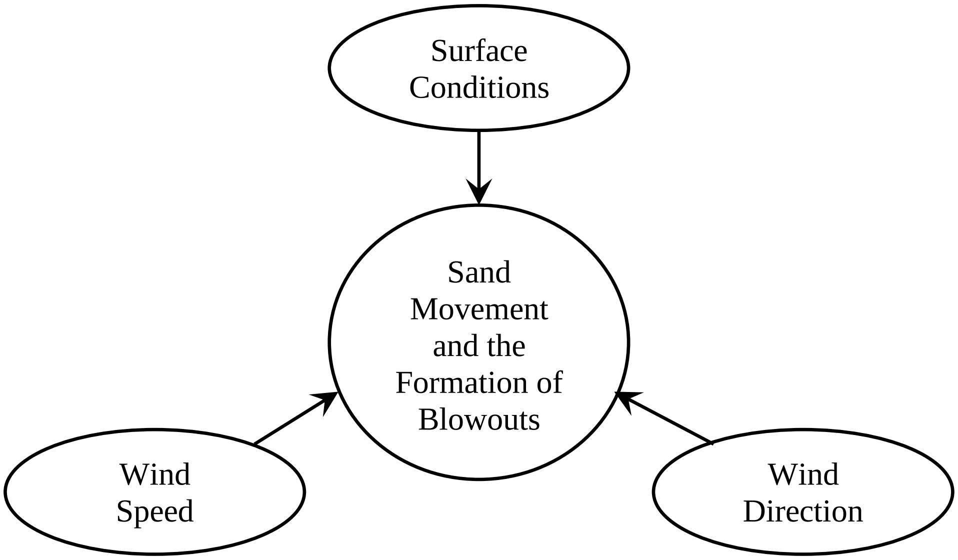


Figure 3: The three environmental variables which affect sand movement and the formation of blowouts. Figure by: Knutt Peterson

2.1 Theory of Sand Movement

The movement of sand has been an on going process since the first sand grains formed. Sand moves in a variety of ways, the most common through conveyance by a fluid. The two fluids that do most of the work are water and air. Both fluids act on sand particles in much the same way. The type of motion of the grains, and the resulting drag on the fluid, appears to be much the same (Bagnold, 1937). Only the basics of wind blown sand transport will be reviewed here. Regions having sparse vegetation, low precipitation, and unconsolidated surface sediment, not tightly bound by root systems, are most vulnerable to wind attack. Most often these regions exhibit evidence of eolian processes. The driving force in eolian processes is the wind.

Certain attributes of the wind, mainly its direction and speed, are responsible for most eolian geomorphic features. The development and preservation of these features depends primarily on whether wind direction is consistent or variable. Wind direction will be discussed below under sand dune morphology. The third element in understanding deposition or deflation within a sand environment is related to the nature of the surface. This will be discussed under surface conditions. Keep in mind that although the literature is divided into three distinct segments, overlaps occur since all factors are in fact integrated.

2.1.1 Wind Velocity and Sand Movement

Wind velocity is important because it is the prime determinant of what material will move under wind attack and what will remain stationary. Wind velocity increases with height above the ground, because it is slowed at the surface by friction (Bagnold, 1941). This surface friction is caused either by the roughness of the ground surface, such as by sand, gravel, or large stones and rocks. Other features causing friction at or near the surface are vegetation and man made objects such as buildings. Closer examination shows surface friction is more complex than this generalization indicates. As wind flows around objects, its velocity can increase or decrease. Decreases occur when wind blows through brushy vegetation or trees. Wind velocity can increase when the wind swirls around the edge of an object like a rock, fence or building. These complexities create a degree of uncertainty when designing experimental plots.

The size of sand particle the wind can carry is related to wind velocity. Increases in wind speed mean larger particles can be carried. In a dust storm, only the smaller particles reach any significant elevation and become suspended in the moving airstream. Whereas larger particles, such as sand, return to the ground surface (Bagnold, 1941). Thus, wind velocity and its interaction with surface elements are important for understanding the dynamics of sand movement.

Sand grains in deserts are primarily transported by wind and avalanching (Bagnold, 1941). There are three modes that the wind can transport a sand particle: saltation, creeping, and reptation. Bagnold, in his classic tome (1941), identified, through careful experimentation and reason, the principals of saltation: the collisions between descending sand grains and the sand bed, and their relation to grain entrainment; the trajectories of sand grains in the wind; and the effect of moving sand grains on the wind velocity profile. He defines saltation as wind-driven sand grains moving in bounds, rising steeply into the air stream, and there being urged forward by the pressure of the wind upon them. By their weight they fall to the ground again, but with a horizontal velocity component acquired from the air. When the saltating sand grain impacts the ground several actions can occur. It can impact a larger grain or stone and bounce, continuing its saltation journey, or it can impact a group of grains of similar size and end its flight. This impact into similar size grains causes another phenomenon called reptation. Reptation is the mode of particle transport in which grains are lifted or ejected only weakly and do not rebound or eject other particles when they return to the bed. Creeping is the rolling of sand grains by being impacted by another grain or shoved along by the wind (Bagnold, 1941).

Because wind velocity is a critical variable in sand movement, one of the strategies for preventing deflation is to lessen wind movement. Surface barriers can be erected to slow the wind speed locally. If the wind speed can be slowed, the capacity of the wind to move sand is reduced. If designed correctly, surface barriers will result in local reduction in wind speed and deposition will occur. Sand barriers also serve the purpose of preventing deflation at a site by reducing wind speed to a level below the entrainment speed. A critical element is to orient the barrier in a way that takes advantage of prevailing wind directions.

2.1.2 Wind Direction and Blowouts

The occurrence of different dune types is generally controlled by vagaries in wind direction combined with wind speed, sand supply, vegetative cover, and particle size (Lancaster 1983). Other variables listed are discussed in different parts of this literature review. The movement of sand by the wind causes a variety of different geomorphic features to be formed. Sand dunes are the feature most associated with eolian processes and come in many forms. Many dunes develop in a distinctive symmetry profile that has three components: the backslope or windward surface, the crest, and the slipface or lee slope. Dune types vary in response to the above mentioned variables and come in many different forms, such as Barchan dunes, Barchanoid dunes, Transverse dunes, Star dunes, Parabolic dunes, Dome dunes, Reversing dunes, Linear dunes, Coppice dunes, and Blowout dunes. These different dune types are created by variances in wind direction, wind speed, and surface conditions.

Many studies have been done on dune formation, structure, and environment by noted scientists like Major R. A. Bagnold, the father of sand movement and associated geomorphology. Bagnold pioneered early exploration of the Libyan Desert in the 1920s and 30s, and from this emerged his ground-breaking work on the physics of sand transport.

For the purposes of this thesis, the focus will be on the geomorphology of the Blowout dune. It is the culprit in exposing pipelines within the Mescalero sand sheet and the study area encompassed in this paper. The alignment of blowouts to wind direction is especially critical.

Blowouts are sandy depressions in a sand dune ecosystem caused by the removal of sediments by wind. Blowouts occur in partially vegetated dune fields or sand hills. A blowout forms when a patch of protective vegetation is lost, allowing strong winds to "blow out" sand and form a depression called a blowout. Although they generally remain small, blowouts can expand to kilometers in size and up to around 70m in depth (Jungerius, 1989).

Causes of vegetation loss include extended droughts, fire (natural and anthropogenic) or, in extreme cases, trampling by humans, cattle, horses (Correa, 2008). Construction of roads and pipelines without some sort of surface treatment in the sand environment, such as a caleche road base in the case of roads and re-vegetation for pipelines, will eventually lead to sand being available for movement. In time, succession will begin again as suitable seeds are blown in and pioneers become re-established (Barbour, 1895). However, if continual disturbance occurs, vegetation can not become re-established and the chances for blowouts to develop will persist.

A study by Fraser (1998), which looked at wind flow patterns in a coastal dune blowout, found that the ambient wind flow direction is changed dramatically when it enters a blowout. The deflection of wind direction and velocity within the blowout depended upon the ambient wind angle relative to the axis of the blowout. Significant veering was evident in the deflationary floor where resulting flows were deflected as much as 90˚ from ambient (Figure 4) suggesting the formation of a helical flow cell under a separated flow. Furthermore, winds in the blowout were directed as much as 180˚ to the ambient flow on the dune crest suggesting that a pronounced flow separation prevails and that flow in the blowout was actually a countercurrent under the separated boundary layer (Figure 5). Maximum wind speeds and shear velocities occurred in the center of the deflationary floor where the countercurrent was strongest. Although none of the winds measured during the monitoring period were sufficiently strong to initiate sand movement, the wind flow patterns in the blowout that did result from the onshore and offshore winds that were experienced, suggest scenarios under which blowout evolution may have occurred. For example, strong westerly-directed flow might produce a helical flow cell oriented parallel to the axis of the blowout with shear velocities sufficient to induce sand transport up the transportational ramp (Figure 6).This helical flow is the force that does the excavation of the blowout. In the study area, this means the prevailing wind direction’s relationship to the de-vegetated right of way and potential blowouts is critical. On test plots, wind barrier experiments need to be oriented in a way that considers these relationships.

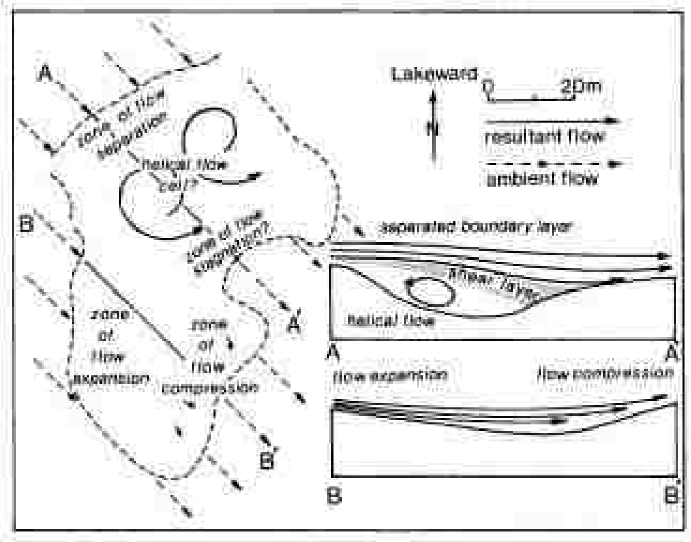


Figure 4: A helical flow cell was established in the deflationary basin where flow separation occurred over the steep northwest wall of the blow-out, but flow expansion and deceleration occurred at the south end where the ambient flow entered the blowout over a relatively gentle slope. (Fraser, 1998)

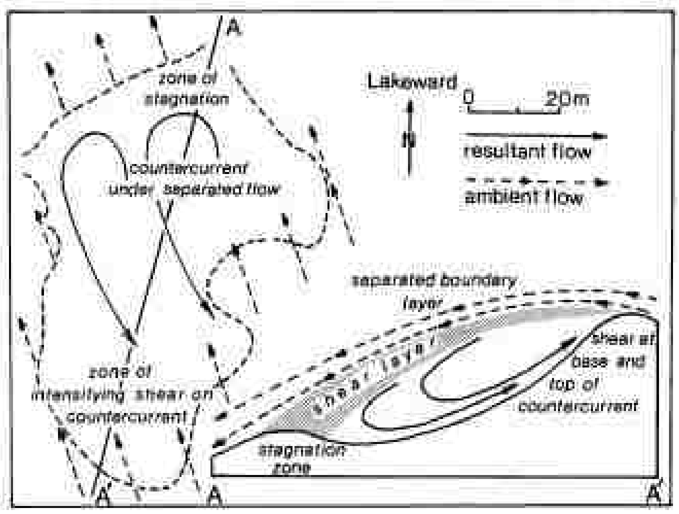


Figure 5: The countercurrent established in the deflationary basin was at nearly 180˚ to the separated ambient flow. (Fraser, 1998)

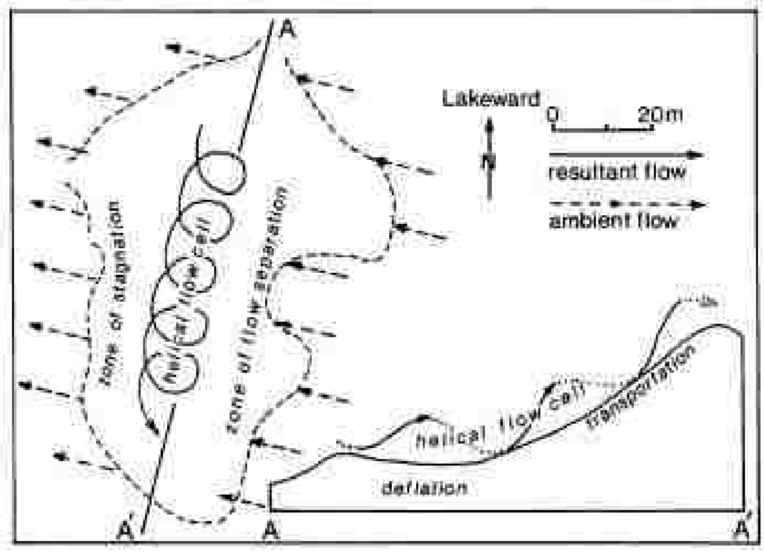


Figure 6: Hypothetical flow patterns that might be established in the blowout under conditions of strong westerly-directed flow. A helical flow cell set up under the separated flow might have shear velocities sufficient to induce sand transport out of the deflationary basin and up the transportational ramp. (Fraser, 1998)

2.1.3 Surface Conditions

Surface condition includes many variables when considering sand movement. The most important are vegetation cover, sand particle size, surface roughness, and sand supply. Vegetation will be covered first.

If the cover of vegetation is locally killed, say at a watering place, a trail, or a farmstead, the persistent wind may scour away the underlying sand, thus exposing and killing the root-systems of the anchoring grasses (Melton, 1940). If conditions favor the growth of vegetation, it may cover the excavation rapidly enough to prevent further wind damage. In fact, if the environmental conditions are sufficiently favorable, grasses may undergo a large degree of damage by natural processes without permitting the wind to scour the soil away from the roots. On the other hand, if the climate is becoming increasingly more arid, or if the groundwater is being diminished by over pumping, the vegetation may find itself unable to grow as quickly as its roots are being unearthed. In this scenario the wind will continue to eliminate sand from the damaged spot. The only thing that will stop the deflation is either the area is re-vegetation or the surface consistency is changed. A continuation of this process will leave a recognizable basin in the sand surface. Since the coarser sand particles usually do not travel very far, some of this coarser sand will build up near the periphery of the excavation on the leeward side, thus forming the crescent-shaped sand ridge and basin which are the typical form of the "blowout" dune. The excavation is usually oval in shape; the rim of sand fitting closely about the lee side is crescent-shaped; and the wings of the crescent open toward the wind. In selecting experimental plots, areas that were de-vegetated were chosen. This was easier than trying to use areas that may have been partially re-vegetated and trying to determine percentage of vegetation coverage as a variable.

As was mentioned above, wind speed influences the size of particle that may be moved. Coarse particles also help shape the blowout. In a study conducted by Stout (2010), field observations of the Mescalero sand sheet confirm that it is fairly uniform with regard to soil texture. Stout (2010) also observed that saltation on the Mescalero sand sheet occurred only when winds are greater than 10 to 10.5 m/s. In addition, the results show that saltation activity is favored at certain times of the day, especially from noon to mid-afternoon, this was shown to be a function of temperature and relative humidity (RH). In this study, it was assumed that all the source material is the same particle size and will behave similarly.

Surface roughness has an impact on wind speed. Surface irregularities cause friction which both slow down the wind and provide places for sand to be deposited. Once deposited on rough surfaces sand is less likely to be dislodged than it is on smooth surfaces. Some mitigation methods change surface roughness and will be incorporated in the experimental design.

Sand supply is the last major variable. The amount of sand that can be moved depends on the supply that is exposed to the wind. If an existing sand supply is cut off from the wind then sand movement is impeded. Several of the mitigation measures discussed below use this approach. This approach was not directly incorporated in the design of experiments but may have had some impact.

2.2 Methods to Mitigate Blowouts in Dune Fields

Broadly speaking, mitigating blowouts is related to the three variables controlling sand movement discussed above. One approach is to change wind speed in ways that create deposition where it is needed. This usually includes structures oriented to the wind in ways that take advantage of local circumstances. Changing the surface conditions can also impact blowouts. It must also be kept in mind that all these variables interact with each other changing the dynamics of sand movement.

More specifically, mitigating a blowout in sand dune country involves an understanding of the dynamics of deflation in that particular spot. The dynamics involved are sand grain size, axial orientation of the blowout in relation to the dominant wind direction and average wind speed (Fraser, 1998) The basic causes of accelerated wind erosion are associated with the equilibrium between climate, soil, and vegetation. Accelerated wind erosion in many parts of the world developed after man began to interfere unduly with the natural equilibrium between the climatic, soil, and vegetative environment (Sears, 1935). Different methods are deployed in sand environments to mitigate movement of sand. In certain circumstances, the objective is to prevent erosion, and in others it is to create a depositional environment. Most research has been conducted along coastal margins, but this research can be applied to inland dune environments.

Two basic approaches are used to mitigate sand movement. One uses barriers, either natural or artificial to slow wind speed. The other approach modifies the surface to change the supply of sand. Some methods incorporate both approaches. For purposes of discussion, mitigation measures are discussed under the two major processes while pointing out interrelationships when appropriate.

2.2.1. Reducing Wind Velocity

2.2.1.1 Sand Fences

Sand fences have been extensively studied for capturing sand in many different environments. Studies have been done on the porosity of fences, and how much material is captured on the leeward side of various permutations. Other factors such as sand grain size, wind velocity, surface roughness of the ground, and height of the fence influence success at different fence porosities. Blode (2003), Alhajraf (2004), Raupach (2001), Rosenberg (1974), Raine and Stevenson (1977) and Lee (2002) used different porosity numbers for each of their experiments. Wind flow patterns around fences of different porosities are described by Hotta (1987). Wind flow around a fence with zero porosity reveals a small circulation pattern upwind of the fence and a large circulation pattern downwind of the fence. As porosity increases, at about 20%, the small circulation cell in front of the fence disappears, and the large leeward circulation cell reduces in size and shifts downwind. This small circulation cell in front of the fence can cause deflation on the windward side of the fence. Differences in porosity result in differences in the form of the accretion of sand behind the fence.

The general consensus is that for a sand fence to be effective it should have porosity between 40 and 60 percent. Orientation of the fence is also paramount for creating a positive depositional environment. Fences should be placed perpendicular to the prevailing wind direction (Mendelssohn, 1991).

Along coastal regions, where dunes are present, sand fences have been employed for a variety of management objectives. In some areas where beach erosion is a problem, fences are used to mitigate wind erosion and help keep sand on the beach (Ruz, 2004). Sand fences cannot prevent erosion where wave attack is both frequent and damaging, but they will encourage foredune growth and resist some erosion. Fences reduce wind speed across the sand surface and encourage foredune deposition (Wallingford, 2000).

Along coastal margins a standard size 1.2 m high fence with wooden slats about 38 mm wide and porosity of 50–65% is generally effective in building foredunes (Mendelssohn, 1991; Nordstrom, 2011). Foredune elevations of up to 10 m have been deposited using sand fences (Hotta, 1991). The rate of growth is greater using fences than under natural conditions and is concentrated in a smaller zone. Sand accretion rates of up to 10–20 m^3 per square meter per year have occurred in The Netherlands, aided by prevailing onshore winds (Nordstrom and Arens, 1998). Sediment accumulated at a single fence during a 12 month period can range from 6.0 to 8.5 m^3 per square meter of ground surface.

All the research shows that sand fences are effective. Different kinds of fences have different degrees of efficiency depending on local circumstances. For this research the main question is whether fences are cost effective when compared with other methods.

2.2.1.2 Netting

Agricultural nets are used in fruit and ornamental production as covering material in various light structures such as anti-hail and/or anti-frost shields, windbreaks, shade coverings, and anti-bird or anti-insect structures. There is limited information in the existing standards for the calculation of wind loads on structures with permeable cladding like nets. Moreover, there are few experimental data concerning the wind pressure distribution around air permeable structures (Briassoulis, 2010). Studies have been done in two circumstances. One used a natural setting to evaluate wind flow through a net covered tunnel. Experiments using net fences have also been done.

Mistriotis (2012) studied airflow around and through a net covered tunnel structure that was experimentally and numerically analyzed for wind speeds above 10 m/s. A full scale tunnel structure covered with four different nets, characterized by different aerodynamic properties, was built. One of the findings of this study was that the net created a moderate windbreak effect. A part of the airflow was forced above the structure resulting in an increased air velocity along the roof. A reduction in airflow was measured within the net structure (Figure 7). The experiments and numerical simulations indicate that the internal air velocity depends on the aerodynamic resistance coefficient of the net, rather than its solidity ratio.

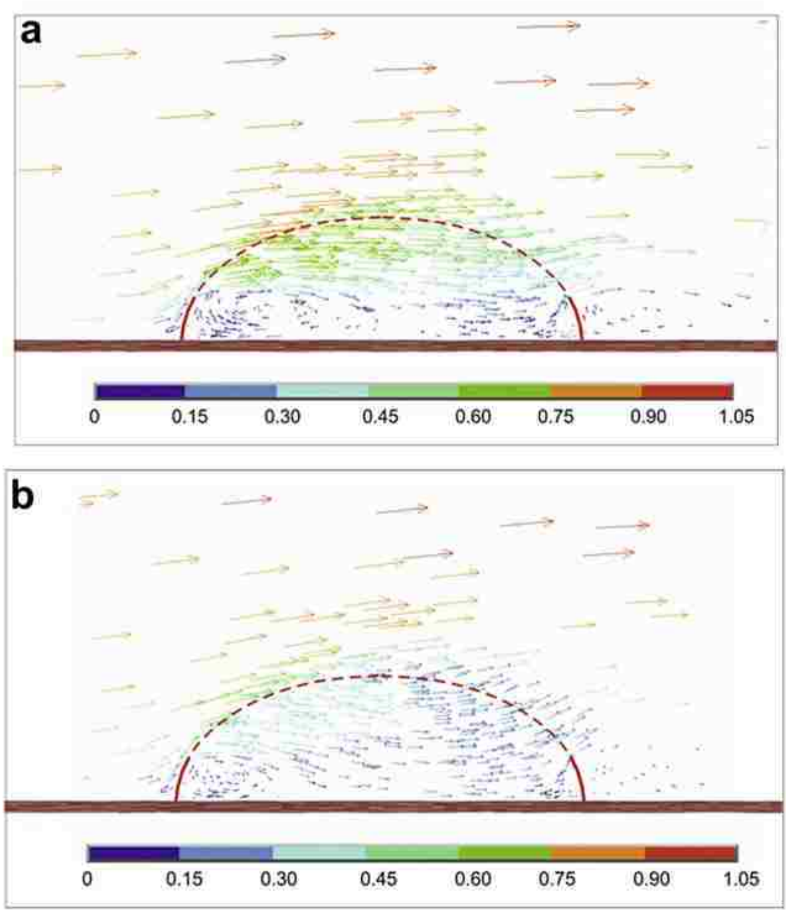


Figure. 7 - Normalized air velocity vector fields around a net tunnel structure in m/s. (Mistriotis, 2012)

The reduction of airflow within covered net structures could be used to create a depositional environment for sand.

Studies related to nets and sand is limited to net fences. Porous nylon net fences 0.8m high and with porosity about 60% are used in China to help control sand movement (Dong, 2004). Dong’s (2004) study found the sheltered distance of the nylon net fence is no more than twice that of the fence height, where as those of the upright porous snow fence and close clustered reed fence exceed 12 times the fence height. In regards to fences, the impact on deposition varies with the fencing material. This could be a factor in determining cost effectiveness.

2.2.1.3 Branches and Brush Piles

Included here is a discussion of brush piles and pine branches. Studies of brush piles for the accumulation of sand is extremely sparse in the literature. However, research has been conducted on sand accumulation around live bushes, grasses and mesquite trees. Mesquite bush, in the Southern High Plains, for example, grows vigorously on loose sand and is not readily killed by slow sand burial. Sand which falls within the bush may thus stay for a considerable time. If this process continues, a mound of sand eventually is built and held together by the coppice (Melton, 1940). Piles of brush should have a similar impact and are low in cost, if they are readily available.

During the late nineteenth and early twentieth centuries, dune stabilization on Cape Cod, Massachusetts was preformed using pine branches. As a means of control for very active sand dunes, pine branches are usually spread on the northwest (“Blow” or “Live”) side of the dune. These branches serve as a barrier against the wind and as a shelter which catches beach grass seed. Beach grass seed which is usually quite plentiful will germinate and establish the grass the next season (Kucinski, 1943). The pine branches are spread one layer deep. Brush piles could perform a similar function and provide opportunity for natural seeding to occur.

2.2.2 Surface Stabilization

In arid environments, stabilization of sand is of great concern. Roads, rail lines, farmland, pipelines and even towns are under threat of wind blown sand. In this section, surface stabilization refers to a surface treatment, and is included because it is the most used treatment method for pipelines in the study area. A discussion of stabilization methods used on pipelines in the study area region and their success, or lack thereof, will be included in the discussion section.

Surface or soil stabilization involves coating, mixing into, or covering the surface to be stabilized. Surfaces can be covered by mulches, chemical coatings, gravel, rock, synthetic and natural geotextiles, and engineered products like articulating concrete block mats. Substances like lime, sand and petroleum products can be mixed into the top strata of the surface to be stabilized. Because most of these methods are expensive, they will not be discussed extensively. Some discussion is warranted because it provides a context for understanding more fully the surface dynamics associated with sand movement.

2.2.2.1 Mulches and Chemical Sprays

Mulch is defined as any material at the soil surface that was grown in place, grown and modified before placement, and any material processed or manufactured and then placed. Examples include crop residues, tree limbs, woodchips, gravel, plastic films, asphalt, and livestock manure (Armbrust, 1977)

Research on chemical stabilization of sand surfaces dates back to the 1930s. More than a half century of research and practice has shown that chemical stabilizers (Tackifers) are particularly suitable for the control of shifting sand and the reduction of damage to railways and highways in deserts characterized by mobile sand. Chemical stabilization of sand forms a binding surface crust that conserves soil water beneath the crust, prevents or impedes wind erosion, and stabilizes the sand (Han, 2007).

Han (2007) found that depending on their chemical properties, sand stabilizers can form three types of binding crust: a rigid crust, a flexible crust, or an elastic crust. All these crusts have smooth surfaces that protect the sand surface from direct erosion by wind. He also found the combination of several sand control measures, including chemical treatments, biological measures, semi-buried sand fences, and upright sand fences, can effectively control damage from blowing sand.

Armbrust's (1977) findings concluded that any mulch material can prevent wind erosion if applied at a sufficiently high rate to the total soil surface. Costs become prohibitive for many materials, particularly the petroleum-based products. Prairie hay, wheat straw, feedlot wastes, and other well-anchored vegetative materials apparently are the best mulch materials and the least expensive to control wind erosion.

2.2.2.2 Vegetation and Grasses

Grass cover performs two functions in regards to the deflation process: it tends to slow the wind near the surface thereby enhancing aeolian deposition, and it stabilizes the surface by preventing deposited sediments from becoming detached and deflated by strong winds (Stout, 2012).

In Burri (2011), it is discussed how vegetation plays an important role in reducing soil erosion by wind in arid and semi-arid environments. The effect of vegetation on wind erosion is attributed to several mechanisms: (i) sheltering of the ground surface from the erosive force of the wind, both by creating wakes of reduced mean wind velocity and by covering a proportion of the ground and thereby limiting the erodible area, (ii) momentum extraction from the wind by absorbing a part of the total shear stress of the wind and thereby decreasing the shear stress acting on the ground and on the downstream plants, and (iii) trapping of windborne soil particles (Wolfe and Nickling, 1993). Furthermore, plants reduce wind erosion by altering soil and atmospheric characteristics, such as soil structural stability and near-surface air moisture (Eldridge and Leys, 2003;

Namikas and Sherman, 1995). The branch piles chosen for this experiment have some of those same attributes.

Re-establishing an intact vegetation cover is a common measure to counteract soil degradation by wind erosion. However, studies of wind erosion in the presence of vegetation are complicated by the variability of vegetation characteristics and their dynamic interactions with different soil properties, atmospheric conditions and land surface-characteristics, e.g. humidity and temperature of the soil and air, topography, soil texture, composition, aggregation and crusting (Shao, 2008).

2.2.2.3 Geotextiles

Geotextile is a general term for a manufactured product composed of natural or synthetic materials that has the general form of a woven fabric. There is a multitude of geotextile products on the market. For the purposes of this thesis, a general discussion of the benefits and drawbacks of synthetic and natural geotextiles is covered.

Geotextiles, manufactured from synthetic polymeric materials are termed synthetic geotextiles. Synthetic geotextiles are non-biodegradable and may cause soil pollution (Fullen, 2007). Furthermore, their production process may cause air and water pollution. Synthetic geotextiles can cost over 10 times as much per unit area as natural ones (Ingold, 1996). Thus, ecological considerations raise doubts about the long-term effects of indiscriminate application of synthetic materials (Banerjee, 1996). The material composition of geotextiles determines their longevity in the field: natural products last about two to five years, whereas synthetic products last 25 years (Oosthuizen and Kruger, 1994). However, Bhattacharyya (2010) argues that once vegetation is established on-site, geotextiles become redundant in terms of erosion control.

Geotextiles constructed from organic materials are highly effective in erosion control and vegetation establishment (Sutherland and Ziegler, 1996; Langford and Coleman, 1996; Ogbobe, 1998). Natural fibers are more effective than synthetic in controlling erosion (Sutherland and Ziegler, 1996) and were the preferred method because of their 100% biodegradability and better adherence to the soil (Langford and Coleman, 1996). Additionally, biomats can help to decrease the penetration of intense solar radiation to the ground, suppress extreme soil temperature fluctuations, reduce water loss through evaporation, and thus conserve soil moisture, which can create ideal conditions for plant establishment and growth (Sprague and Paulson, 1996).

Natural fiber erosion control mats come in several different varieties and can be a cost effective way to control erosion. A simple single layer jute mat costs about $0.14 per sq. ft. The cost to cover a mile of ROW 20ft wide is about $14,000 for mat materials. During installation, natural fiber mats need to be staked down to the soil surface to prevent movement of the mat, an additional cost to the project.

Mats of different configurations have become popular to control degradation of soils by erosive forces. Mats have been used to control the erosive force of water on ROWs crossing stream channels, shorelines, banks of ponds and lakes, and hillsides. Articulating concrete block mats, like those produced by companies like Submar (Figure 8), Contech, and International Erosion Control Systems provide a heavy armored surface against erosion.

Figure 8: Articulating concrete mat at one of Submar's testing sites in Southeast New Mexico. Photo courtesy of Submar.

In a phone conversation with a representative for Submar about articulating concrete block mats, it was noted that Submar was working on reconfiguring their mats to be used for control of blowouts on pipeline ROWs. Their conventional 8ft by 20ft by 4.5 inch thick articulating concrete block mats are heavy, 6200 lbs, while they have worked well in test plots, they are over kill for mitigating deflation in sandy environments. Two reasons for the reconfiguration are: (i) The mats are not economical, at $20/ sq ft, to put on long stretches of pipeline ROWs . For a conventional mat, it was estimated to cost 2.1 million dollars per mile installed. (ii) The mats can only be transported eight at a time on a semi truck due to their weight. Submar is working on making the concrete blocks thinner and out of a lighter weight concrete. This would cut the cost and weight of each mat, making installation per mile less. No figure was given as to how much the cost per mile would be for the new mats. There are several benefits to using concrete mats for deflation control on sandy surfaces: (i) The mats can be removed from the pipeline ROW and then replaced after pipeline maintenance is completed. (ii) The gap between the concrete blocks, which are held together by nylon cables, is sufficient to capture seeds and moisture which allows vegetation to gain a foot hold (Figure 8). (iii) Moisture that percolates between the blocks and wets the soil underneath the mat is maintained in the soil for a longer period of time and thus available to plants for a longer duration.

Submar’s initial studies on sandy surfaces have found that one of the drawbacks to the articulating concrete block mat is if the outer edge of the mat is not angled downward and buried at an outward angle, a pressure wave shaped by the wind can form at the edge of the block mat. This pressure wave can start to remove sand from the upwind edge creating a blowout, which in time can undermine the mat. The potential for blowout can be mitigated with proper installation of the mat.

2.3 Summary

The problem of mitigating blowouts in a sandy environment rests on an understanding of the dynamics that cause sand to become entrained and the factors which prevent entrainment.

For sand to be mobilized surface conditions need to be advantageous for entrainment of sand. There needs to be a readily available supply of sand, of sufficient depth, for entrainment to occur and dunes to form. Grain size determines at what wind speed entrainment will occur. The smaller the grain size the lower the wind speed needs to be for mobilization. Relative humidity (RH) and sand moisture levels also impact when entrainment occurs, the lower the RH and sand moisture levels, the sooner sand can be mobilized. Surface friction plays a role in entrainment of sand by reducing the wind speed at the ground surface. Surface friction is caused either by a combination of the roughness of the ground surface, vegetation, or man made structures. Surface friction on the ground is caused by sand, gravel, large stones and rocks. Vegetation, including surface forbs, grasses, bushes and trees slow the wind speed at or near the ground surface thus increasing surface friction. Vegetation in the course of providing ground cover, shade and reducing wind speed is a significant dynamic in soil moisture levels and relative humidity levels. The percentage of vegetative cover plays a key role in dictating the mobilization of sand. Manufactured objects and anthropogenic structures play less of a role in sandy environments as they are not very numerous. Debris such as old tires, abandoned machinery, and other discarded items increase surface roughness in a very localized area. Barbed wire and net wire fences have a larger impact when tumbleweeds and other detritus are blown against them, reducing the flow of air through the fence, thus creating a depositional environment on the leeward side of the fence. This has a similar effect to the snow fence, which are also put out on the landscape.

Mitigating the entrainment of sand is simply accomplished by increasing the surface roughness of a body of sand that is primed for mobilization. Increasing the surface roughness can be accomplished in several ways. The wind speed at the ground surface must be reduced to below the carrying capacity of the effected sand grain size. This can be done through the planting of vegetation either as linear wind breaks or in an expansive regime. Coating the sandy surface with gravel, rocks or mulch increases the surface roughness and prevents mobilization of the sand. Another way to increase surface roughness is to increase the size of the sand grain. This can be accomplished by cementing the grains together through the use of chemical or biological tackifiers, thus making them unavailable for entrainment.

Wind speed and wind direction are the two other factors that need to be addressed in the mitigation of blowouts. These two factors are not something that can be affected on a large scale. Seasonal winds, gust front winds generated by thunderstorms, and winds associated with cold fronts are large scale events. Wind speed and direction can only be changed on a very local level.

If the average wind speed at a site is not high enough for an adequate amount of time, mobilization of large quantities of sand will not happen, therefore blowouts are less likely to occur. If the average wind speed is adequate and for a sufficient duration to entrain large amounts of sand, mitigation measures to increase surface roughness need to be implemented.

Wind direction is important to the formation of blowouts in particular. Wind moving over a flat surface in any direction at any speed will not create a blowout. The wind will simply mobilize sand from one place to another, building dunes of other types. For blowouts to form wind needs to abruptly change direction and form a helical flow cell. This helical flow cell causes a digging effect on the ground surface. The helical flow cell forms when some the wind flow is separated from the ambient wind flow as noted in the study by Fraser (1998). On the Mescalero sand sheet, vegetation and sand movement cause coppice dunes to form. As wind moves over the coppice some of the wind flow is separated from the ambient wind flow and a helical flow cell forms on the leeward side of the coppice dune. If the ground surface is devoid of vegetation on the leeward side of the coppice dune, say from a pipeline ROW that has lost its vegetation, a blowout will form.

These three factors, surface conditions, wind speed, and wind direction, play a roll in the formation of a blowout (Figure 9). It must also be kept in mind that all these variables interact with each other changing the dynamics of sand movement. In the study area, this means the prevailing wind direction's relationship to the devegetated right of way and potential blowouts is critical.

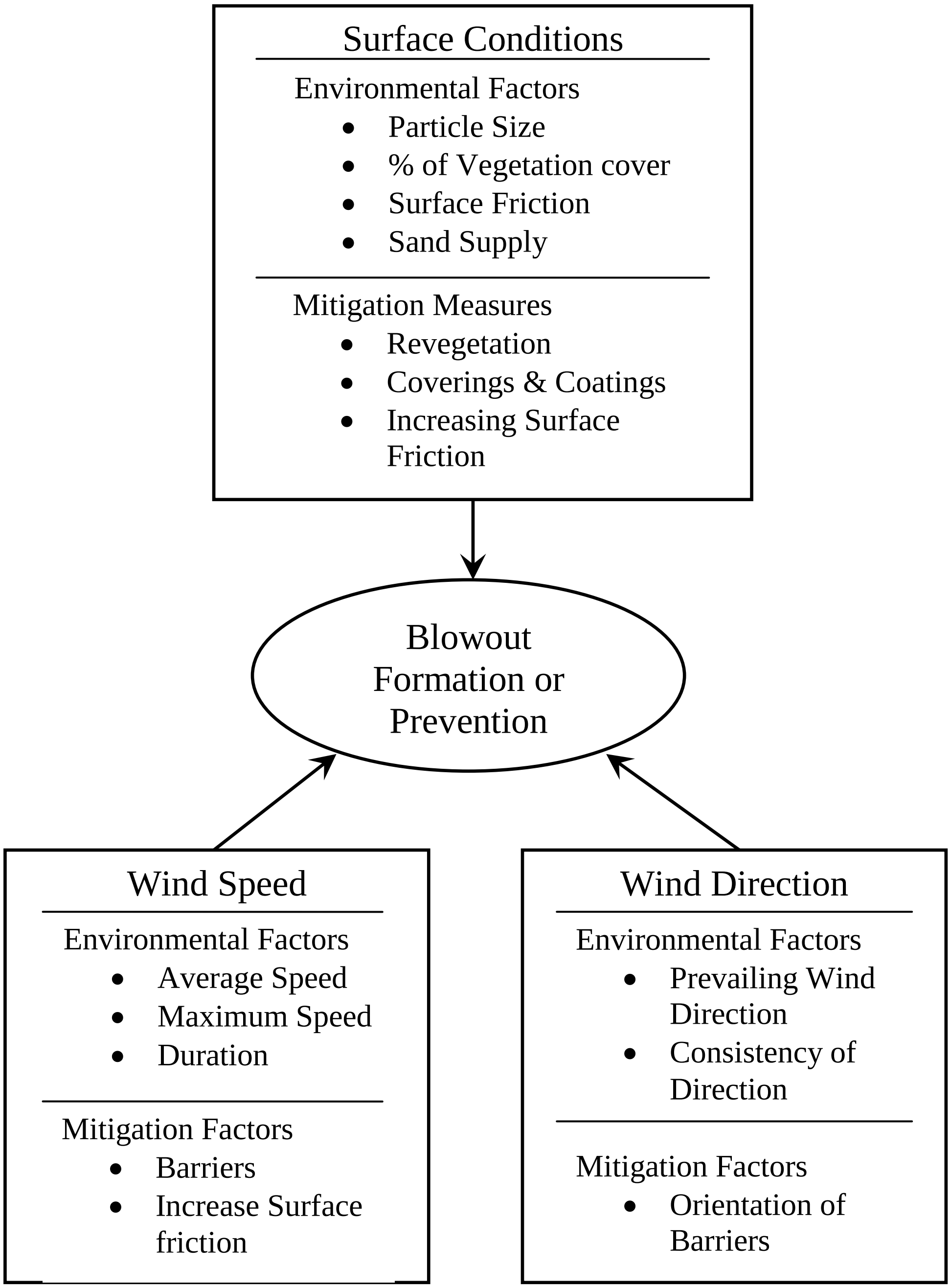


Figure 9: The three factors, surface conditions, wind speed, and wind direction, which play a roll in the formation of a blowout. Environmental and mitigation factors need to be considered in relation to each other. Chart by: Knutt Peterson

3. Methodology

3.1 Current Situation

If blowouts are to be mitigated through anthropomorphic interdiction then an understanding of the local relationship between surface conditions, prevailing wind direction, and wind speed must be taken into account. Prior to starting this thesis, many miles of pipeline in southeastern New Mexico were driven to observe current blowouts on pipelines and mitigation methods.

Local pipeline maintenance companies, who are in charge of mitigating blowouts on pipeline ROW on the Mescalero sand sheet, employ several different methods to mitigate blowouts. First and foremost is to rebury the exposed pipe with a mound of sand and stake down a geotextile over the mound. This is a good short term solution. However, in the long term the mound sets up the helical flow cell on its leeward side, creating another blowout. The wind also attacks the geotextile and eventually displaces it from the mound of sand, which is then susceptible to the same wind forces that created the blowout in that spot in the first place (Figure 10).

Figure 10: One year old geotextile repair, placed over sand mounded on top of exposed pipeline. Geotextile is already being torn away from repair. Photo: Knutt Peterson

Sand fences have been utilized on some ROW blowouts with varied degrees of success. In successful applications, the orientation of the fence was perpendicular to the prevailing wind direction. These fences were observed to be mostly buried. At other sites, no accumulation of sand was found near the sand fence, and deflation had continued in the blowout, as evidenced by the bottom of the fence being 1 to 2 ft above the sand surface and once buried tee posts suspended from the fence. These fences were oriented nearly parallel to the prevailing wind direction.

Another method used on the Mescalero sand sheet is the articulating concrete mat. This method has been successful in the long term protection of pipelines to blowouts. However, the cost of this mitigation method is very expensive.

The success or failures of the current blowout mitigation methods used on the Mescalero sand sheet are clearly tied to an understanding of the factors that created the blowout in the first place.

In devising the experiments used in this thesis to mitigate deflation in blowouts, an understanding of surface roughness, wind speed, and wind direction were applied to each. Each experiment was designed to create an element of increased surface roughness to slow wind speed and be oriented to the prevailing wind direction but also be effective to varied wind directions.

3.2 Field Experiment

The data collection method for the experiment consists of three test sites made up of four plots. Each test site contains one net experiment, one fence experiment, one branch experiment, and one control plot. Each test site is fairly similar and located in an active blowout.

The test area picked for the construction of the experimental plots is located approximately 72 kilometers east of Roswell, New Mexico (Figure 2). The test area is located within the Mescalero sand sheet. Over most of its range, the Mescalero sand sheet has been partially stabilized by a complex mixture of vegetation, including shinnery oak (Quercus havardii), yucca (Yucca campestris), sand sagebrush (Artemisia filifolia), mesquite (Prosopis glandulosa), and various grasses (Hall, 2002). The terrain is composed of coppice dunes primarily stabilized by shinnery oak. The dune field is traversed by several pipeline ROWs. Two of these ROWs were looked at as potential sites to set up test plots (Figure 11). The first was the ROW belonging to Transwestern Pipeline Company. The second was the ROW belonging to El Paso Pipeline Company.

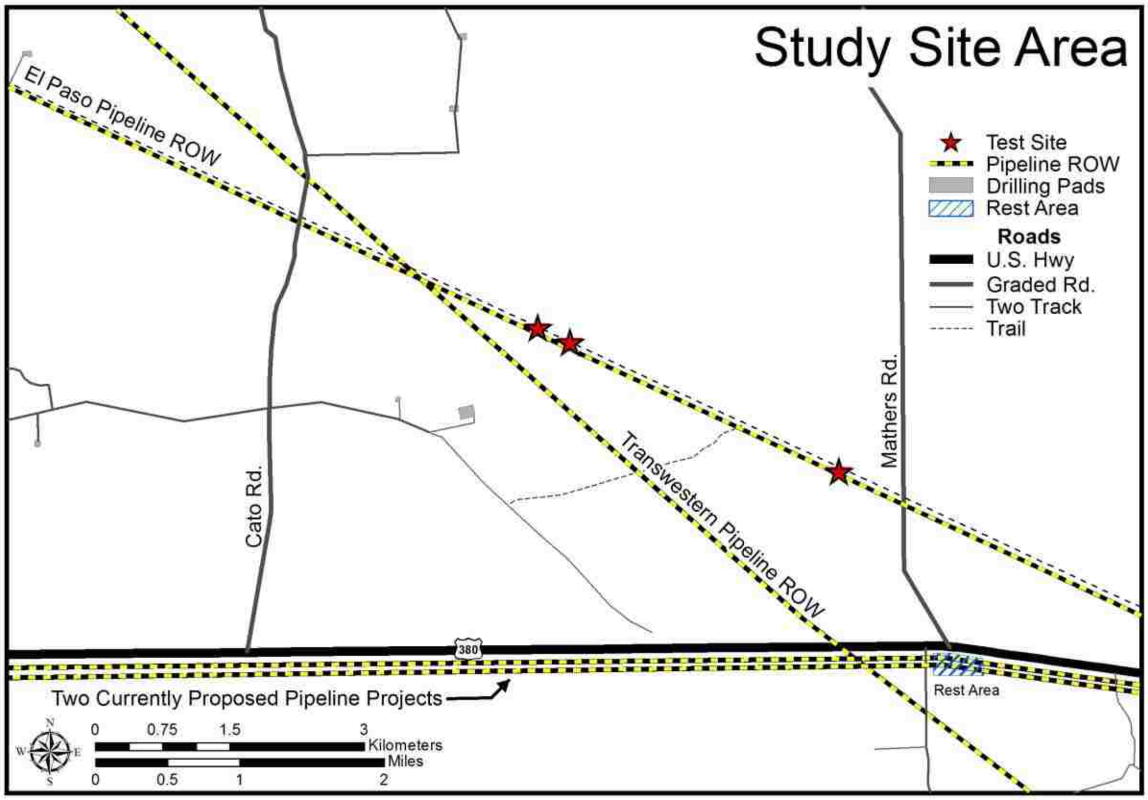


Figure 11: Map of the test site locations on the El Paso pipeline ROW. Note that there are two currently proposed pipeline projects that are being routed next to US highway 380 to avoid disturbance to habitat in the ACEC. Map by: Knutt Peterson

Four factors were used to select test site locations. (i) Could permission be obtained from the ROW holder to use the ROW for experimental plots? (ii) Access to the test sites by vehicle had to be relatively easy as multiple trips would be necessary to construct the test plots and record data. (iii) Were the sites representative of the different environments that the experiments were meant to solve? (iv) Were there indications that sand was moving through the immediate area of potential test sites?

It is assumed that particle size throughout the Mescalero sand sheet is relatively uniform from the study conducted by Stout (2010). It is also assumed the wind speed and direction across the sites would be similar, as all three sites were located within a 3.8 km stretch of the pipeline ROW. Along the ROW where the potential test sites could be located, there were sections of pipeline exposed by blowouts, indicating a blowout environment was present.

After the sites were picked, two other items were needed. The first was to discuss with the Bureau of Land Management whether an Environmental Impact Statement would be necessary to conduct the experiments on public lands and on a federally administered ROW. In this case it was not. Secondly, New Mexico One Call had to be consulted. New Mexico One Call is an organization that facilitates the marking of underground utilities. This is very important when working in the area of buried high pressure gas lines. New Mexico One Call marked the pipelines locations prior to the experiments being set up.

3.2.1 ROW Determination

The Transwestern Pipeline Company was contacted, and they agreed to grant permission if the site was chosen. The ROW had good dune formations, blowouts and several open areas where test plots could be setup. However, access by vehicle was near impossible due to portions of the ROW having re-vegetated since construction of the pipeline. The heavy vegetation on the ROW also prevented movement of sand over a broad area. Only small pockets of exposed sand were available to set up test plots and these were protected from free flowing wind by shinnery oak and mesquite at the margins, thus limiting sand transport. As a result this ROW was unusable for test sites.

The El Paso Pipeline Company was contacted, and they agreed to grant permission if the site was chosen. The ROW had good dune formations, blowouts and many open areas where test plots could be setup. Access by four wheel drive vehicle was difficult but feasible. The ROW was relatively free of vegetation, and there were wide areas of sand available for transport to and through potential test plots.

The ROW that belongs to the El Paso Pipeline Company was picked as the location for test plots. El Paso Pipeline Company granted permission to use the ROW for the experiments. BLM RFO gave permission to use the ROW for erection of test plots without doing an Environmental Impact Statement.

3.2.2 Test Site Determination

The approved section of the El Paso Pipeline ROW chosen to set up the experiments is bounded by Cato road on the west and Mathers road on the east (Figure 11). Multiple potential site locations were identified using aerial imagery, and their coordinates recorded. The ROW was visited and the potential sites analyzed to see if they met the criteria. The three sites that were finally picked all had similar characteristics. The criteria were that the area was a blowout, fairly open with little to no vegetation, an ample supply of sand, and a combination of deflationary and active deposition areas.

Each of the final three test site locations are large blowouts about one acre in area along the pipeline ROW. Several factors change the wind dynamics in a blowout over time, prevailing wind directions and morphology of the blowout, as its shape changes over time. At each of the three test sites a visual evaluation was done to spot areas of deflation, accumulation, and neutrality in regards to sand movement. Deflationary areas were identified as areas where there was no loose sand on the ground surface and a surface of hard pan was evident. Areas of active sand accumulation were identified by new surface ripple features being evident, and a base of loose wind blown sand. All other areas were designated as neutral.

Four areas, three meters by four meters, were picked that fell into the deflationary or neutral surface type. The reasoning for this was that these experiments are trying to determine which method is best at collecting sand on a particular site or preventing deflation. The blowout areas chosen for each test site are not particularly large, about one acre in size, and had a good mix of deflationary, neutral, and accumulative areas. If a site actively collects sand, then there would be no reason to purposefully collect sand there. If a site was losing sand or neutral to sand migration, then it would mimic a potential blowout site. An additional criterion for site selection was relative levelness.

The three areas picked as test sites were marked with a tee post, flagged and then GPSed. New Mexico One Call was contacted, given the GPS locations, and told to mark any and all underground utilities within a 200 meter buffer around the flagged tee post.

3.3 Experimental Plots

This section covers how the individual experimental test plots were placed within each blowout test site. Also covered are how the plots were constructed, as well as the design and construction of the different sand capturing experiments.

3.3.1 Plot Determination

In determining the final test sites, a survey of deflationary and neutral surfaces was conducted. These areas were marked with different colored pin flags, red for deflationary and blue for neutral deposition. Three experimental plots and one control plot were located on these flagged sites. A primary consideration was to make sure that one sand capturing experiment was not robbing another of sand entrained in the prevailing wind. NOAA wind rose data for the area revealed that the prevailing wind direction at the test locations for the months the experiments were conducted, April thru August, range from the southwest to the south-southeast.

Control plots, not having a sand capturing experiment on them could be placed up wind of a plot with a sand capturing device. Control plots were located up wind of other plots and on neutral ground surfaces. The other three experimental plots were arranged roughly perpendicular to the prevailing wind direction so as not to rob each other of entrained sand in the prevailing wind. The three plots were also spaced so that none were closer than 15 meters from each other, most were more than 40 meters apart. This was done to prevent sand robbing when the wind direction was from a different direction than prevailing. Maps of plot locations are included in Appendix 3.

Each test plot was determined to be three meters by four meters in size. This size was dictated by the cost and volume of materials needed to cover each of the 9 experimental plots.

3.3.2 Plot Construction

All plots were determined to be 3 meters by 4 meters in size, for the reason described above. The length of each side of the plot was chosen to utilize the 3,4,5 method of constructing a rectangle with 90 degree corners. Six foot long steel tee posts were used to delineate the corners of the test plots. The first tee post was driven into the ground, leaving one meter above ground. The second tee post was driven into the ground three meters away from the first. The third post was placed at a 90 degree angle from the azimuth of posts one and two, at a distance of 4m from the second post. A measurement of five meters was obtained between the first and third posts insuring 90 degree angles at each corner. The process was repeated for the fourth post using posts one and two (Figure 12).

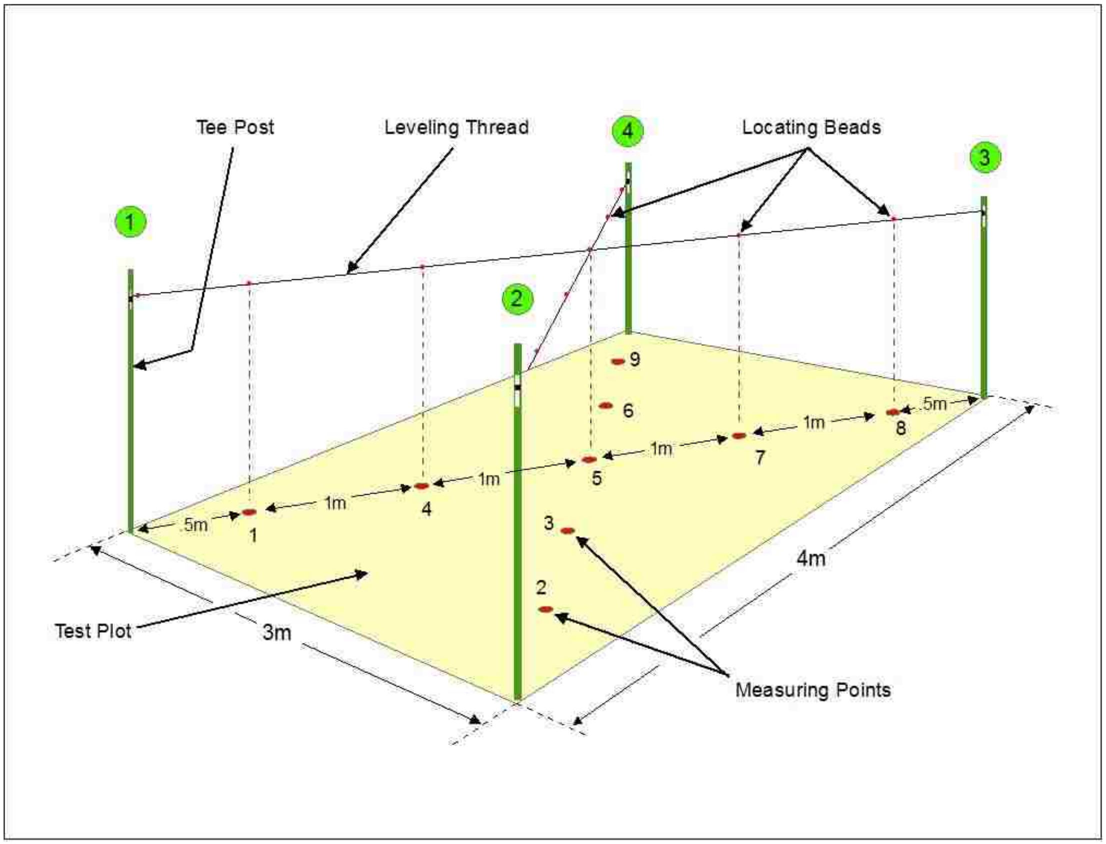


Figure 12: Diagram of base plot. By: Knutt Peterson

The tee post with the lowest elevation of the four tee posts making up the plot was located. This post was measured twenty centimeters down from the top of the post and the top of a metal Binder Clip was positioned at the 20 cm level. White spray paint was sprayed over the clip and surrounding area of the tee post (Figure 13). This created a permanent mark on the tee post so the binder clip could be repositioned in the same exact place on the tee post if it was removed during the data collection period. A Suunto Tandem precision compass and clinometer was used to transfer the height of the top of the Binder Clip to the other three posts on the plot, where binder clips were placed and marked with spray paint. This created a level plain intersecting the tops of the Binder Clips approximately 80 cm above the ground. This plain is the constant that the change in surface elevation will be measured against. More on this in section **3.3.4.**

Figure 13: Spray paint showing where the binder clip will be placed each time the leveling thread needs to be attached for measurement. Photo: Knutt Peterson

3.3.3 Design and Construction of sand capturing structures

When wind of sufficient speed blows over a surface covered with cohesionless sediment, the fine particles will be transported by suspension, while the coarse particles will be transported by either saltation or creeping on the surface. In the absence of any obstructions the wind will continue to carry more sediment until it reaches its full carrying capacity. A semi-permeable obstacle, such as natural vegetation, protects the underlying fine particles from being carried by the wind and also acts as a sand trap. As the wind loaded with sand encounters an obstacle, the wind speed is reduced and thus its carrying capacity decreases. This results in sand accumulation around the obstacle (Zaghloul, 1997).

Zaghloul (1997) also notes that the aerodynamic action of a windbreak is simple in principle. The windbreak exerts a drag force on the wind field, causing a net loss of momentum, and thus providing a shelter effect.

This basic principle is what the design of each of the sand capturing devices in this experiment were based on. All branch piles, net structures, and fences covered or encompassed all nine sample points within the plot (Figure 12).

3.3.3.1 Net Structure

It is known that netting can affect the flow of wind (Mistriotis, 2012). The idea behind the net structure used in this experiment is to separate the sand from the wind that entrains it in the process of saltation. Looking at Figure 7, in section 2.2.1.2., one can see that the idea is to deflect the wind flow up and over the net structure, creating a net loss of momentum in the wind speed under the netting, thus lowering the carrying capacity of the wind at that spot. Grains of sand being carried along in the saltation process would bounce along until they bounce into the area covered by the netting. The area under the netting having reduced wind speed would stop the saltation process and the grain would fall out of the entrainment process and accumulate in mass.

The net structure was constructed by selecting an affordable piece of netting that would hold up to heavy wind and strong sunlight. The netting mesh size that was selected was chosen after consulting with a netting engineer at the Christensen Net Works of Everson, Washington. It was decided that a tighter, smaller pattern would create a more substantial surface for the wind to be deflected over the net structure. The net mesh size picked was 1 inch by 1 inch squares and twine size was #18 (1.9mm). Knowing the size of the test plot and the arc of the structure, it was determined that the netting would have to be 3.5 meters by 4.5 meters in size. PVC pipe, ¾" OD, was used in conjunction with various fittings to construct a frame that the netting would be attached to using plastic zip ties (Figure 14). The frame was transported to the site partially constructed and glued together at the location of the experiments.

The PVC frame was attached to the ground using two foot long rebar stakes and bailing wire. The ends of the netting were staked down using wood stakes. The choice of materials and method of staking worked well for the duration of the experiment.

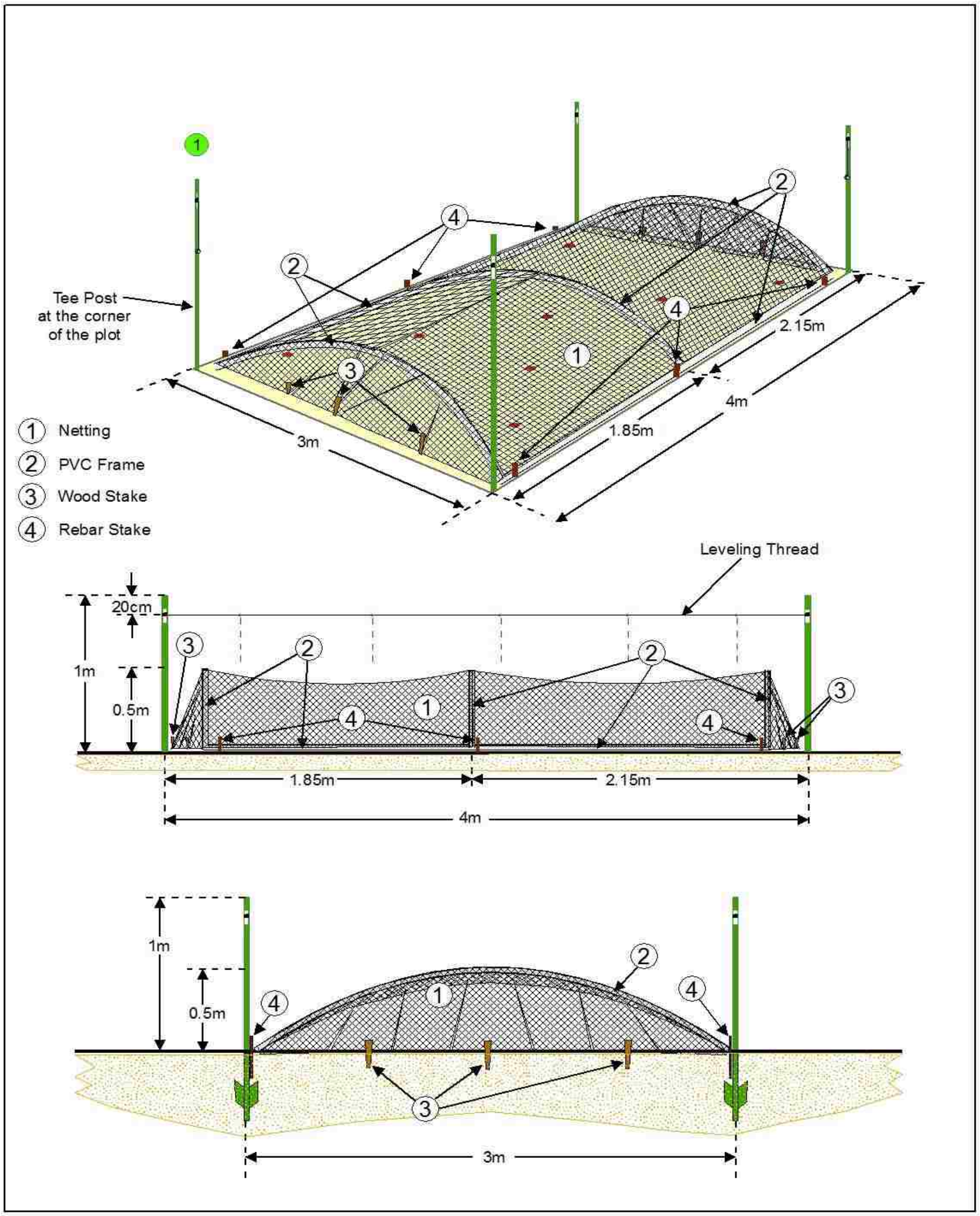


Figure 14. Diagram of net plot, oblique and profile views. By Knutt Peterson

3.3.3.2 Snow Fence Structure

The snow fence is perhaps the most widely used and best understood method for capturing sand. 37.5 meters (~125 feet) of snow fence, with a porosity of 50 percent was acquired and cut into 12.5 meter sections. One 12.5 meter section of fence was used for each test plot. The fence was transported to the site in a rolled form, and wired to four tee posts pounded into the test plot confines (Figure 15). The tee posts that supported each corner of the snow fence were located 20 cm inside the plot boundary at each corner.

The snow fence was constructed to form a box around the inside parameter of the test plot. This configuration was picked to see if a cell configuration would retain sand within its confines and protect the sand surface from wind scour. Cell configurations have been used in China utilizing rock wall checkerboard sand barriers that were patterned after the straw checkerboard sand barrier, which is effective for fixing mobile sand in arid and semi-arid regions (Zhang, 2009).

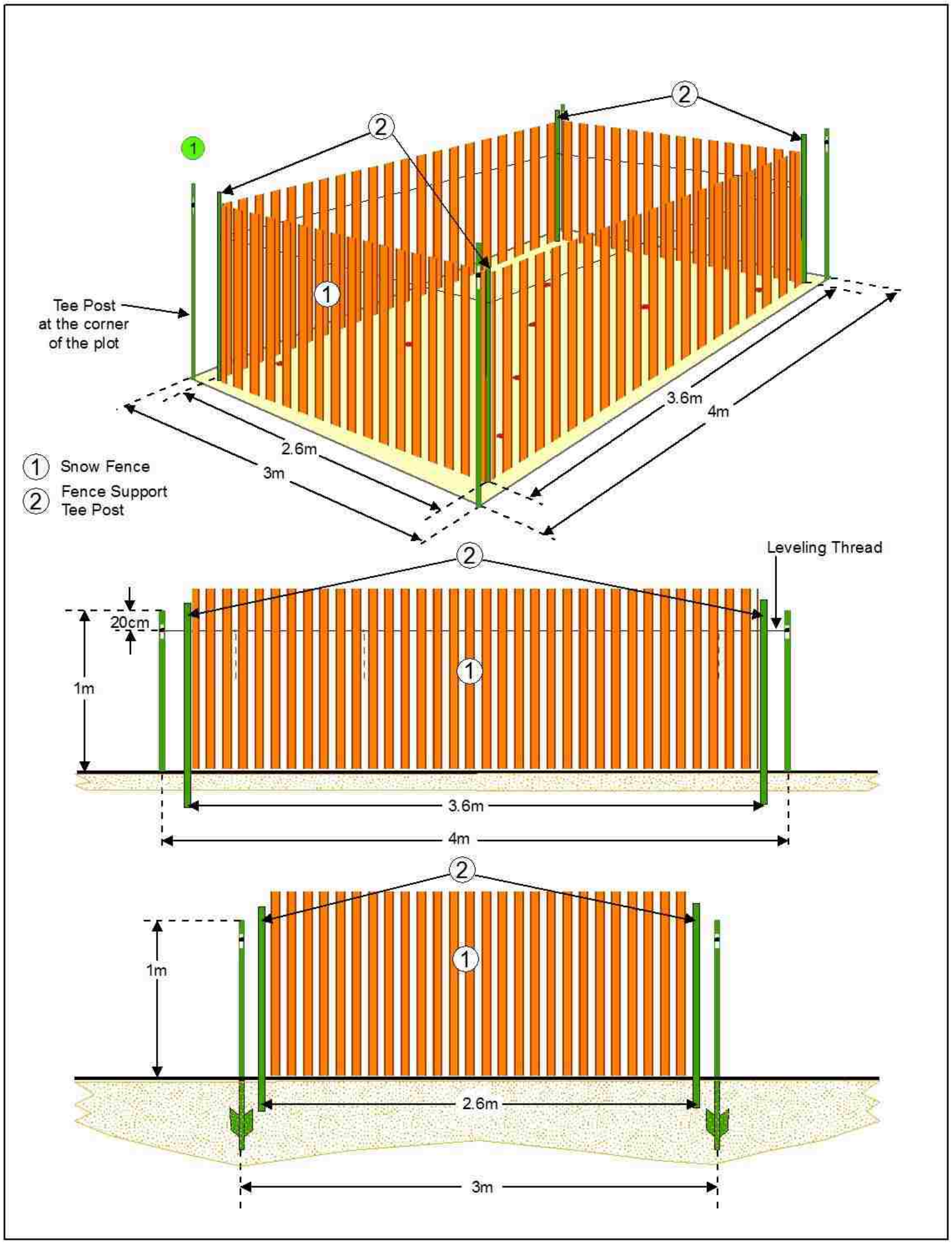


Figure 15. Diagram of fence plot, oblique and profile views. By: Knutt Peterson

3.3.3.3 Branch Structure

The branch structure was created using two to three meter long pecan branches devoid of leaves acquired from a pecan orchard in Roswell, New Mexico. The local orchards trim their trees every spring and have a surplus of branches, many of which get burned as a means of disposal. Each branch pile was constructed to mimic the natural effect of vegetation on wind erosion by sheltering the ground surface from the erosive force of the wind by covering a proportion of the ground, thereby limiting the erodible area. Momentum extraction from the wind by the branch pile should absorb a part of the total shear stress of the wind and therefore decrease the shear stress acting on the ground. It is postulated that this should have the effect of trapping windborne sand particles within the branch pile and prevent deflation on the test plot. Branches were piled to a depth of 18 inches.

Two tee posts were pounded into the ground outside of the branch test plot perpendicular to the branch stem direction and were used to anchor a rope which was tied to several of the branches. The purpose for this was two fold: first, to secure the branches within the test plot to guard against the wind blowing the branches out of the test plot; and, secondly, to discourage animals from dragging the branches out of the test plot. The branch test plot was constructed as demonstrated in Figure 16.

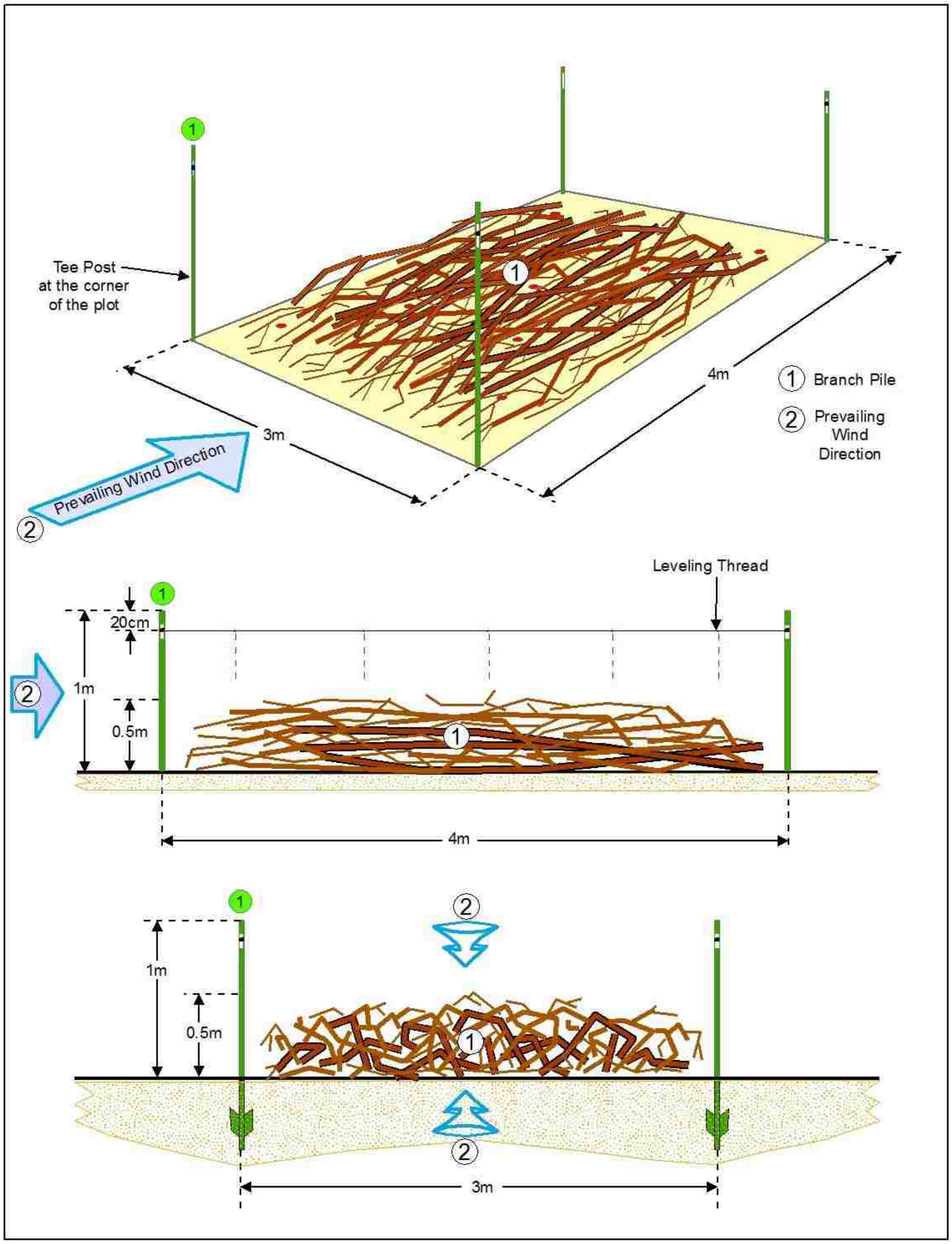


Figure 16. Diagram of branch plot, oblique and profile views. By: Knutt Peterson

3.3.4 Data Measurement Methodology

The measuring system to record the accumulation or deflation of sand within the test plots, used a modification of the stadia rod technique. The stadia rod technique is commonly used in archeology, stream channel profiles (Hudson, 1982), and other surveys where ground elevation differences along a transect need to be recorded. In stadia surveying, a level is used to determine a base elevation above and along the transect. Distances from a known point along the transect to data sampling points are measured using a tape measurer. A stadia rod, essentially a long pole with calibrated measurements marked on it, is moved to each measurement point along the transect. Measurements on the stadia rod are observed through the lens of the level and recorded. The measurements below the level line give a profile of the surface along the transect. Two people are required for the stadia rod technique, one to observe the reading through the level and one to hold the stadia rod at the data sampling point in view of the level for the reading.

The modification of the stadia method used for data collection for this study's test plots is as follows. A thread was fixed to two fixed points on tee posts at each corner of the test plot. This thread represents the level line projected by the level in stadia survey. Glass beads were tied to the thread at measured intervals, including a "zero bead". The beads are fixed at the points, where measurements are to be taken in the plot along the transect represented by the thread. The "zero bead" is placed against a clip attached to one of the tee posts, this allows the measuring thread to be placed in the exact same place each time the thread is placed between two tee posts (Figure 17). The other end of the thread is held in a clip in a reproducible position on the tee post located diagonally across the plot, and has a counter weight attached. Both ends of the measuring thread have weights attached. The end with the zero bead is heaver, so as to hold the zero bead tight against to binder clip. The lighter weight at the opposite end of the thread is to provide tension to the thread.

The distance diagonally across the plot is 5 meters. The sampling point locator beads were tied 0.5m, 1.5m, 2.5m, 3.5m and 4.5 meters from the zero bead. This created four sampling points a half meter inside the parameter of the test plot, four sampling points in the mid-parameter of the plot, and one sampling point in the center of the plot (Figure 12). These sampling points were numbered 1 thru 9. A "stadia rod" was made using a straight stick with a metric tape measurer glued to it. This rod also had a 1 inch diameter flat metal plate attached as a flat base to prevent the stick from sinking into the loose sand (Figure 17).

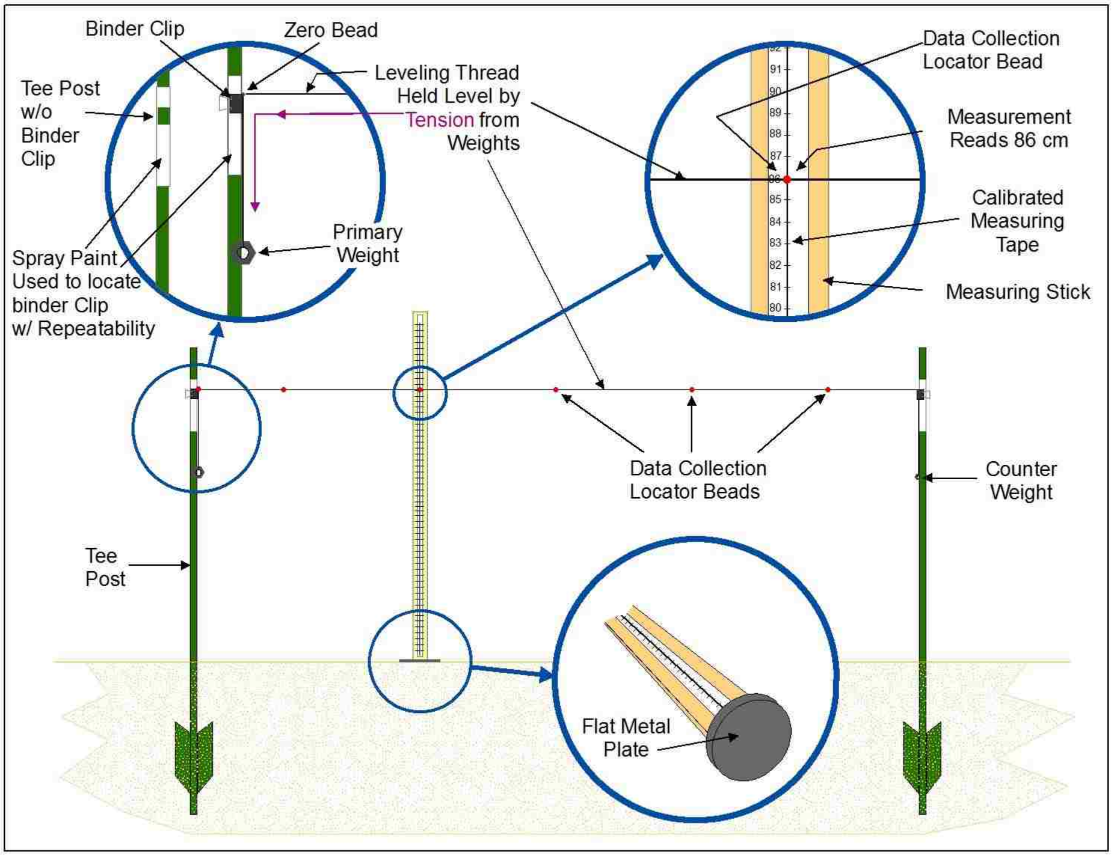


Figure 17. Modified Stadia Rod measurement system used to record change in ground surface height. Diagram not to scale. By: Knutt Peterson

To measure the change in ground surface elevation over the course of the data collection period a sampling interval for the two transects was defined. Nine sampling points within the test plot were laid out by crossing a nylon thread diagonally across the plot from post one to post three. The first data collection point is 50 cm from the corner of post one, the second is located 1.5 meters from the post, the third is located 2.5 meters from the post and is located in the center of the plot. The fourth data collection point is located 3.5 meters from the post and the fifth data collection point is located 4.5 meters from the start post or 50 cm from the end post (Figure 12). The other collection points occur when the thread is placed between posts two and four, but the center data collection point is not recorded, because it was recorded earlier at the 2.5 meter distance during the first transect.

The objective for this study is to determine if deflation or deposition is occurring on each of the test plots. It was determined that surface measurements for each plot would be taken in the same location within the plot each time data are recorded. This would give an idea if the same location measured before would show signs of deposition or deflation. The dual transect, at repeatable locations, fit best with the modified stadia rod measurement technique. Given the small size of the test plots 3 x 4 meters, 5 sampling locations per transect were chosen. This resulted in 9 sample points per test plot.

3.4 Data Logging

The primary objective of this thesis is to compare the sand capturing characteristics of the three different sand capturing structures and determine the variability in the performance of the three structures.

The three structures were erected in the manor described in the methodology section. Construction of the plots, structures and control plots occurred over four weekends. This was due to the logistics of transporting materials and limited personal for constructing the different structures. At the time of plot construction, the four metal tee posts, used to capture the data measurements, were placed and driven into the ground, and then a ground surface measurement was made. After the ground surface measurement was recorded, the sand capturing structure was built on the test plot. On April 3 2010, the branch structures and their plots were constructed on test sites 1, 2, 3. Also on the 3rd control plots were built on test sites 1 and 2. The following weekend, April 11th, data are recorded for the plots set up the previous weekend and the control plot for site 3 was constructed. On the weekend of April 16, all 3 of the fence plots and structures were built and base ground surface measurements were recorded in addition to the previously constructed plots. On the weekend of April 25, in addition to recording data for all previously constructed plots, the three net structures and their plots were constructed. By April 25th, 2010 all experiments were up and running. Data are collected at all plots again on May 16th, June 3rd, and lastly on August 22nd.

Data are recorded at each test plot using the thread and meter stick described in the methodology section. Data are recorded on field data sheets created for this project. See Appendix 1.

3.5 Data Processing

Data that are recorded on field data sheets are inputted into an Excel spread sheet. Within Excel, a sheet was created for each test site, containing a section for each of the three experiments and control plot. Tabs are labeled Site 1, Site 2, Site 3, and Stats Sheet. The data are laid out so that equations would average the nine data points for each date that data are collected and give an average accumulation for each site on that date. The averages for each date were summed to give either a total average accumulation or deficit for each experiment over the entire data collection period. See appendix 2.

3.5.1 Statistical Testing

The data from the three sites are feed into the Stats Sheet and compiled as site averages and treatment averages from the beginning to the end of the data collection period. See table 4.

4. Results and Discussion

4.1 Accumulation Results

Accumulation and deflation on each of the test plots varied during the collection period. During some data collection periods a plot would show deposition on the test plot and data from other periods showed deflation. This variance is attributed to the complex nature of the physical dynamics playing out at the location of each individual plot location.

As mentioned above, the primary objective of this thesis is comparing the long term sand capturing characteristics of the three different sand capturing structures and determine the variability in the performance of the three structures.

The data collection period was from April 3rd 2010 to August 22nd 2010. All experiments were deployed by April 25th. A synopsis for each type of experiment at test sites 1,2, and 3 are given. The date of experiment installation, and total deposition or deflation numbers for the data collection period are given in tables included in the text. For complete data collection tables, which include data for each collection date and each of the nine data points within each plot, see Appendix 2.

When reading the data tables, keep in mind the method used for collecting the data is similar to the stadia rod method. The “zero” plain is above the ground surface, and measurements are made down to the ground surface. For example, if an initial measurement between the “zero” plain and the ground is one meter, and the second measurement at that same spot was 1.1 meters, then 0.1 meters of deflation has occurred. If the second measurement happened to be 0.9 meters then 0.1 meters of accumulation would have occurred.

4.1.1 Control Plots

Control plots were installed and surface base data are collected at test sites 1 and 2 on April 3rd, 2010. The control plot on test site 3 was installed on April 11th, 2010 and surface base data are collected. Data are collected through August 22nd, 2010. Data were collected at nine measuring points within each test plot and averaged to give a mean surface height. The initial surface height recorded on the installation date was subtracted from the average surface height recorded on August 22nd to give a value determining whether there was deposition or deflation occurring at the test site during the collection period.

The control plot at test site 1 showed an average surface height change of -6.11 mm. The control plot at test site 2 showed an average surface height change of +60.89 mm. The control plot at test site 3 showed an average surface height change of +7.89 mm (Table 1).

Control Plot - Cumulative Surface Data

Site	Date	Average Surface Height
Site 1	4/3/2010	814.33 mm
	8/22/2010	820.56 mm
		Total Change = - 6.11 mm
Site 2	4/3/2010	676.11 mm
	8/22/2010	615.22 mm
		Total Change = 60.89 mm
Site 3	4/11/2010	714.56 mm
	8/22/2010	706.67 mm
		Total Change = 7.89 mm

Table 1: Cumulative Surface Data for Control Plots on Sites 1, 2 and 3.

4.1.2 Fence Plots

Fence plots were installed and surface base data are collected at test sites 1, 2 and 3 on April 16th, 2010. Data are collected through August 22nd, 2010. Data are collected at nine measuring points within each test plot and averaged to give an average surface height. The initial surface height recorded on the installation date was subtracted from the average surface height recorded on August 22nd to give a value determining whether there was deposition or deflation occurring at the test site.

The fence plot at test site 1 showed an average surface height change of +2.33 mm. The fence plot at test site 2 showed an average surface height change of -95.89 mm. The fence plot at test site 3 showed an average surface height change of +112.78 mm (Table 2).

Fence Plot - Cumulative Surface Data

Site	Date	Average Surface Height
Site 1	4/16/2010	887.78 mm
	8/22/2010	885.44 mm
		Total Change = 2.33 mm
Site 2	4/16/2010	786.78 mm
	8/22/2010	882.67 mm
		Total Change = -95.89 mm
Site 3	4/16/2010	796.22 mm
	8/22/2010	683.44 mm
		Total Change = 112.78 mm

Table 2: Cumulative Surface Data for Fence Plots on Sites 1, 2 and 3.

4.1.3 Net Plots

Net plots were installed and surface base data are collected at test sites 1, 2 and 3 on April 25th, 2010. Data are collected through August 22nd, 2010. Data are collected at nine measuring points within each test plot and averaged to give an average surface height. The initial surface height recorded on the installation date was subtracted from the average surface height recorded on August 22nd to give a value determining whether there was deposition or deflation occurring at the test site.

The net plot at test site 1 showed an average surface height change of +18.11 mm. The net plot at test site 2 showed an average surface height change of +25.56 mm. The net plot at test site 3 showed an average surface height change of -91.44 mm (Table 3a). Table 3b is included to reflect control data during the deployment time of the net structures.

Net Plot - Cumulative Surface Data

Site	Date	Average Surface Height
Site 1	4/25/2010	695.44 mm
	8/22/2010	677.33 mm
		Total Change = 18.11 mm
Site 2	4/25/2010	750.67 mm
	8/22/2010	725.11 mm
		Total Change = 25.56 mm
Site 3	4/25/2010	715.56 mm
	8/22/2010	807.00 mm
		Total Change = -114.33 mm

Table 3a: Cumulative Surface Data for Net Plots on Sites 1, 2 and 3

Control Site - Cumulative Data for Date Range of Net Plot Deployment

Site	Date	Average Surface Height
Site 1	4/25/2010	811.00 mm
	8/22/2010	820.56 mm
		Total Change = - 9.56 mm
Site 2	4/25/2010	662.00 mm
	8/22/2010	615.22 mm
		Total Change = 48.76 mm
Site 3	4/25/2010	711.11 mm
	8/22/2010	706.67 mm
		Total Change = 4.44mm

Table 3b: Control Site Cumulative Data, for Date Range of Net Plot Deployment.

4.1.4 Branch Plots

Branch plots were installed and surface base data were collected at test sites 1, 2 and 3 on April 3rd, 2010. Data are collected through August 22nd, 2010. Data were collected at nine measuring points within each test plot and averaged to give an average surface height. The initial surface height recorded on the installation date was subtracted from the average surface height recorded on August 22nd to give a value determining whether there was deposition or deflation occurring at the test site.

The branch plot at test site 1 showed an average surface height change of +87.89 mm. The branch plot at test site 2 showed an average surface height change of +217.78 mm. The branch plot at test site 3 showed an average surface height change of +88.89 mm (Table 4).

Branch Plot - Cumulative Surface Data

Site	Date	Average Surface Height
Site 1	4/3/2010	761.44 mm
	8/22/2010	673.56 mm
		Total Change = 87.89 mm
Site 2	4/3/2010	821.22 mm
	8/22/2010	603.44 mm
		Total Change = 217.78 mm
Site 3	4/3/2010	688.00 mm
	8/22/2010	599.11 mm
		Total Change = 88.89 mm

Table 4: Cumulative Surface Data for Branch Plots on Sites 1, 2 and 3.

4.2 Discussion of experiments

The physical dynamics at play in a blowout are a complicated interaction between wind speed, wind direction and surface conditions. Wind speed and wind direction are factors that are dictated by nature, of which there is little to no control. Generally in the confines of the blowout, there is a lack of adequate surface roughness to slow the attack of the wind, thus the reason the blowout exists.

Remembering the three elements that work dynamically together to cause deflation or deposition at a given spot, these experiments were designed to manipulate the one element that we can affect, surface roughness. By manipulating this factor, wind speed is also influenced.

Surface conditions or surface roughness on each test plot are created by each of the three different experiments. The surface roughness created by each experiment is different and out comes will be varied, and that is what we are testing. In other words, the surface roughness created by each experiment can only reduce the carrying capacity of the wind by a certain amount. Therefore, the experiments are only effective up to a certain wind speed. For example, a wind speed slightly above the speed to entrain sand into saltation has the ability to move sand to a test plot. The experiment on the plot can reduce the carrying capacity of the wind by a certain factor. If that factor is enough to cause sand to fall out of entrainment, then deposition will occur on the test plot. On the other hand, if the wind speed is higher, entrainment will also occur. However, when the mobilized sand passes through the experiment, it will not be deposited, because the experiment fails to reduce the carrying capacity of the wind sufficiently and sand passes through the experiment, resulting in no deposition. Furthermore, if the wind speed is even higher, as it passes through the experiment sand will be mobilized and entrained from within the experiment causing deflation.

The experiments were designed to be somewhat effective in relation to varied wind direction. The branch and net sand capturing devices were meant to be most effective when oriented to the prevailing wind, but also reduce carrying capacity when wind direction was from perpendicular quadrants. The fence structure design was assumed to be equally effective from all angles of wind attack.

The control plots results were as expected (Please refer to Table 5 in regards to the discussion below.). The goal was to determine if there was a depositional or deflationary environment within each of the blowout test sites, keeping in mind that not all areas of the blowouts are equally affected. Results for the control plots on test sites 1 and 3 showed a nominal change of -6.11 mm and +7.89 mm of average surface change respectively, implying a relatively neutral deposition / deflation environment. The control plot on test site 2 gained 60.89 mm of average surface elevation, suggesting that the blowout was comparatively more depositional than test sites 1 and 2.

The fence plot experiments were primarily designed to protect the sand surface contained within the parameter of the plot from deflation and secondarily to create a depositional environment. The outcome for the fence structures at each test site was varied. At test site 1, a gain of 2.33 mm in the average surface elevation was observed. When the data from each sampling point within the test plot are analyzed, extreme deflation occurred inside the margins of the fence and high amounts of deposition took place in the center of the plot.

This same pattern was recorded on test plot 2, but there was a 95.89 mm decrease in average surface elevation. The fence plot on site 2 was situated in an area of the blowout subject to extremes in wind speed. The test plot was located only 6 meters from a high coppice dune, of which 3 sides were near vertical. It was later understood that prevailing wind coming from the southeast would be funneled between this high coppice and the adjacent bermed edge of the blowout, causing an area of increased wind speed and thus intensified deflation in the location of the fence experiment on test site 2. As we will see this was not characteristic of the rest of the blowout at test site 2.

At test site 3 the fence plot was located in the middle of a large shallow blowout with a low bermed edge. A 112.78 mm increase in average surface elevation was recorded between the dates April 16th and August 22nd. However, between the dates of June 3rd and August 22nd there was an increase in average surface elevation of 123.56 mm, whereas in the time period between April 16th and June 3rd the average surface elevation decreased by 11 mm. The control plots point to similar depositional or deflationary environments within test sites 1 and 3. The fence data from site 1 for the dates April 16th to June 3rd show the average surface elevation increased only by 10.78 mm. Something happened on the fence plot on site 3 between the dates of June 3rd and August 22nd to cause 123.56 mm of deposition as opposed to a surface deflation of 8.44 mm on the fence structure at test site 1. One of two possibilities could have occurred, either data collected on August 22nd at site 3 was incorrectly measured or a wind event at site 3 for a sustained period was ideal for the experiment to capture sand on the test plot. This remains uncertain given a lack of wind speed data for the test sites. At test site 3 the same phenomena of deflation occurring inside the margins of the fence and high amounts of deposition taking place in the center of the plot were observed between April 16th and June 3rd, but were not observed on August 22nd.

At all three fence plots the observation was made as time passed that on the outside margins of the fence structure, deflation was occurring. This is believed to be caused by a pressure wave created on the windward side of the fence, and documented in many wind tunnel experiments (Hotta, 1987, Dong, 2010, Zaghloul, 1997). This deflation eventually undermined the fence, allowing wind to move under the fence and remove sand from inside the margins of the fence structure. This phenomenon was observed at all fence structures on all three test sites. The pressure wave is indicative of not enough airflow through the fence. The locally sourced snow fence, with a porosity of 50 percent, is what was readily available and fell within accepted porosity parameters.

The Net plot experiments were principally designed to protect the surface underneath from deflation and create a depositional environment. The netting is attached snugly to an arched shaped frame constructed from ¾” O.D. PVC tubing, excess netting is pulled taut and staked to the ground, closing the open ends of the arch (Figure 14). This design was inspired by the shape of a wing, but given a porous surface which would allow some wind and hopefully much of the sand to enter the protected area, while deflecting much of the ambient air flow over the structure. Sand in the state of saltation bounces along the surface as it is being carried along by sufficient wind speed. The idea was to create an area under the netting where wind flow would be low enough to cause bouncing grains of sand to fall out of the entrainment cycle. The wind carrying the grains would be deflected over the net structure and bouncing grains would fall through the netting into an environment where wind speed would be below the carrying capacity for that grain size. The net structure is designed to have the axis of the arch oriented perpendicular to the prevailing wind, so the majority of wind would flow over the arch.

During the time when the net structure was being designed there was no literature available to confirm whether this concept would work. At the time of this writing, experiments done by Mistriotis (2012) were discovered and incorporated into this thesis. He studied the airflow over and through net covered arch shaped greenhouses. He found that some of the ambient air flow would be deflected up and over the net covered arch shaped greenhouse while another portion would flow into the greenhouse, but at a reduced velocity. His study validates the design concept behind the net structures.

The net structure preformed mostly as expected. Net structures on test sites 1 and 2 both collected sand, thus increasing average surface elevations under the experiment 18.11 mm and 25.56 mm, respectively. The net structure at test site 3 lost 91.44 mm of average surface elevation. Data from sites 1 and 2 show that the net structures consistently had gains in sand accumulation with the exception of data recorded on June 3rd at test site 1, where a loss of 0.33 mm was recorded. Data collected through June 3rd at site 3 showed a net accumulation of 22.89 mm. However, between June 3rd and August 22nd there was a loss of 114.33 mm of average surface elevation. Once again something happened at site 3 between June 3rd and August 22nd that caused a significant change to the average surface elevation under this experiment. Perhaps a significant wind event occurred exclusively at test site 3 or data are miscollected. It should be noted that test sites 1 and 2 are located .35 km apart and test sites 2 and 3 are located 3.3 km apart. It is conceivable that sometime between June 3rd and August 22nd, when large thunderstorms are common in southeastern New Mexico, that a significant wind event occurred at test site 3 and did not have as big an impact at test sites 1 and 2.

The Branch plot experiments were principally designed to protect the surface underneath from deflation and create a depositional environment. The design of the branch plots was modeled after the coppice dune. The coppice dune is formed when a bush such as Shinnery oak or Mesquite increases surface roughness which slows the wind speed enough to cause sand to fall out of entrainment at the base of that bush. For the purposes of these experiments large amounts of uprooted bushes were not available, so branches, trimmed annually from pecan orchards in Roswell, NM, were used. One of the benefits of the branch pile is that it is effective in slowing wind attack from all quadrants.

At branch test sites 1, 2, and 3 average surface elevations increased by 87.89 mm, 217.78 mm, and 88.89 mm respectively. Accumulation on test sites 1 and 3 correlate well with changes on the control plots for test sites 1 and 3. Data from the control site at test site 2 indicated that site 2 was more of a depositional site, and that translates into the bigger gain seen for the branch plot at test site 2. Of the 18 readings (6 readings x 3 test sites) taken for the branch plots all but one, a loss of 9.33 mm on test site 1, were gains in average surface elevation. Even at test site 3, during the dates of June 3rd and August 22nd there was a gain of 14.67 mm of average surface elevation. Consistently, the largest gains in average surface elevation, with the exception of the anomaly on the fence plot at site 3, were the branch plots. Between April 25th and May 16th, a period of 21 days, the branch plot at test site 1 gained 70.22 mm of average surface elevation. Between April 11th and April 16th, a period of 5 days, the branch plot at test site 2 gained 71.44 mm of average surface elevation. Also on the branch plot at test site 2, between April 16th and April 25th, a period of 9 days, average surface elevation increased 93.11 mm. A theorized result for the branch plots manifested itself in the form of vegetation. On all three branch test plots at least one native plant took root and grew, and on test plot 2 there were three individual plants growing at the end of the data collection period.

Table 5 shows the changes in average surface height for each plot at each test site. Site averages for all three types of experiment are shown along with treatment averages. Keep in mind that site averages for test site 3 maybe skewed, due to the anomalous readings for the fence and net plots between the dates of June 3rd and August 22nd. If these readings are taken into account, or negated, the site averages fall in line with the expected values from the control plots. Also remember that the location of the fence plot at test site 2 was located in an extreme deflationary location. Without a more clear understanding of the anomalous data the data will have to stand as collected.

Change in Average Surface Height in mm

Test Site ID.	Control	Branches	Fence	Net	Site Average in mm
Site 1	-6.11	87.89	2.33	18.11	25.56
Site 2	60.89	217.78	-95.89	25.56	52.08
Site 3	7.89	88.89	112.78	-91.44	29.53
Treatment Average in mm	20.89	131.52	6.41	-15.93	

Table 5: Individual plot surface changes, site averages, treatment averages.

Table 5 paints a picture of variability from site to site and from experiment to experiment. Variability also becomes apparent on a temporal scale when the data in Appendix 2 is analyzed. From week to week there are indications of deposition then deflation at the same location. This variability extends to each of the nine data points within each test plot. Looking at Figure 18 thru 21 Variability is evident in almost all sampling points, some more than others, and from site to site.

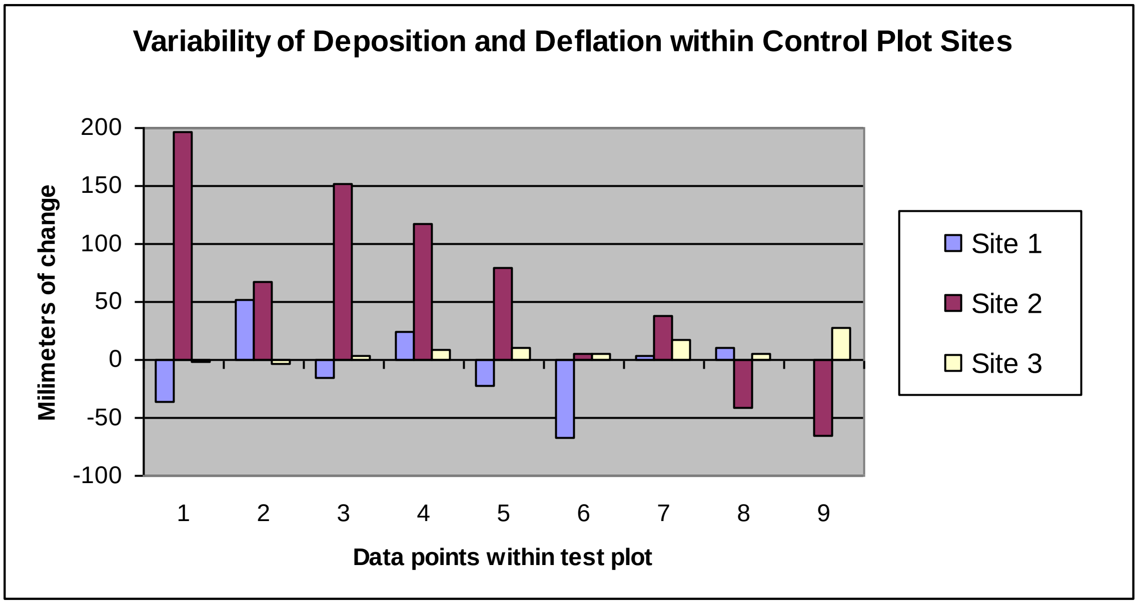


Figure 18: Variability of Deposition and Deflation within Control Plot Sites.

Figure 18 shows the variability of deposition at each test point within a control plot, at all three test sites. This variability on the control plots only indicates a general trend for the plot, whether it is trending towards being a depositional or deflationary site. Each test point is independent in that it is affected not by a test structure, but by its surroundings.

Figure 19 shows the variability at each of the data collection points within branch plots. What is different here is the trend for each test site is the same, the amount of deposition may be different, but all data collection points for each test site indicate deposition, except data collection point 1 on test site 1. Data collection point 1 on test site 1 is located on the upwind side of the experiment, and may not have been as sheltered by branches as the other points. Overall this indicates that the branch structure is particularly effective in creating a depositional environment across the entire plot.

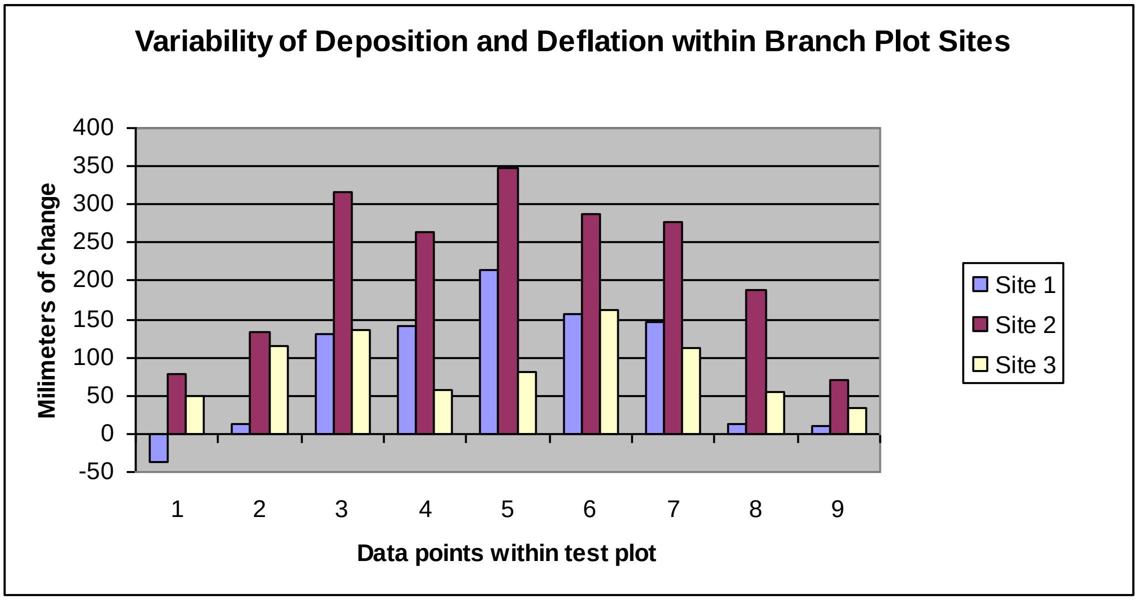


Figure 19: Variability of Deposition and Deflation within Branch Plots

Figure 20 shows extreme variability across each of the fence plots. Only data collection point 5, the center of the plot, showed consistent gains. This variability across each plot and from site to site indicates that the fence structure preformed differently at each test site and can not be considered reliable in different scenarios.

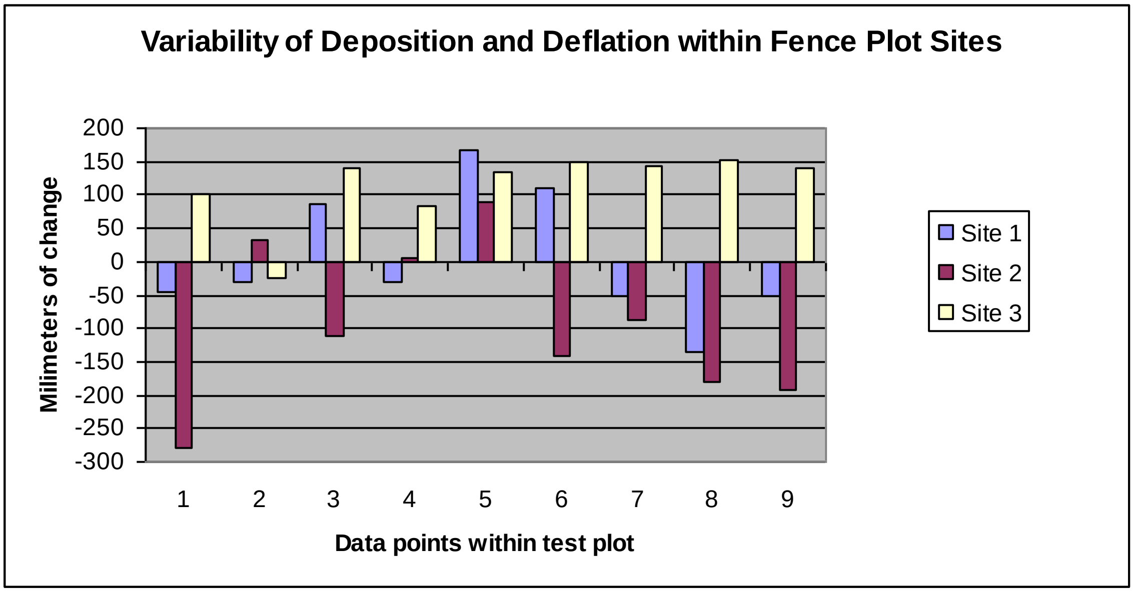


Figure 20: Variability of Deposition and Deflation within Fence Plot Sites.

Figure 21 shows the variability in the net plot sites for each data point. The net plots also showed a large amount of variability across each plot and from site to site. Remember that the data collected on August 22nd for test site 3 may have been skewed by an anomalous wind event. Removing this anomalous data still leaves variability which still makes the net structure questionable as a reliable sand capturing device.

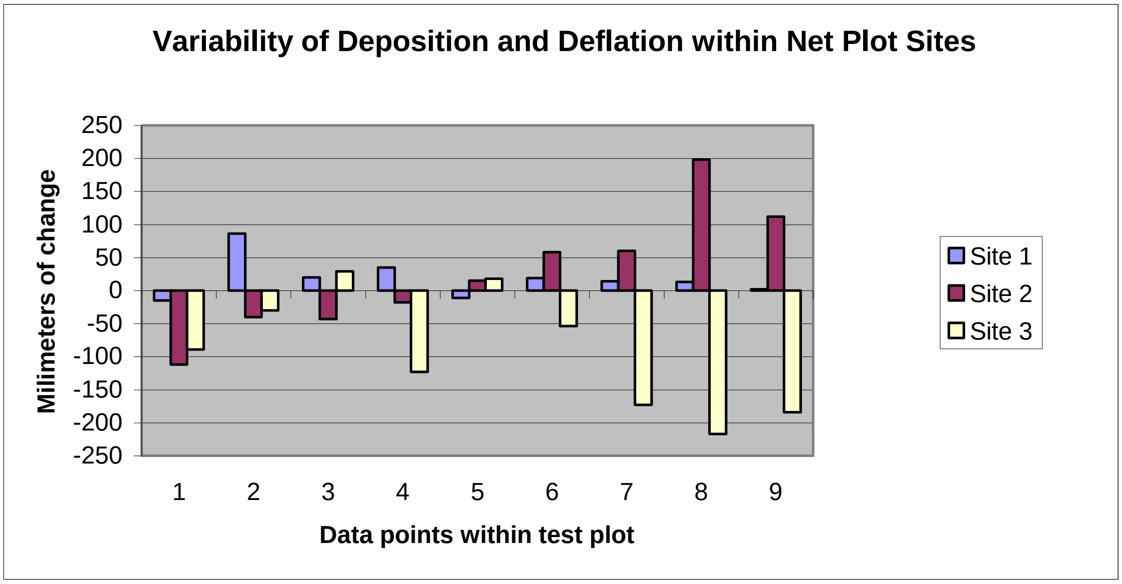


Figure 21: Variability of Deposition and Deflation within Net Plot Sites.

If the data are taken as it stands, the branch experiments, as a treatment, out preformed the net and fence treatment experiments. The fence experiments marginally out preformed the net treatment experiments.

In an attempt to massage / normalize the data, Table 6 was created. All data collected between the dates June 3rd to August 22nd are removed. This removed the anomalous data that occurred on test site 3. A new standard deviation was calculated for each of the treatments. It was felt that the fence data for site 2, which also incurred large amounts of deflation for the May 16th data recording, would be left in the analysis.

Looking at this set of data with anomalous data removed, we see that the control plots reflect a similar trend in comparison to the unmassaged data. Control plots on test sites 1 and 3 showed a nominal change of 0.56 mm and 0.33 mm of average surface change respectively, implying a neutral deposition / deflation environment. The control plot on test site 2 gained 45.00 mm of average surface elevation, suggesting that the blowout remains comparatively more depositional than test sites 1 and 2. No big changes here.

However, the treatment averages for the original data and the massaged data now paint a different picture, and there is a reason for this. Remember the massaged data had all data collected after June 3rd removed. Within these removed data there were the anomalous readings on test site 3 for the net and fence structures.

Change in Surface Height in mm

Test Site ID.	Control	Branches	Fence	Net	Site Average in mm
Site 1	0.56	97.22	10.78	9.22	29.44
Site 2	45.00	170.22	-94.00	20.56	35.44
Site 3	0.33	74.22	-10.78	22.89	21.67
Treatment Average in mm	15.30	113.89	-31.33	17.56	

Table 6: Individual plot surface changes, site averages, treatment averages for data collected between June 3rd and August 22nd removed.

As mentioned above, the control plots illustrate the same pattern of surface change. The branch plots are showing a similar pattern, with test site 1 being slightly more depositional than test site 3, and as expected, heavy deposition on the depositionaly rich test site 2. The data for this collection period still confirms that the Branch plots are performing well.

Fence plots on test sites 1 and 3 are relatively close in that they show a marginal gain and loss. Remember that test site 2 was situated in an extremely deflationary environment, and the numbers reflect that. The overall performance of the fence plots was not up to par, resulting in an overall loss for the treatment average. If the extreme deflation that occurred to the fence plot on site 2 is removed from the table and only the results from plots 1 and 3 are used, the fence plots show no gain or loss overall. This suggests that the fences in this configuration do not create a deflationary or depositional environment.

The massaged data changes the outcome for the net plots in a dramatic way. With the anomalous data removed the net plot on site 3 had a modest gain of 22.89 mm of average surface gain, similar to the net plot on site 2, 20.56 mm of average surface gain. The net on site 1 had a nominal gain of 9.22 mm of average surface gain. The overall treatment average for the net plot was 17.56 mm of average surface gain.

This modified analysis demonstrates that the branch piles still create the best depositional environment. The net plots now illustrate modest deposition at all three test sites. The fence plots in this configuration during the data collection period did not perform well.

4.3 How the experiments did

Going into this project, the highest hopes were for the branch piles and the net plots to create depositional environments. The design of the fence plots was untried and lessons were learned. Overall the results of the experiments are meaningful, and despite the successes and failures realized during this study, much was learned**.**

4.3.1 Successes

The branch pile experiment was the most successful of the three experiments conducted. It is believed that branch piles could be an effective, low cost, long term solution to mitigating small to medium sized blowouts along pipelines. The availability of branches in the Roswell, New Mexico area makes this treatment even more appealing in southeastern New Mexico. The BLM office in Roswell has shown some interest in seeing the results of this thesis. Pipeline maintenance companies that were consulted during the course of this thesis also are interested in the outcome of this study.

The net experiments are also considered to be a success. To my knowledge, and an extensive search through the literature, nets in this configuration have not been used for capturing sand. Although the gains produced by the net structures were modest, they were none the less gains, and further refinement of net structures to capture sand may yield better results in the future.

4.3.2 Failures

The sand fence experiments, in the configuration adopted for this experiment, were not successful in creating a depositional environment. It has been realized that a single cell, 3 meters by 4 meters, does not stand much of a chance by itself. It created an object on the sand surface that created a small circulation cell on the windward side of the fence and dug a hole in the sand. The center of the cell was somewhat protected, but over time if the hole under the fence was to enlarge, the protected center could become vulnerable to wind attack.

By not collecting wind data at each site, large gains or losses of sand within an experiment could not be explained.

4.4 Implications for applications on pipelines

Pipelines will remain, for the foreseeable future, the most economical method to transport large volumes of liquid or gaseous fluids over long distances. Inevitably these pipelines will cross through areas of unconsolidated materials, such as sand dunes. The problem of blowouts forming along a pipeline ROW can be mitigated before they even start by re-vegetating the ROW right after the pipeline is installed. The re-vegetation process needs to be monitored for years after to ensure that a strong layer of vegetation becomes well established for the long term. Re-vegetating a pipeline ROW after construction is currently the accepted practice (Argonne, 2007). However, if pipeline companies fail to follow through and vegetation does not become fully established, then surface degradation can occur. Re-vegetation is important on all pipelines, because erosion comes not only from wind, but water. Some environments, like desert sand dunes, do not easily lend themselves to re-vegetation because of a lack of water or poor soil type.

Where the environment does not lend itself to the establishment of vegetation, or vegetation has been destroyed, other methods of surface stabilization need to be employed. Natural geotextiles are not a permanent solution. Articulating concrete mats are a permanent and effective solution but are very expensive. Chemical sprays come in two forms, organic and petroleum. These chemical sprays form a crust and if disturbed will crumble and become ineffective. Organic chemical sprays are more cost effective than petroleum sprays and less toxic to the environment. Modifying the surface roughness with mulches is the most effective and cost efficient method to increase surface roughness and mitigate attack from the wind.

In regards to the methods tested in this thesis, snow fencing, netting, and branch piles, several things became evident. Snow fences have been effectively deployed throughout the world to create deposition at a site. Much study has been done on sand fences and what makes them most effective in a given situation. The deployment of a sand fence needs to be thought out, as orientation to prevailing winds is paramount to success. The proper porosity is critical to success in regards to wind speed for the regions that the fence is deployed.

The use of netting to mitigate blowout along pipelines is promising. This study did find modest gains in deposition using net structures. Further study on the ideal net kirf and shapes of sand capturing devices needs to be undertaken. For use on small isolated blowouts, the cost of net structures may be acceptable. However, for expansive sections of pipeline, the cost of net structures may be a limiting factor.

Branch piles show the most promise for application to pipelines where blowouts are a problem. Unlike mulches, which only prevent deflation, branch plies create a depositional environment. If the branch piles covered complete blowouts, it is believed that the blowout could be completely filled in, if there was an ample supply of sand available for transport to the blowout. Branch piles also offer a place for wind blown seeds to become lodged and take root, thus helping to establish vegetation. Under extreme wind velocities, a completely sand covered branch pile can experience deflation of the surface. But as more branches become exposed, surface roughness becomes higher, and deposition resumes. Branch piles also conserve moisture by increasing shade. The cost to deploy branch piles is relatively low compared to some other permanent treatments. In many regions, there is a supply of branches or brush somewhere nearby. In active oilfields access roads are being cleared, usually of brush which could be trucked to nearby blowouts. In the case of the pipelines near Roswell, NM, there are hundreds of acres of pecan orchards, in which pruning operations generate plenty of easily transported branches.

Seeing how well the branch piles worked to create a depositional environment, perhaps an artificial branch pile could be invented. Biodegradable branchlike structures made from recycled materials could be created and deployed.

Branch piles offer pipeline maintenance companies a low cost, easily deployable, and effective method to mitigate deflation on a pipeline ROW. If a blowout can be detected in the early stages, before the pipeline becomes exposed, branch piles of relatively low height could be scattered in the affected area and prevent the pipeline from being exposed. If the pipeline has already become exposed, a deeper branch pile could be deployed to create a depositional environment where the wind would do the work of filling in the blowout and covering the exposed pipeline. These branch piles would also serve to trap native seed and facilitate re-vegetation of the blowout, thus increasing the surface roughness even more and preventing further deflation on the pipeline ROW.

4.5 Future studies

Future studies should focus on net structures and branch piles, as fence structures have been extensively studied. In regards to net structures, net porosities should be examined in relation to variability in wind speed, trying to find a net kirf that would deflect wind around the structure and yet let sand to enter the structure. The shape of the net structure should be experimented with to create a structure that would be equally effective from all angles of wind attack, perhaps a dome shape.

Future studies of branch piles ought to focus on larger areas and deeper piles. Studies could be done to quantify the optimum density of branches for various wind speeds. A study on how problematic buried branch piles would be to the future maintenance of a pipeline could be undertaken.

5. Conclusions

This study set out to evaluate the performance of three low cost sand capturing structures. The three experiments accomplished that goal by being relatively low in cost to deploy per square foot. The branches used in the experiment were agricultural waste and acquired for free. The orchard that the branches used in this experiment were sourced, is operated by a subsidiary of one of the local oil companies. The cost to deploy branch piles would be fairly low in the grand scheme of the oil and gas world. Branches could be acquired for free or at relatively low cost, then transportation and labor to build the branch piles are the remaining costs.

The net experiment carries a higher cost, but not prohibitive. High quality netting that can stand up to years of abuse from the wind and sun is about ¢10 per square foot. Additional costs would come from the frame to support the netting, labor, and transportation to the site.

Snow fence is already known to be a relatively low cost solution to creating depositional environments. Snow fence in Roswell, NM costs about $1.60 per linear foot. I’m sure it could be acquired in bulk from a manufacturer for considerably less. Labor and transportation are the other costs involved in the fence equation.

Looking at transportation and labor costs, in terms of what would be necessary transporting large quantities of branches would require a large truck, given that a pile of branches is volumetrically quite large. Branches could be bundled tightly to compress the load and increase the amount of branches being transported in each load. The amount labor to setup branch piles is relatively low and could be fairly unskilled, as branches need to be taken from where the truck dumps them to the blowout and piled.

Netting and a structure that can be assembled on site does not require as large truck to be transported. However labor to set up the structure and hang the netting can be labor intensive and require skilled labor. Perhaps a different low cost method could be found to suspend the netting.

Snow fenceing is quite heavy along with the tee posts needed to hold the fence up. Snow fence is not as volumetrically large as branches, but will need a substantial truck to handle the weight. Snow fence needs to be erected, and requires pounding many fence posts. Orientation of the fence is critical and would require that skilled labor be involved alongside unskilled.

All three sand capturing devices studied in this thesis have merit and have been proven to capture sand. This study demonstrated the validity of branch piles to capture sand. With further research the net structures could be improved and be a viable mitigation method in certain applications. The fence, in the configuration tested was a failure. But in standard straight line configurations, snow fence has been proven by many studies to create a depositional environment - orientation is the key. As was hypothesized, the branch pile mimicking a form found in nature was the most successful.

Using branch piles is a viable low cost method to mitigate blowouts and rebury pipelines or prevent deflation from unburying pipelines in the future. Keeping pipelines buried will ultimately protect the pipeline from environmental damage, protect the public, and prevent damage to the environment.

Looking forward, it is my hope that pipeline maintenance companies will adopt a form of the branch pile to protect the pipelines they maintain. The basic principles revealed in this thesis about how blowouts develop and the complex forces involved in their formation can be applied to the development of alternative mitigation methodologies.

5.1 Limitations and Recommendations

Limitations encountered during this thesis were many. Primarily there was a lack of funding and labor to create larger scale experiments. Due to the scale of the project and time limitations a non-quantitative research approach was taken. A failure to use more advanced sampling techniques significantly limits our ability to make broader generalizations from the results (i.e., the ability to make statistical inferences from the data to the processes being studied). The addition of wind data would have been helpful, but was not feasible.

With limited funding and available labor, experiments had to be scaled appropriately. The branches were sourced for free from a local orchard; the 300 dollars BLM supplied funded the purchase of the 3 nets and 125ft of snow fence. The PVC net structure and fuel were purchased out of pocket. The addition of wind data collected at each test site for the duration of the data collection period would have helped to understand some of the depositional anomalies. Wind data would have also helped in understanding the depositional limitations for each structure.

If future studies were to be undertaken, more funding to support the acquisition of more materials to create larger scale experiments, and hiring of more labor to deploy the experiments more quickly would be pursued. The acquisition of weather stations for each test site would add data critical to understanding the depositional results for each type of experiment for given time periods.

6. References Citied

Alhajraf, S., 2004. Computational fluid dynamic modeling of drifting particles at porous fences. Environmental Modeling & Software 19 (2004) 163–170.

Argonne National Laboratory, 2007. Overview of the Design, Construction, and Operation of Interstate Liquid Petroleum Pipelines. This report is available, at http://www.osti.gov/bridge.

Armbrust, D. V., 1977. A Review of Mulches to Control Wind Erosion. Transactions of the American Society of Agricultural Engineers Vol. 20, No 5, p 904-905, 910, September-October 1977.

Bagnold, R. A. 1937. The Transport of Sand by Wind. The Geographical Journal, Vol. 89 No. 5: pp. 409-438.

Bagnold, R. A. 1941. The Physics of Blown Sand and Desert Dunes. London: Methuen.

Banerjee, P. K., 1996. Development of new geosynthetic products through blends of natural fibres. In: Rao, G.V., Banerjee, P.K. (Eds.), Environmental Geotechnology with Geosynthetics. Asian Society for Environmental Geotechnology, New Delhi, India, pp. 337–346.

Barbour, E. H. 1895. Report of the geologist: Soils. In: Furnas, R.T. (ed), Annual Report, Nebraska State Board of Agriculture for the year 1894, pp. 61-92.

Bhattacharyya, R., Smets, T., Fullen, M. A., Poesen, J., Booth, C. A., 2010.Effectiveness of geotextiles in reducing runoff and soil loss: A synthesis .CATENA, Volume 81, Issue 3, 15 June 2010, Pages 184-195.

Billingsley, E. 2002. New Mexico Business Weekly. El Paso Corp. settles with victims' families. http://www.bizjournals.com/albuquerque/stories/2002/09/16/story3.html?page=all

Bolde, U., 2003. About the penetration of a horizontal axis cylindrical vortex into the nearby downwind region of a vertical porous fence. Journal of Wind Engineering and Industrial Aerodynamics 91 (2003) 859–872.

Briassoulis, D., Mistriotis, A., Giannoulis, A., 2010. Wind forces on porous elevated panels, Journal of Wind Engineering and Industrial Aerodynamics, Volume 98, Issue 12, Pages 919–928.

Burri, K., Gromke, C., Lehning, M., Graf, F., 2011. Aeolian sediment transport over vegetation canopies: A wind tunnel study with live plants. Aeolian Research, Volume 3, Issue 2, November 2011, Pages 205-213.

Christensen Net Works, 401 Lincoln St. Everson, WA 98247, USA.

Correa, A. C., Agnello, M. F., Todd, R. and Peterson, R. (ed) 2008. Water in the Arid and Semiarid Lands. Proceedings of the 2006 International Conference, 15-17 November 2006, Lubbock, Texas, ICASALS Publication 2008-1, pp. 191-199.

Dong, Z., Chen, G., He, X., Han, Z., Wang, X., 2004. Controlling blown sand along the highway crossing the Taklimakan Desert, Journal of Arid Environments, Volume 57, Issue 3, May 2004, Pages 329–344.

Dong, Z., Luo, W., Qian, G., Lu, P., Wang, H., 2010. A wind tunnel simulation of the turbulence fields behind upright porous wind fences. Journal of Arid Environments, Volume 74, Issue 2, February 2010, Pages 193–207.

Eldridge, D. J., Leys, J. F., 2003. Exploring some relationships between biological soil crusts, soil aggregation and wind erosion. Journal of Arid Environments 53, pp. 457–466.

Fullen, M. A., Booth, C. A., Sarsby, R. W., Davies, K., Kugan, R., Bhattacharyya, R., Subedi, M., Poesen, J., Smets, T., Kertesz, A., Toth, A., Szalai, Z., Jakab, G., Kozma, K., Jankauskas, B., Jankauskiene, G., Bühmann, C., Paterson, G., Mulibana, E., Nell, J. P., van der Merwe, G. M. E., Guerra, A. J. T., Mendonça, J. K. S., Guerra, T. T., Sathler, R., Bezerra, J. F. R., Peres, S.M., Yi, Z., Yongmei, Li, T., Panomtarachichigul, M., Peukrai, S., Thu, D.C., Cuong, T.H., Toan, T.T., Jonsyn-Ellis, F., Jallow, S., Cole, A., Mulholland, B., Dearlove, M., Corkill, C., 2007. Contributions of biogeotextiles to sustainable development and soil conservation in developing countries: the BORASSUS Project. Ecosystems and Sustainable Development. WIT Press, Southampton, UK, pp. 123–141.

Fraser, G. S. 1998. Windflow Circulation Patterns in a Coastal Dune Blowout, South Coast of Lake Michigan. Journal of Coastal Research, 14(2), 451-460.

Hall, S. A., 2002. Field Guide to the Geoarchaeology of the Mescalero Sands, Southeastern New Mexico. State of New Mexico Historic Preservation Division and New Mexico Bureau of Land Management, Project No. 35-00-15334.11, pp. 59.

Han, Z., Wang, T., Dong, Z., Hu, Y., Yao, Z., 2007. Chemical stabilization of mobile dune fields along a highway in the Taklimakan desert of China. Journal of Arid Environments 68 (2), 260–270.

Hotta, K. S., Horikawa, K., 1987. Function of sand fences in controlling wind-blown sand. In: Coastal Sediments'87. American Society of Civil Engineers, New York, pp. 772–787.

Hotta, K. S., 1991. Functioning of Multi-Row Sand Fences in Forming Foredunes. In: Coastal Sediments, 1991. American Society of Civil Engineers, New York, pp. 261-275.

Hudson, H. R., 1982. A field technique to directly measure river bank erosion. Canadian Journal of Earth Sciences, Vol. 19, No. 2 : pp. 381-383 .

Ingold, T. S., 1996. Market study. In: CFC/IJO, Technical specification and market study of potentially important jute geotextiles. Project Completion Report by Silsoe College, Cranfield University (Project Executing Agency).

Jungerius, P. D. and van der Meulen, F. 1989. The development of dune blowouts, as measured with erosion pins and sequential air photos. Catena 16(4-5):369-376.

Kucinski, K., and Eisenmenger, W.S., 1943. Sand Dune Stabilization on Cape Cod, Economic Geography , Vol. 19, No. 2 (Apr., 1943), pp. 206-214.

Lancaster, N. 1983. Controls on dune morphology in the Namib Sand Sea. In Eolian Sediments and Processes, pp261-290. Ed. By M. Brookfield and Ahlbrandt. Amsterdam: Elsevier.

Langford, R. L., Coleman, M.J., 1996. Biodegradable erosion control blankets prove effective on Iowa wildlife refuge. XXVII Int. Erosion Control Assoc. Proceedings of Conf., Seattle, USA, pp. 13–20.

Lee, Sang-Joon, 2002.Wind tunnel observations about the shelter effect of porous fences on the sand particle movements. Atmospheric Environment 36 (2002) 1453–1463.

Melton, F. A., 1940. A Tentative Classification of Sand Dunes Its Application to Dune History in the Southern High Plains. The Journal of Geology, Vol. 48, No. 2 (Feb. - Mar., 1940), pp. 113-174.

Mendelssohn, I. A., Hester, M. W., Monteferrante, F.J., Talbot, F., 1991. Experimental dune building and vegetative stabilization in a sand-deficient barrier island setting on the Louisiana coast, USA. Journal of Coastal Research 7, 137–149.

Mistriotis, A., & Castellano, S.,2012. Airflow through net covered tunnel structures at high wind speeds, Biosystems Engineering, http://dx.doi.org/10.1016/ j.biosystemseng .2012.08.002

Namikas, S. L., Sherman, D. J., 1995. A review of the effects of surface moisture content on aeolian sand transport. In: Tchakerian, V. P. (Ed.), Desert Aeolian Processes. Chapman & Hall, London, pp. 269–293.

Nordstrom, K. F., and Arens, S. M., 1998. The role of human actions in evolution and management of foredunes in The Netherlands and New Jersey, USA. Journal of Coastal Conservation. 4:169–180.

Nordstrom, K.F., Jackson, N.L., Korotky, K.H., Puleo, J.A., 2011. Aeolian transport rates across raked and unraked beaches on a developed coast. Earth Surface Processes and Landforms. Volume 36, Issue 6, pages 779–789.

NTSB, (National Transportation Safety Board), 2003.Natural Gas Pipeline Rupture and Fire, Near Carlsbad, New Mexico, August 19, 2000. Pipeline Accident Report NTSB/PAR-03/01. Washington, D.C.

Ogbobe, O., Essien, K. S., Adebayo, A., 1998. A study of biodegradable geotextiles used for erosion control. Geosynthetics International 5, 545–553.

Oosthuizen, D., Kruger, D., 1994. The use of Sisal fibre as natural geotextile to control erosion. In: Rao, G.V., Balan, K. (Eds.), Coir Geotextiles—Emerging Trends, Proceeding of the 5th International Conference on Geotextiles, Geomembranes and Related Products, Singapore, 5–9 September, pp. 18–23.

Raine, J. K., Stevenson, D. C., 1977. Wind protection by model fences in simulated atmospheric boundary layer. Journal of Industustrial Aerodynamics 2, 159–180.

Raupach, M. R., 2001. The entrapment of particles by windbreaks. Atmospheric Environment 35 (2001) 3373–3383.

Rosenberg, N. J., 1974. Microclimate: The Biological Environment. Wiley, New York.

Ruz, M.H., Meur-Ferec, C., 2004. Influence of high water levels on aeolian sand transport: upper beach/dune evolution on a macrotidal coast, Wissant Bay, northern France. Geomorphology, Volume 60, Issues 1–2, 3, Pages 73–87.

Sears, P. B. 1935. "Deserts on the March." Univ. Oklahoma Press, Norman, Oklahoma. Coastal Planning and Management Manual, 2003. http://www.planning.wa.gov.au/publications/768.asp

Shao, Y., 2008. Physics and Modeling of Wind Erosion. Springer Science + Business Media B.V.

Sprague, C. J., Paulson, J.N., 1996. Project-specific selection of erosion control geosynthetics. Erosion control technology: bringing it home, Proceedings of Conference XXVII, International Erosion Control Association, 27 February–1 March, Seattle, Washington, pp. 213–226.

Stout, J.E., 2010. Threshold wind velocities for sand movement in the Mescalero Sands of southeastern New Mexico. Journal of Arid Environments Volume 74, Issue 11, Pages 1456-1460.

Stout, J.E., 2012. A field study of wind erosion following a grass fire on the Llano Estacado of North America. Journal of Arid Environments, Volume 82, July 2012, Pages 165-174.

Sutherland, R.A., Ziegler, A.D., 1996. Geotextile effectiveness in reducing interill runoff and sediment flux. International Erosion Control Association Proceedings of Conference XXVI, 1995, Atlanta, USA, pp. 359–370.

Wallingford, H.R., 2000. A guide to managing coastal erosion in beach/dune systems. Scottish Natural Heritage. http://www.snh.org.uk/publications/online/heritagemanagement/erosion/appendix_1.4.shtml

Wolfe, S.A., Nickling, W.G., 1993. The protective role of sparse vegetation in wind erosion. Progress in Physical Geography 17 (1), 50–68.

Zaghloul, N.A., 1997. Sand accumulation around porous fences. Environmental Modelling & Software, Volume 12, Issues 2–3 Pages 113-134.

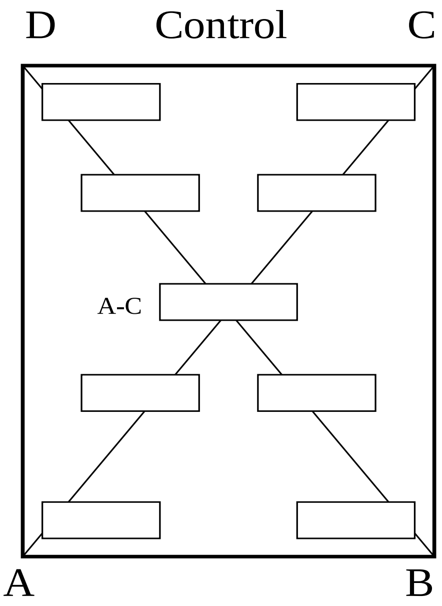
Zhang, K., Qu, J., Liao, K., Niu, Q., Han, Q., 2009. Damage by wind-blown sand and its control along Qinghai-Tibet Railway in China. Aeolian Research Volume 1, Issues 3–4, Pages 143-146.

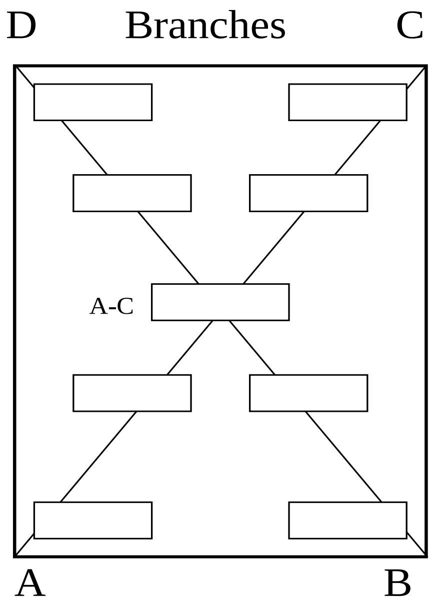
7. Appendices

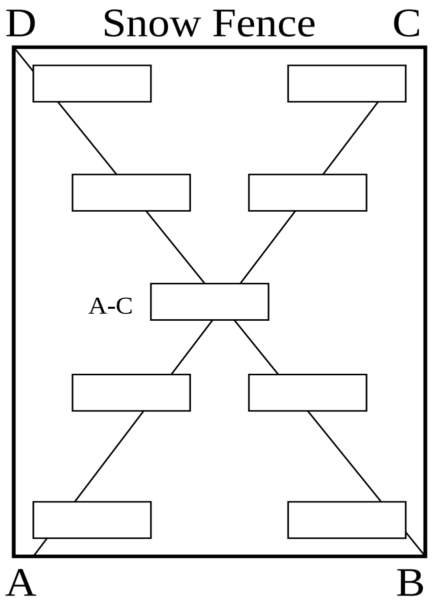
Appendix 1

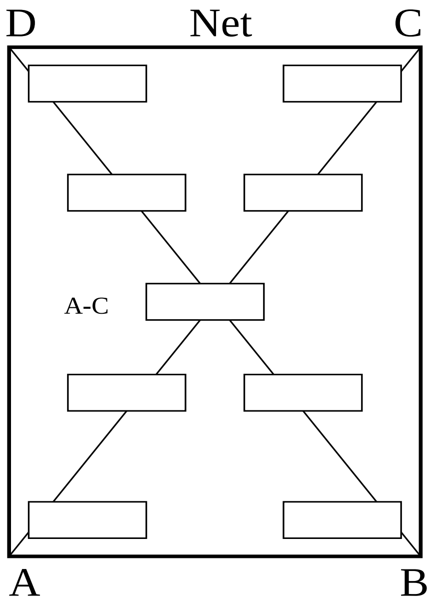
Field data collection sheet.

Data Sheet Site #________ Date:_________









Appendix 2

Data tables for control plots.

Control Plot - Site 1

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10	872	831	879	833	810	820	744	830	710	814.33	0
4/11/10	881	824	879	837	804	811	748	835	711	814.44	-0.11
4/16/10											0
4/25/10	893	810	890	836	795	799	740	833	703	811.00	3.44
5/16/10	909	809	904	840	801	764	755	834	711	814.11	-3.11
6/3/10	917	804	896	833	815	786	747	817	709	813.78	0.33
8/22/10	918	773	895	813	827	879	744	825	711	820.56	-6.78
Accumulation in mm	-37	51	-16	24	-23	-68	4	10	0	-6.11	

Control Plot - Site 2

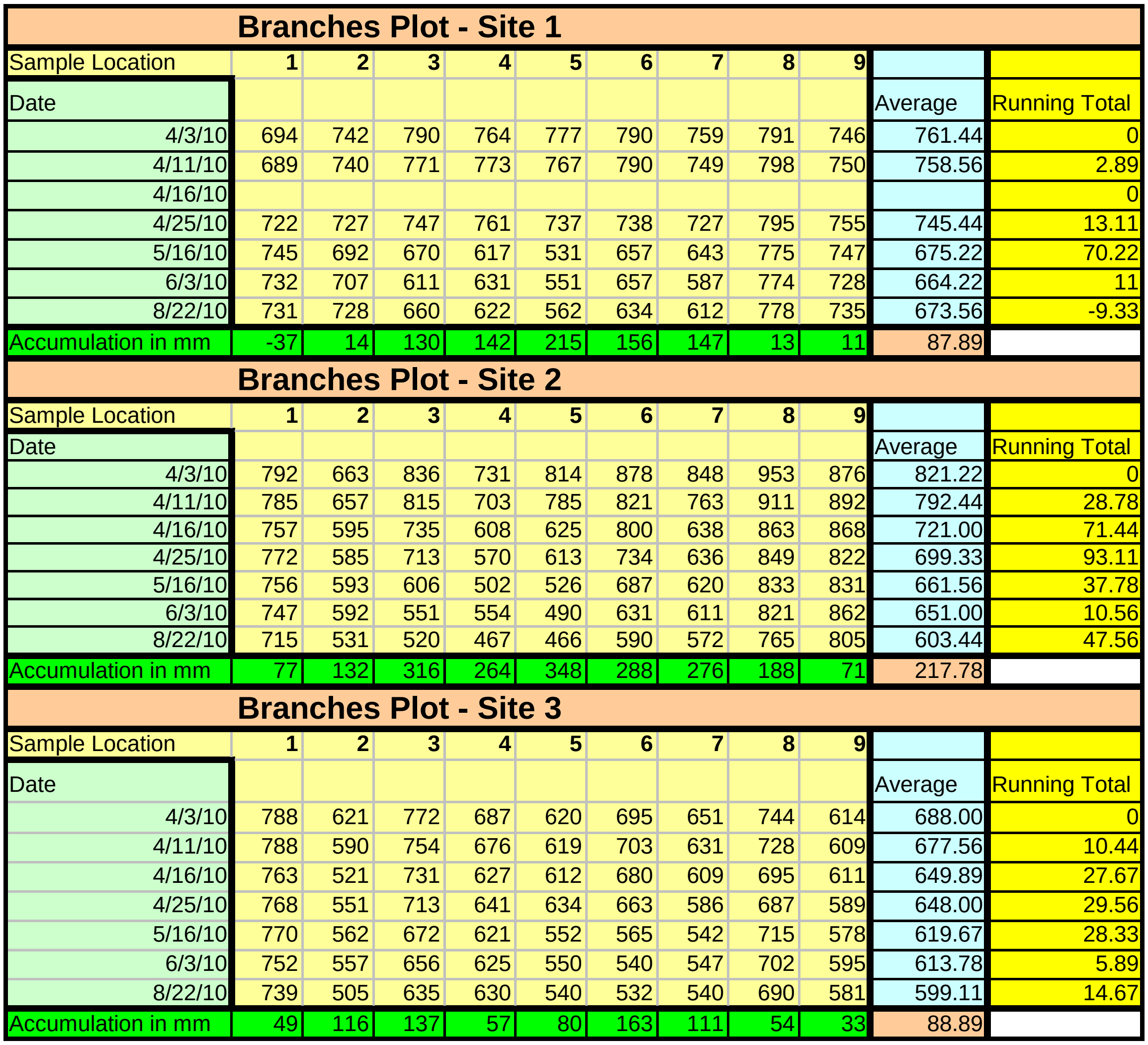
Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10	731	587	722	654	693	717	658	736	587	676.11	0
4/11/10	579	573	638	635	707	730	718	735	754	674.33	1.78
4/16/10	556	531	604	583	654	709	667	730	722	639.56	34.78
4/25/10	572	520	647	627	717	728	696	754	697	662.00	12.33
5/16/10	587	524	633	579	644	697	624	747	628	629.22	32.78
6/3/10	571	524	604	575	639	727	624	762	654	631.11	-1.89
8/22/10	534	519	571	537	614	712	620	777	653	615.22	15.89
Accumulation in mm	197	68	151	117	79	5	38	-41	-66	60.89	

Control Plot - Site 3

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10										0.00	0
4/11/10	579	602	663	690	767	797	777	765	791	714.56	0
4/16/10	579	600	664	690	767	795	760	777	789	713.44	1.11
4/25/10	578	603	660	688	764	790	764	763	790	711.11	3.44
5/16/10	586	607	670	691	767	792	774	765	793	716.11	-5
6/3/10	582	604	665	692	765	797	762	771	790	714.22	1.89
8/22/10	581	606	660	682	757	791	759	760	764	706.67	7.56
Accumulation in mm	-2	-4	3	8	10	6	18	5	27	7.89	

Explanation of data table: All measurements are in millimeters. If data was not collected on a particular date, no data was entered in that row. Sample locations are labeled 1 thru 9. An average surface elevation for the plot was arrived at by averaging the 9 sampling locations and is shown in the blue column under Average. A running total of average surface elevation change is given in the last column. The bottom row in green shows total surface change for each sample location within the plot. The orange box under the blue column and to the right of the green column shows the total average surface elevation change for the plot from the beginning of the data collection period to the end.

Data tables for branch plots.



Branches Plot - Site 1

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10	694	742	790	764	777	790	759	791	746	761.44	0
4/11/10	689	740	771	773	767	790	749	798	750	758.56	2.89
4/16/10											0
4/25/10	722	727	747	761	737	738	727	795	755	745.44	13.11
5/16/10	745	692	670	617	531	657	643	775	747	675.22	70.22
6/3/10	732	707	611	631	551	657	587	774	728	664.22	11
8/22/10	731	728	660	622	562	634	612	778	735	673.56	-9.33
Accumulation in mm	-37	14	130	142	215	156	147	13	11	87.89	

Branches Plot - Site 2

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10	792	663	836	731	814	878	848	953	876	821.22	0
4/11/10	785	657	815	703	785	821	763	911	892	792.44	28.78
4/16/10	757	595	735	608	625	800	638	863	868	721.00	71.44
4/25/10	772	585	713	570	613	734	636	849	822	699.33	93.11
5/16/10	756	593	606	502	526	687	620	833	831	661.56	37.78
6/3/10	747	592	551	554	490	631	611	821	862	651.00	10.56
8/22/10	715	531	520	467	466	590	572	765	805	603.44	47.56
Accumulation in mm	77	132	316	264	348	288	276	188	71	217.78	

Branches Plot - Site 3

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10	788	621	772	687	620	695	651	744	614	688.00	0
4/11/10	788	590	754	676	619	703	631	728	609	677.56	10.44
4/16/10	763	521	731	627	612	680	609	695	611	649.89	27.67
4/25/10	768	551	713	641	634	663	586	687	589	648.00	29.56
5/16/10	770	562	672	621	552	565	542	715	578	619.67	28.33
6/3/10	752	557	656	625	550	540	547	702	595	613.78	5.89
8/22/10	739	505	635	630	540	532	540	690	581	599.11	14.67
Accumulation in mm	49	116	137	57	80	163	111	54	33	88.89	

Explanation of data table: All measurements are in millimeters. If data was not collected on a particular date, no data was entered in that row. Sample locations are labeled 1 thru 9. An average surface elevation for the plot was arrived at by averaging the 9 sampling locations and is shown in the blue column under Average. A running total of average surface elevation change is given in the last column. The bottom row in green shows total surface change for each sample location within the plot. The orange box under the blue column and to the right of the green column shows the total average surface elevation change for the plot from the beginning of the data collection period to the end.

Data tables for snow fence plots

Snow Fence Plot - Site 1

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10											0
4/11/10											0
4/16/10	894	842	891	915	932	888	906	770	952	887.78	0
4/25/10	922	852	920	892	891	877	892	800	952	888.67	-0.89
5/16/10	975	788	912	738	689	807	879	819	990	844.11	44.56
6/3/10	982	847	851	891	748	781	944	868	981	877.00	-32.89
8/22/10	940	872	805	946	765	778	956	905	1002	885.44	-8.44
Accumulation in mm	-46	-30	86	-31	167	110	-50	-135	-50	2.33	

Snow Fence Plot - Site 2

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10										0.00	0
4/11/10										0.00	0
4/16/10	722	712	825	783	830	805	818	840	746	786.78	0
4/25/10	806	701	830	773	790	828	789	856	797	796.67	-9.89
5/16/10	1111	672	1000	696	753	970	817	942	995	884.00	-87.33
6/3/10	1000	661	991	756	733	967	836	977	1006	880.78	3.22
8/22/10	1001	680	935	777	740	947	904	1021	939	882.67	-1.89
Accumulation in mm	-279	32	-110	6	90	-142	-86	-181	-193	-95.89	

Snow Fence Plot - Site 3

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10										0.00	0
4/11/10										0.00	0
4/16/10	824	763	828	795	812	815	779	811	739	796.22	0
4/25/10	845	791	847	771	767	827	744	828	740	795.56	0.67
5/16/10	872	731	850	785	679	873	766	836	845	804.11	-8.56
6/3/10	864	753	825	848	654	815	801	867	836	807.00	-2.89
8/22/10	723	789	688	712	679	666	637	659	598	683.44	123.56
Accumulation in mm	101	-26	140	83	133	149	142	152	141	112.78	

Explanation of data table: All measurements are in millimeters. If data was not collected on a particular date, no data was entered in that row. Sample locations are labeled 1 thru 9. An average surface elevation for the plot was arrived at by averaging the 9 sampling locations and is shown in the blue column under Average. A running total of average surface elevation change is given in the last column. The bottom row in green shows total surface change for each sample location within the plot. The orange box under the blue column and to the right of the green column shows the total average surface elevation change for the plot from the beginning of the data collection period to the end.

Data tables for net plots

Net Plot - Site 1

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10										0.00	0
4/11/10										0.00	0
4/16/10										0.00	0
4/25/10	775	617	762	667	703	744	654	777	560	695.44	0
5/16/10	797	566	769	640	691	728	636	790	556	685.89	9.56
6/3/10	791	558	772	636	702	731	643	781	562	686.22	-0.33
8/22/10	790	531	742	632	714	725	640	764	558	677.33	8.89
Accumulation in mm	-15	86	20	35	-11	19	14	13	2	18.11	

Net Plot - Site 2

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10										0.00	0
4/11/10										0.00	0
4/16/10											0
4/25/10	718	592	797	722	845	840	780	808	654	750.67	0
5/16/10	652	845	752	848	847	718	754	558	671	738.33	12.33
6/3/10	633	829	754	835	874	718	776	548	604	730.11	8.22
8/22/10	830	632	840	740	830	782	720	610	542	725.11	5
Accumulation in mm	-112	-40	-43	-18	15	58	60	198	112	25.56	

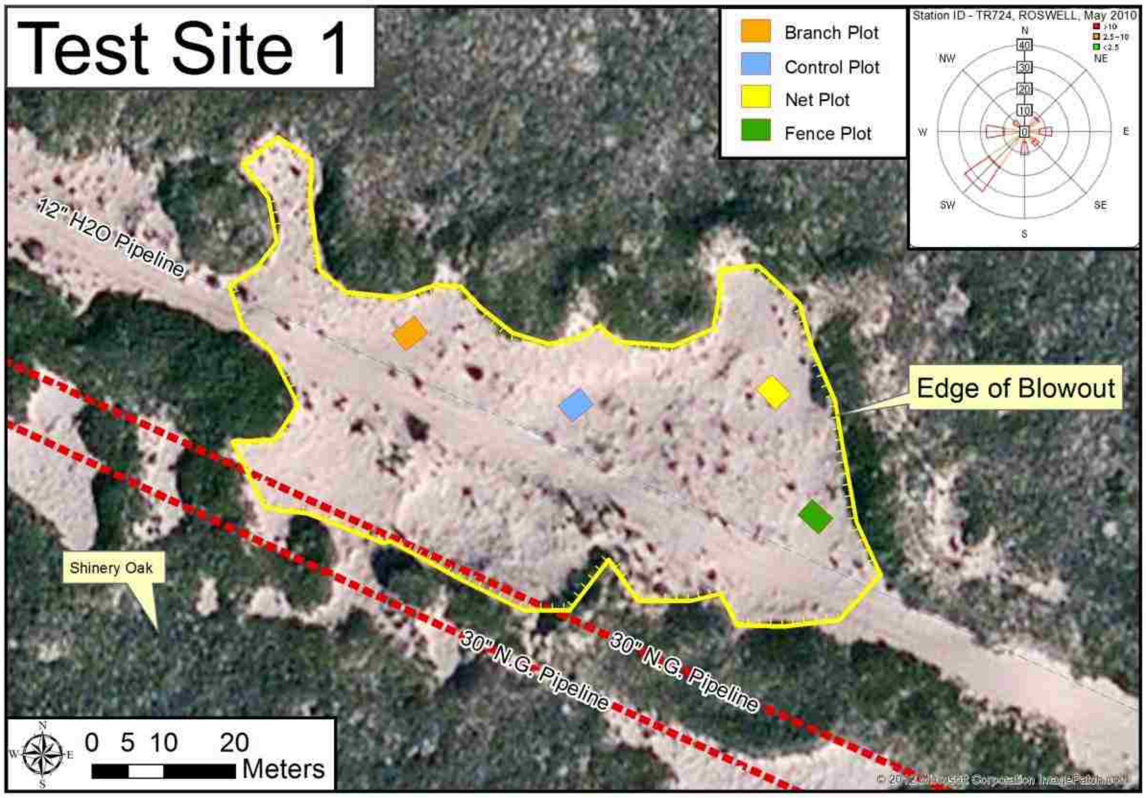
Net Plot - Site 3

Sample Location	1	2	3	4	5	6	7	8	9		
Date										Average	Running Total
4/3/10										0.00	0
4/11/10										0.00	0
4/16/10											0
4/25/10	778	747	740	748	718	713	660	702	634	715.56	0
5/16/10	692	716	623	704	674	674	641	664	636	669.33	46.22
6/3/10	751	760	709	708	685	680	644	671	626	692.67	-23.33
8/22/10	867	777	711	871	700	767	833	919	818	807.00	-114.33
Accumulation in mm	-89	-30	29	-123	18	-54	-173	-217	-184	-91.44	

Explanation of data table: All measurements are in millimeters. If data was not collected on a particular date, no data was entered in that row. Sample locations are labeled 1 thru 9. An average surface elevation for the plot was arrived at by averaging the 9 sampling locations and is shown in the blue column under Average. A running total of average surface elevation change is given in the last column. The bottom row in green shows total surface change for each sample location within the plot. The orange box under the blue column and to the right of the green column shows the total average surface elevation change for the plot from the beginning of the data collection period to the end.

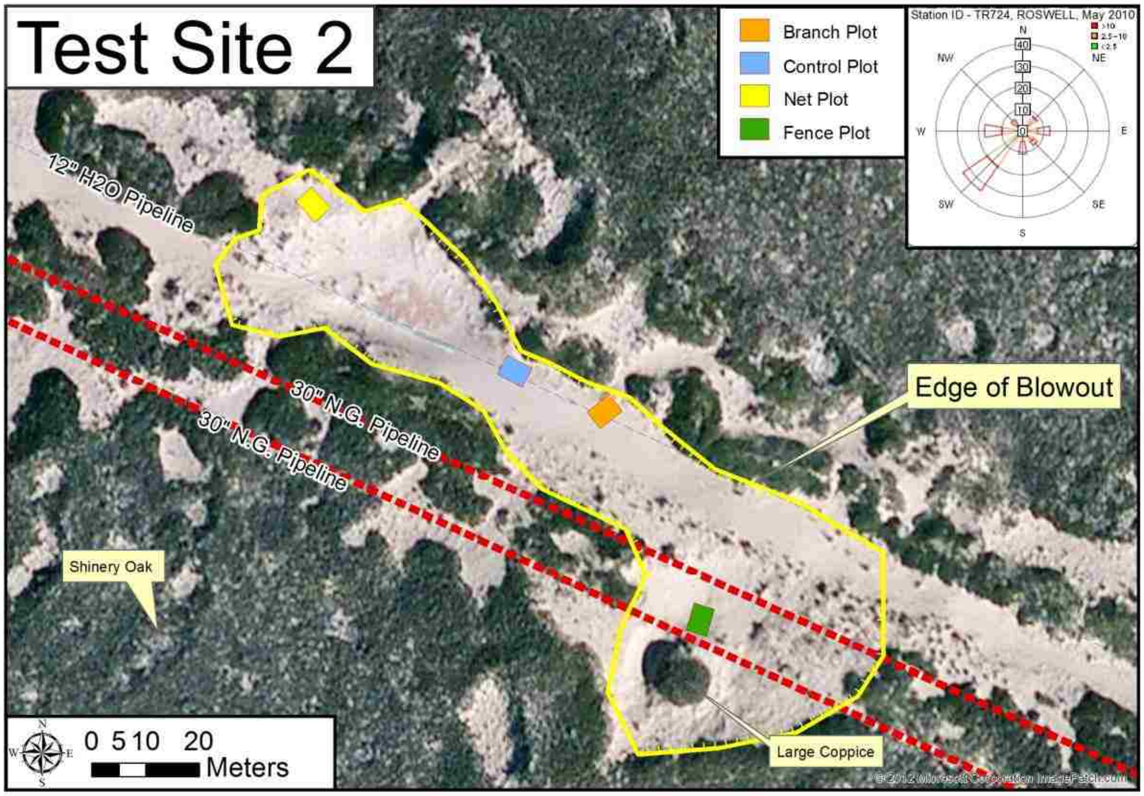
APENDIX 3

Areial image of test site 1.



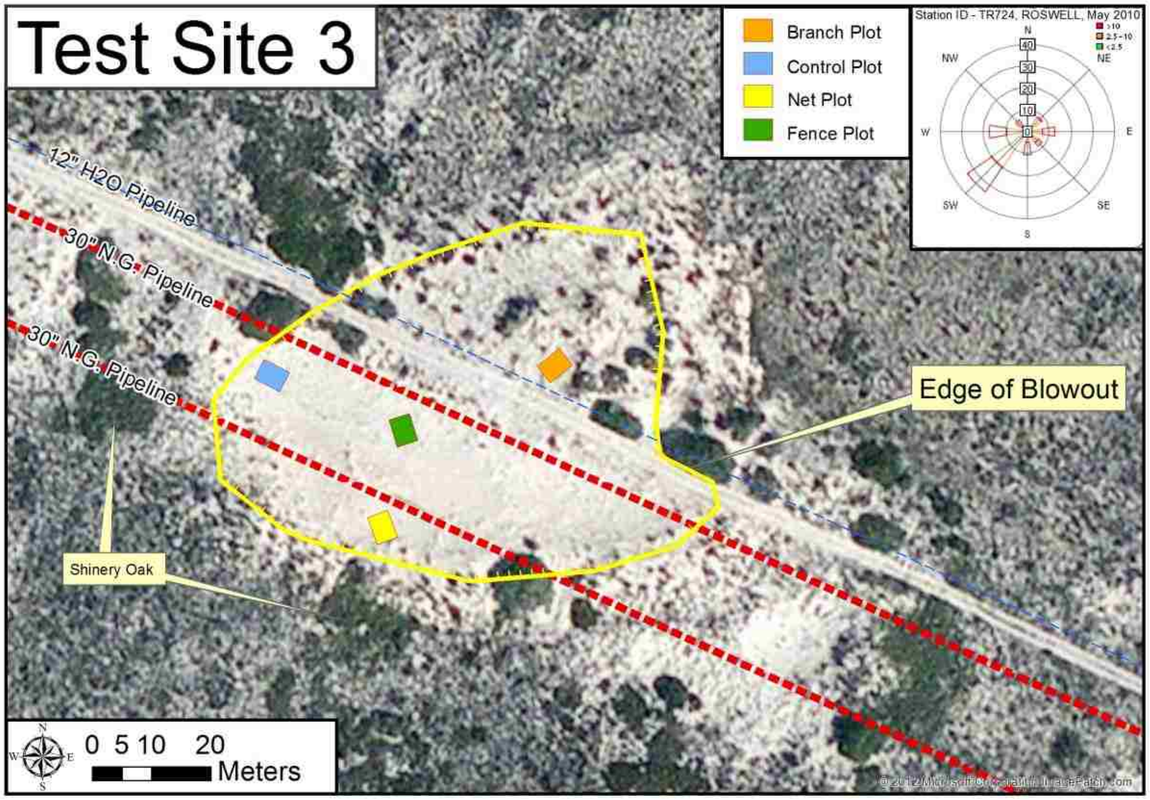
The blowout is defined by the yellow hashed line. The test plots are to scale and orientated properly. Wind rose shows wind direction and speed for the month of May, 2010. The locations of two 30' high pressure natural gas pipelines are shown with red dashed lines. A 12' water pipeline in shown with a blue dashed line. Note that the 12' water pipeline is exposed about 5 meters to the southwest of the control plot (light blue line). Map by: Knutt Peterson

Areial image of test site 2.



The blowout is defined by the yellow hashed line. The test plots are to scale and orientated properly. Wind rose shows wind direction and speed for the month of May, 2010. The locations of two 30’ high pressure natural gas pipelines are shown with red dashed lines. A 12’ water pipeline in shown with a blue dashed line. Note that the 12’ water pipeline is exposed about 12 meters to the west of the control plot (light blue line). Map by: Knutt Peterson

Areial image of test site 3.



The blowout is defined by the yellow hashed line. The test plots are to scale and orientated properly. Wind rose shows wind direction and speed for the month of May, 2010. The locations of two 30’ high pressure natural gas pipelines are shown with red dashed lines. A 12’ water pipeline in shown with a blue dashed line. Map by: Knutt Peterson