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Plant and Soil Recovery Along Transmission Power Line Corridors in the Colorado Desert of Southern California

A dissertation submitted in partial satisfaction of the requirements for the degree of

Doctor in Environmental Science and Engineering

by

Setal Sridhar Prabhu

2017

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ABSTRACT OF THE DISSERTATION

Plant and Soil Recovery Along Transmission Power Line Corridors in the Colorado Desert of Southern California

by

Setal Sridhar Prabhu

Doctor in Environmental Science and Engineering

University of California, Los Angeles, 2017

Professor Richard F. Ambrose, Chair

The desert habitats of southern California have been subject to numerous anthropogenic disturbances. Recovery of the disturbed habitat can occur naturally or through human intervention (active restoration). Increasing energy demand and a push towards renewable sources like solar thermal and wind, often located in desert regions, will continue to impact the deserts of southern California. Electricity generated at the source (e.g. solar plant) is transported over long distances to the customer using transmission power lines which also traverse the desert habitat. This dissertation focuses on the natural recovery of vegetation and soil following impacts from transmission power line construction. The main objectives of this dissertation are to: 1. Evaluate vegetation recovery in sites impacted by transmission line construction using

Landsat imagery and normalized difference vegetation index (NDVI); 2. Evaluate vegetation recovery about thirty years after construction using field survey data; and 3. Evaluate natural soil recovery in sites impacted by transmission line construction. The study area, dominated by creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*), is in the lower Colorado Desert in southern California. Data are collected in areas impacted during transmission power line construction and in areas undisturbed during construction. I assess vegetation recovery in the field by measuring species richness, plant density, and percent cover. Soil recovery is assessed by comparing soil characteristics such as infiltration rate, texture, bulk density, soil compaction, salinity, pH, soil organic matter, carbon stocks, and soil moisture content between impact and control sites. The dissertation is subdivided into the following five chapters: an introduction (chapter 1), three chapters of original research addressing the main objectives listed above (chapters 2–4), and a conclusion of the work (chapter 5).

In chapter 2 I evaluate the impact of transmission power line construction on vegetation by comparing the NDVI measured before construction and immediately following construction. There is no significant difference in NDVI immediately after construction compared to NDVI before construction in disturbed sites implying that the impact is not detected in the Landsat images. In chapter 3 I evaluate vegetation recovery with field survey data thirty-three years after construction by comparing impact and control sites. Results indicate no significant differences between the control and impact sites. In chapter 4 I evaluate soil recovery thirty-one years (old impact) and less than one year (new impact) after construction. The results show no significant differences in soil characteristics between control and old impact, except with soil compaction at 3 cm from surface. The new impact differed significantly from control in soil organic matter, carbon stocks to a depth of 8 cm, and compaction at 3 cm. Though not significant ($p > 0.05$) bulk density, pH, and salinity at new impact are slightly different ($p < 0.1$) from control sites implying that there may be some immediate effects from construction. Confirming the “fertile island” effect, significant differences are observed between the data collected under shrubs compared to the data collected in the bare ground between shrubs. In chapter 5, I present the overall conclusion, suggest some research opportunities, and discuss land management implications.

The dissertation of Setal Sridhar Prabhu is approved.

Daniela F. Cusack

Philip W. Rundel

Thomas W. Gillespie

Richard F. Ambrose, Committee Chair

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2017

Dedicated to my family

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PUBLICATIONS AND PRESENTATIONS

Pincetl, S., **Prabhu, S.S.**, Gillespie T.W., Jenerette D.G., Pataki D.E. The evolution of tree nursery offerings in Los Angeles County over the last 110 years. 2013. Landscape and Urban Planning 18:10-17.

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AWARDS

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CHAPTER 1

Introduction

1.1. Background

Increases in population and urbanization is resulting in growing utility demand, and consequently, increases in environmental impacts (Abella, 2010). Infrastructure construction of public utilities, such as power, gas, and water, is increasing in the deserts of southern California to support the growing demand and have resulted in disturbances to the desert landscape (Abella, 2010; Lathrop and Archbold, 1980a, 1980b; Lovich and Bainbridge, 1999; Reible et al., 1982; Vasek et al., 1975b, 1975a; Walsh and Hoffer, 1991). Land is cleared during pipeline, aqueduct, and transmission power line construction for trenching, piling, refilling, grading, campsites, storage areas, tower sites, conductor pulling and splicing sites, and service roads (Brum et al., 1983; Lathrop and Archbold, 1980a, 1980b; Lovich and Bainbridge, 1999; Vasek et al., 1975b, 1975a). Heavy equipment used for digging and transport of materials can affect soil characteristics by increasing compaction (Bolling and Walker, 2000; Lovich and Bainbridge, 1999; Webb, 2002) and disrupting the soil surface stabilizers (Lovich and Bainbridge, 1999). Removal of vegetation can affect desert wildlife species (Esque et al., 2003; Lovich et al., 2011), increase soil erosion and fugitive dust release (Grantz et al., 1998), alter fire events (Abella, 2010; Lovich and Bainbridge, 1999), and facilitate the establishment of invasive nonnative species (Abella et al., 2012; Bainbridge, 2012).

Plant growth and establishment are naturally slow in the extreme conditions of the desert because of high temperatures, intense sunlight, limited moisture availability, high levels of herbivory, and low soil fertility (Abella, 2010; Abella and Newton, 2009;

Bainbridge, 2012; Berry et al., 2015, 2016; Lovich and Bainbridge, 1999). Utility construction (Berry et al., 2015, 2016; Brum et al., 1983; Hessing and Johnson, 1982; Lathrop and Archbold, 1980a, 1980b; Turney and Fthenakis, 2011; Vasek et al., 1975a, 1975b), abandoned towns and roads (Bolling and Walker, 2000; Johnson et al., 1975; Knapp, 1991, 1992; Walsh and Hoffer, 1991; Webb et al., 2009; Webb and Wilshire, 1980), military training activities (Belnap and Warren, 2002; Kade and Warren, 2002; Prose and Wilshire, 2000), grazing by domesticated cattle (Guo and Pärtel, 2004; Pei et al., 2008; Sassi et al., 2009), and recreational activities such as off-road vehicle use (Brooks and Lair, 2005; Webb and Wilshire, 2012) can increase the severity of these conditions and affect natural soil and vegetation recovery (Abella, 2010; Bainbridge, 2012; Webb et al., 2009). Disturbances can be especially noticeable in deserts where rainfall is low and variable, soils are sandy and salty, and vegetation regrowth is not slow (Berry et al., 2015). Historically, impacted areas in the desert have been left to recover via natural processes and the outcome can depend on the type of, severity of, and time since disturbance, soil type and quality, precipitation events, topography, climate, and presence of nonnative invasive species (Abella, 2010; Berry et al., 2015; Lathrop and Archbold, 1980b, 1980a; Lovich and Bainbridge, 1999; Vasek et al., 1975b, 1975a; Webb et al., 1983).

Roads, power lines, and pipelines are the most noticeable anthropogenic elements of the deserts of southern California and they are all characterized by long and relatively narrow corridors of disturbance (Lovich and Bainbridge, 1999). Vasek et al. (1975a) studied natural vegetation recovery along a 33-year-old transmission line in the Mojave Desert on land impacted during construction. Focusing on creosote bush

(*Larrea tridentata*) scrub, they observed that ground cover was enhanced under wires when compared to the ground cover in adjacent undisturbed control sites. The authors, however, observed high variability in ground cover under towers compared to control sites and suggested low predictability of the time required for recovery. Similarly, Lathrop and Archbold (1980b) studied vegetation recovery along five pipelines and seven transmission lines varying in age and levels of impact. The authors observed that ground cover was on average lower at the transmission power line impact sites (road edge sites, under wires, under towers) but still comparable to ground cover at control sites in adjacent undisturbed areas. Lathrop and Archbold (1980b), like Vasek et al. (1975a), observed that the area under transmission line towers experienced the most damage and exhibited the highest variability in vegetation recovery. They also reported plant density was higher in impact relative to control sites along transmission power lines. Using a linear model to estimate biomass recovery, the authors predicted a recovery time of about a century for transmission power line road edges and towers, and 20 years for the areas under transmission line wires. They noted that while impact and control sites may appear to have similar vegetation cover, biomass, and density, those do not account for the differences in the qualitative aspects such as the proportion of long-lived species and the presence of dominant natives. Both studies (Lathrop and Archbold, 1980b; Vasek et al., 1975a) focused on vegetation recovery in the Mojave Desert after transmission power line construction. More recently, using a distance from impact study design, Berry et al., (2016, 2015) studied the recovery of both perennials (2016) and annuals (2015) 36 years after the construction of an aqueduct pipeline in the Mojave Desert. They noted that native annual species significantly increased in species richness, but not in density or cover, with increasing distance from impact (road verge), with richness being highest in the control transect located 100 m away. Considering only native species of annuals, the authors estimated a recovery time of several centuries (148–1800 years) for impact sites to become homogeneous with control sites located in adjacent undisturbed habitat. Interestingly, they also observed that nonnative annuals increased in density, cover, and richness with increasing distance from impact (Berry et al., 2015). When nonnative species were also included, the authors estimated a recovery time ranging from 63–281 years. Perennial species richness, density, and cover increased with increasing distance from impact (Berry et al., 2016). Depending on the similarity index used by the authors the time estimated for recovery of perennial species composition at the sites closest to the impact ranged from 175–600 years. In summary, natural recovery of vegetation can take several decades.

Soil is essential to the recovery of the desert habitat after a disturbance and the degree of soil compaction is a major determinant of the rate of vegetation recovery and community structure (Bolling and Walker, 2000; Knapp, 1991; Webb et al., 1987). Knapp (1991) found significant differences in vegetation community structure between disturbed and undisturbed sites 77 years following disturbances associated with abandoned roads in mining towns in Montana. Compacted soil has a lower infiltration rate and moisture-holding capacity and can inhibit the establishment of vegetation by affecting root growth of the seedlings and the subsequent growth rates by limiting access to water and nutrients (Adams et al., 1982; Bainbridge and Virginia, 1990; Prose and Wilshire, 2000; Webb, 2002). Various land uses in the desert may lead to severely compacted soils including military exercises, off-road vehicle use, livestock grazing, and construction of utility corridors (Bolling and Walker, 2000; Lovich and Bainbridge, 1999; Prose and Wilshire, 2000; Vasek et al., 1975a, 1975b; Webb, 2002; Webb and Wilshire, 2012). But most studies have focused on abandoned towns, roads, and military exercises, presumably with minimal subsequent impacts, to help provide information on natural recovery rates of severely compacted soils (Bolling and Walker, 2000; Kade and Warren, 2002; Knapp, 1992; Prose and Wilshire, 2000; Webb, 2002; Webb and Wilshire, 1980). Individual tank tracks from the military exercises during World War II and in 1964 were still visible in the Mojave Desert 50–60 years after the disturbance (Belnap and Warren, 2002; Prose and Wilshire, 2000). Prose and Wilshire (2000) suggested compaction resulting from recreational vehicles may be even greater than tanks because of the higher ground pressure inflicted by conventional tires. Webb and Wilshire (1980) discovered that soils were still highly compacted 51 years after a town was abandoned in southern Nevada. Webb (2002) studied natural recovery of soil on land in the Mojave Desert impacted by military training exercises and abandoned towns. Focusing on the metrics of penetration resistance and bulk density, the author estimated that recovery may take at least 100 years or longer. This long recovery period estimate is in agreement with the results of research by Knapp (1992) and Webb et al., (1986) focusing on abandoned towns. Bolling and Walker (2000) studied soil and vegetation characteristics along eight abandoned roads with varying times since disturbance in southern Nevada and determined that time since disturbance was not a significant factor in recovery of soil and vegetation characteristics. However, they discovered that the soil parameters differed between roads created by surface vehicular traffic versus bull-dozing suggesting that recovery may be linked to the type and intensity of disturbance more than the time since disturbance. Since active rehabilitation of severely compacted soils is expensive and usually requires decompacting the soils with heavy equipment, most sites disturbed in the past have been abandoned without active soil restoration (Webb, 2002). Studies indicate the rate of vegetation recovery can be affected by the degree of soil compaction (Bolling and Walker, 2000; Knapp, 1991; Qi et al., 2015; Webb, 2002; Webb and Wilshire, 1980). Webb and Wilshire (1980) observed the lack of creosote bush 51 years after impacts from an abandoned town in the Mojave Desert and suggested that it was incapable of establishment on compacted soils.

The direct effects of transmission power line construction activities on desert soil and vegetation in the lower Colorado Desert have not been studied. Electricity is generated at the source, which is often located at a significant distance away from the customer, and transmitted at a high-voltage over long distances using transmission power lines. Substations along the route serve to lower the voltage and deliver usable electricity to the customer using distribution power lines. Impacts associated with construction of transmission lines can be classified as temporary and permanent. Permanent impacts include major disturbances to soil and vegetation associated with the construction of the service road that is maintained throughout the life of the line. Besides the presence of the towers and the conductors (wires) being permanent impacts, a small area near the tower, the spur road, connecting it to the service road is also kept clear for repair and maintenance access. Temporary impacts include the clearing and mowing of vegetation and compaction of soils associated with installing the towers, pulling and splicing the conductors, campsites, staging areas, and the usage of heavy ground equipment to complete all activities associated with construction (Brum et al., 1983; Lathrop and Archbold, 1980b; Rorabaugh, 2013).

Abella, (2010) pointed out several key reasons why understanding both natural recovery and recovery via active restoration of impacted lands in desert habitats is critical. Understanding natural recovery after a disturbance is important to: 1. Assist with decision-making on whether active restoration is a more effective option; 2. Help improve active restoration methodologies to mimic natural recovery processes; 3. Estimate the time required for plant communities to reestablish; and, 4. Assess if vegetation communities are capable of full recovery without intervention. The specific purpose of this dissertation is to assess the natural recovery of soil and vegetation on land impacted by transmission power line construction in the desert habitat.

1.2. Outline of the Research

This study specifically focuses on the construction impacts of a transmission line (Devers-Colorado River No. 1 or DCR1) located in the Colorado Desert in southern California and constructed in the early 1980s (1980–1982). DCR1 is owned and operated by the Southern California Edison Company (SCE). Data regarding impact areas and the immediate effects of construction on vegetation were not collected at the time of construction.

My hypothesis is as follows: Desert habitat impacted by transmission power line construction thirty years ago has recovered completely without intervention (i.e., without active restoration). In chapter 2, to assess the immediate effects of construction of the transmission towers on the vegetation, remote sensing is conducted using archival

Landsat images. Normalized difference vegetation index (NDVI) time-series have been used in numerous studies to assess impacts of climate change, drought, conservation, and desertification of lands (Anyamba and Tucker, 2005; Barbosa et al., 2006; Kerr and Ostrovsky, 2003; Nemani et al., 2003; Peters et al., 2002; Roerink et al., 2003; Turner et al., 2003; Verbesselt et al., 2010; Wang et al., 2003; Zhou, 2003) and is used here to assess impacts of construction by measuring the changes in NDVI before and immediately after construction. I use a paired study design with impact sites (location of the towers) and control sites (located south of the impact sites) to conduct before and after construction analyses.

In chapter 3, I evaluate the long-term effects of transmission tower construction activities on vegetation by using a distance from impact study design with belt transects. The control transect is in undisturbed habitat 100 m away from impact. I use percent cover, species richness, and plant density of perennial and annual species as metrics of comparison between the impact and control transects to assess recovery.

In chapter 4, I evaluate the effect of construction on soil characteristics. A new transmission line (Devers-Colorado River No. 2 or DCR2) was constructed (completed in 2014) parallel to DCR1. The impact sites in this chapter include areas impacted during transmission tower construction and conductor pulling and splicing along both DCR1 and DCR2. Bulk density, infiltration rate, compaction, soil moisture content, soil organic matter, soil carbon stocks, soil pH, texture, and salinity are measured at DCR1 impact sites, DCR2 impact sites, and control sites. In addition, the “fertile island” effect (Rostagno et al., 1991; Schlesinger et al., 1996; Titus et al., 2002; Walker et al., 2001;

Whitford et al., 1997) is examined by comparing measurements from under shrub canopies to the measurements from the bare ground located in between shrubs.

In the concluding chapter, the results are summarized and the implications of this study are discussed.

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CHAPTER 2

Vegetation Recovery on Lands Disturbed During Transmission Power Line Construction in the Colorado Desert of Southern California

2.1. Abstract

This project evaluated natural vegetation recovery at sites impacted thirty years ago during transmission power line construction. Normalized difference vegetation index (NDVI) using Landsat imagery was used to assess vegetation recovery. The study area, dominated by creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*), was in the lower Colorado Desert in southern California. A paired-site study design was utilized with control and impact sites. The transmission power line was constructed between 1980 and 1982. Data from 1978 served as the baseline. A before-after-control-impact (BACI) analysis conducted using a two-factor analysis of variance (ANOVA) with one before-year (1978) and one after-year (1983) showed no significant difference in NDVI between control and impact sites. Matched-pairs analysis conducted using a paired t-test did not detect a significant difference between the control and impact sites of 1978. It also did not detect a significant difference between the control and impact sites of the years 1980–1983. A pre/post pairs analysis conducted using a single-factor ANOVA was used to compare NDVI differences at both control and impact sites between two time periods (1978 and 1983). The analysis indicated that the paired differences among control and impact sites between both years were not significantly different. A linear mixed model comparing the difference in NDVI between control and impact sites of each year (1980–1985, 1990, 1995, 2000, 2005, 2010, and 2014) to the

difference in NDVI measured in the baseline year of 1978 showed no significant differences. The lack of evidence of an impact suggests that transmission power line construction activities are not substantial enough to be detected using Landsat imagery.

2.2. Introduction

Impact to the environment is one of the consequences of population growth, progress, and development (Abella, 2010). Mining, military activities, recreation, livestock grazing, settlement, and land clearing for energy infrastructure are some of the types of anthropogenic disturbances that have impacted the desert habitats of southern California (Abella, 2010; Abella et al., 2007; Lovich and Bainbridge, 1999; Webb et al., 1983; Webb and Wilshire, 1983). These activities have been assessed for their potentially negative impacts on wildlife, vegetation, soils, and air quality (Abella, 2010; Andrews, 1990; Artz, 1989; Bolling and Walker, 2000; Brooks and Lair, 2005; Grantz et al., 1998; Hernandez et al., 2014; Hessing and Johnson, 1982; Lovich et al., 2011; Lovich and Bainbridge, 1999; Lovich and Ennen, 2011).

In the past, most disturbed areas in the desert were left to natural recovery processes rather than being revegetated through the application of active restoration techniques such as seeding, planting, weed abatement, and soil manipulation (Abella, 2010; Bainbridge, 2012). Plant growth and establishment are naturally slow in the extreme conditions of the desert owing to high temperatures, intense sunlight, limited moisture availability, herbivory by rodents, variability in precipitation events, and low soil fertility (Bainbridge and Virginia 1990). Utility construction (Berry et al., 2016, 2015; Brum et al., 1983; Hessing and Johnson, 1982; Lathrop and Archbold, 1980a, 1980b;

Turney and Fthenakis, 2011; Vasek et al., 1975a, 1975b), abandoned towns and roads (Bolling and Walker, 2000; Johnson et al., 1975; Knapp, 1992, 1991; Walsh and Hoffer, 1991; Webb et al., 2009; Webb and Wilshire, 1980), military activities (Kade and Warren, 2002; Lathrop, 1983; Prose and Wilshire, 2000), grazing (Guo and Pärtel, 2004; Pei et al., 2008; Sassi et al., 2009), and recreational off-road vehicle use (Brooks and Lair, 2005; Vollmer et al., 1977; Webb and Wilshire, 2012) can increase the severity of these conditions and affect soil and vegetation natural recovery rates (Abella, 2010; Bainbridge, 2012). Vasek et al. (1975a) studied natural vegetation recovery along a 33-year-old transmission line in the Mojave Desert on land impacted during construction. Focusing on creosote bush (*Larrea tridentata*) scrub, they observed that ground cover was enhanced under wires when compared to the ground cover in adjacent undisturbed control sites. The authors, however, observed high variability in ground cover under towers compared to control sites and suggested low predictability of the time required for recovery. Similarly, Lathrop and Archbold (1980b) studied vegetation recovery along five pipelines and seven transmission lines of varying ages in areas with varying levels of disturbances. The authors observed that ground cover was on average lower at the transmission power line impact sites (road edge sites, under wires, under towers) but still comparable to ground cover at control sites in adjacent undisturbed areas. Lathrop and Archbold (1980b), like Vasek et al. (1975a), observed that the area under transmission line towers experienced the most damage and exhibited the highest variability in vegetation recovery. Using a linear model to estimate biomass, the authors predicted a recovery time of about a century for power line road edges and towers and 20 years for the areas under power line wires.

Recovery of anthropogenically disturbed desert areas may take decades without active intervention (Bainbridge, 2012; Lovich and Bainbridge, 1999). Application of active restoration techniques have the potential to catalyze recovery (Abella, 2010; Bean et al., 2004). However, success of active restoration, like natural recovery, is dependent on several factors, including type and intensity of disturbance, soil quality, local weather, and presence of competing nonnative species (Abella, 2010; Berry et al., 2016, 2015; Bolling and Walker, 2000; Brum et al., 1983; Hessing and Johnson, 1982; Lathrop and Archbold, 1980b; Lovich and Bainbridge, 1999; Webb et al., 1983). In addition, the methods of restoration used can result in varying levels of success (Bainbridge and Virginia, 1990; Brum et al., 1983; Kay and Graves, 1983). Active restoration of large areas of desert lands can be expensive, time consuming, and unpredictable (Abella, 2010; Bainbridge, 2012; Brum et al., 1983). The goal of active restoration is to catalyze natural recovery processes and thus, understanding natural recovery is fundamental to restoration decision-making and in establishing effective active revegetation processes (Abella, 2010).

Impacts associated with the construction of transmission power lines can be classified as temporary and permanent impacts. Permanent impacts include major disturbances to the soil and vegetation associated with construction of the service road that is maintained throughout the life of the line. In addition, the spur road connecting the towers to the service road for repair and maintenance access is also kept clear of vegetation. Temporary impacts include the clearing and mowing of vegetation and compaction of soils associated with installing the towers, pulling and splicing the conductor wires, campsites, staging areas, and usage of heavy ground equipment to complete all activities associated with construction (Brum et al., 1983; Lathrop and Archbold, 1980b; Rorabaugh, 2013). This study focuses on the construction impacts of a transmission power line, Devers-Colorado River No. 1 (DCR1), located in the lower Colorado Desert in southern California. This 500-kilovolt line, owned and operated by Southern California Edison Company (SCE), was constructed in the early 1980s (1980-1982). Data regarding impact areas and effects of construction techniques were not collected at the time of construction. Thus, remote sensing using archival Landsat images was used to study the impacts of transmission line construction on the vegetation.

The Landsat satellite sensor has been shown to be an effective means to monitor large-scale changes in the vegetation cover types of California (Fischer et al., 2004; Rogan et al., 2003; Rogan and Franklin, 2001). When controlling for soil background reflectance, the normalized difference vegetation index (NDVI) from Landsat data has been closely correlated with percent cover measurements of green vegetation canopies in arid ecosystems, as reported in numerous published studies (Anderson et al., 1993; Elmore et al., 2000; Huang et al., 2010; Olexa and Lawrence, 2014; O'Neill, 1996; Pickup et al., 1993; Todd and Hoffer, 1998; Weiss et al., 2004). Ramsey et al., (2004) found that NDVI from Landsat Thematic Mapper (30 m resolution) imagery was highly correlated with total percent cover of live vegetation in a semi-arid sagebrush ecosystem in south-central Utah. All NDVI values for these vegetation communities were detected at less than 0.2 NDVI units. Similarly, Montandon and Small (2008) found NDVI to be highly correlated with cover in creosote-dominated shrubland sites in New Mexico.

The purpose of this study is to ascertain the impact of transmission power line construction and then to evaluate natural vegetation recovery on impact sites in creosote bush scrub habitat. In this study, post-disturbance recovery is defined as the return of plant cover represented by NDVI at impact sites relative to adjacent control sites and relative to the baseline values measured prior to construction. Impact sites are areas disturbed during the construction of transmission towers. A paired site design is implemented such that for every impact site, a corresponding control site is also established. A total of 38 impact and 38 control sites are evaluated in this study. NDVI is calculated based on analyses of Landsat image data from 1978 to 2014 for live green vegetation in all areas impacted by the construction of transmission towers associated with DCR1. The two main hypotheses are: 1. NDVI measured immediately after construction will demonstrate the effects of construction resulting in a significant difference in NDVI between impact and control sites; and 2. NDVI will drop immediately after construction but will eventually return to pre-construction levels such that the difference between NDVI measured at impact and control sites will be insignificant.

2.3. Methods

The study area was located from 33°39’41.56” N, 115°37’45.61” W to 33°35’37.48” N, 114°59’58.27” W and covered approximately 60 km of transmission line. The study focused on the recovery of land temporarily impacted during construction of the towers of a transmission power line (DCR1). Information on construction impact areas associated with DCR1 was not available, but recent construction of similar transmission towers resulted in a 30 m x 30 m area of impact

(California Public Utilities Commission, 2006) at each tower. Impact sites in this study were chosen using satellite imagery in Google Earth Pro (https://www.google.com/earth/) such that proximity to mountains, camp grounds, roads, and other natural or anthropogenic sources of anomalies and disturbances were avoided. A total of 38 impact sites were included in this study.

Construction of the entire DCR1 transmission line occurred over a two-year period from 1980 to 1982 (Rorabaugh, 2013). Data from 1978 was pre-construction data and served as baseline for the analyses. Data from 1983 served as post-construction data. Data from the years 1980, 1981, 1982, 1984, 1985, 1990, 2000, 2005, 2010, and 2014 were also collected and used in the data analyses. Cloud-free images from the Landsat Multi Spectral Scanner (MSS) and Thematic Mapper (TM) sensors were selected from the years 1978, 1980–1985, 1990, 1995, 2000, 2005, 2010, and 2014 and downloaded from the U.S. Geological Survey Earth Explorer data portal (http://earthexplorer.usgs.gov/). Full image data corresponding to the TM path/row 39/37 were consistently acquired for an anniversary window between late July and mid-September each year to minimize variation caused by seasonal precipitation, vegetation growth, and sun angle differences. The image dates acquired and processed are listed in Table 2-1 along with the spatial resolution of each image. All images used in this study acquired by Landsat MSS and TM sensors were geometrically registered (UTM Zone 11) using terrain correction algorithms (Level 1T) applied by the U. S. Geological Survey EROS Data Center, and then converted to at-sensor reflectance using the Environment for Visualizing Images (ENVI) software application (www.exelisvis.com, version 5.1) following the algorithms from Chander et al. (2009). No further corrections for atmospheric scattering were applied, since the reflectance indices used in this study employed the near-infrared (NIR) wavelengths that are minimally affected by atmospheric scattering (Avery and Berlin, 1992), especially during the dry summer months for the southern California study area (Miller et al., 2009).

NDVI (scaled from 0 to 1) was computed using the ENVI software application for all Landsat images. NDVI is the differential reflectance between the red and near-infrared (NIR) portions of the spectrum, computed by the equation:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}) \qquad \text{(Rouse et al., 1974)}$$

where NIR is the reflectance of wavelengths from 0.76 to 0.9 µm and Red is the reflectance of wavelengths from 0.63 to 0.69 µm. Advantages of NDVI for vegetation monitoring include its mathematical simplicity and ease of comparability across numerous multi-spectral remote sensing platforms (Lentile et al., 2006). Low values of NDVI (near 0) indicate barren land cover, sparse vegetation cover show NDVI values < 0.2 (Huang et al., 2010), and relatively high values of NDVI (near 0.9) indicate dense canopy vegetation cover. Negative NDVI values generally indicate an absence of vegetation (Myneni et al., 1995; Pettorelli et al., 2005). For the purposes of this study, negative NDVI values were set to 0 to represent land cover barren of vegetation.

To study construction effects, a circular buffer 30 m in diameter centered at the transmission tower was established using ArcGIS software (www.esri.com; version 10.1). This buffer included the spur road that connects each tower to the service road for maintenance purposes. The NDVI within the buffer was computed using the Zonal Statistics tool in ArcGIS. For the 60 m Landsat imagery (1978, 1980–1984), the tool recorded NDVI only when a pixel was enclosed at least 50% within the buffer. If more than one pixel was enclosed within the buffer, an average NDVI value was recorded. For the 30 m Landsat imagery, the tool provided a single mean NDVI value in every case. For every impact site, a control site (circular area of 30 m diameter) was assessed just south of the impact site, about 50 m away from the boundary of the impact buffer. The south side was chosen because the service road and other utility lines are located just north of the impact sites. A total of 38 impact sites and 38 control sites were analyzed. Due to the lack of concrete information regarding exact impact areas, the location of the control sites assumed that the crews would have only disturbed areas necessary for construction. This was confirmed in conversation with a construction supervisor who was part of the crew during the construction (Rorabaugh, 2013) of DCR1. The values of NDVI were multiplied by 100 for all analyses, including in the figures.

Historical yearly average precipitation data (millimeter) was obtained from the "Global Summary of the Year" dataset available from NOAA (https://www.ncdc.noaa.gov/cdo-web/datasets). Data from the Desert Resorts Regional Airport (33°37'36.0" N, 116°09'34.0" W) and the Blythe Airport (33°37'07.0" N, 114°42'51.1" W) weather stations were used in this study. Both stations had data available in the year range required and were located at the approximate western and eastern ends of the study area (Figure 2-1). The Desert Resorts Regional Airport station did not have precipitation data available for years 1989, 1990, and 2006 (Figure 2-2) and the Blythe Airport station did not have the data for years 1981, 1990, 1991, and 1995 (Figure 2-2).

It was assumed that the NDVI in control sites would be different from the NDVI in the impact sites immediately after construction. In order to study this, a simplified Before-After-Control-Impact or BACI (Green, 1979; Schroeter et al., 1993) analysis with just one before-year (1978) and one after-year (1983) was conducted using a two-factor analysis of variance (ANOVA) comparing the NDVI between the control and impact sites of 1978 and 1983. Matched pairs analysis (Wiens and Parker, 1995) considered paired sites (control and impact) within a single year and utilized a paired t-test to detect significant differences in the NDVI. This analysis was conducted for 1978 and years 1980–1983. Pre/post pairs analysis (Wiens and Parker, 1995) focusing on the mean NDVI differences between the time periods (i.e., before – after) at both control and impact sites was conducted. A one-factor ANOVA was conducted to assess significance in the mean NDVI differences between 1978 and 1983 at both control and impact sites.

It was also assumed that the NDVI at both control and impact sites would be similar after a certain length of time had passed following construction owing to vegetation reestablishment and growth at the impact sites. In order to study this, a linear mixed model (Bates et al., 2015) was used to compare the between-year and within-year differences in NDVI between control and impact sites. The model included categorical variables for each year (1978, 1980–1985, 1990, 1995, 2000, 2005, and 2010) and interaction terms for year and site type (control or impact) to model the change in NDVI over time. It was assumed that the baseline NDVI (1978) would vary between locations and a random intercept term was included for site location (i.e., locations 1-38) to account for this variation. No random slope terms were included because it was assumed that the change in NDVI over time would be similar between all impact sites and between all control sites regardless of the respective baseline NDVI. All hypotheses testing using the linear mixed model were performed using joint Wald tests. The linear mixed model was used to determine if the change in NDVI at impact sites over time is different from the change in NDVI at control sites over time. It was also used to determine if the difference between NDVI at control and impact sites ("delta" or Δ) of a year was different from the ΔNDVI observed in the baseline year of 1978.

All analyses were performed with R version 3.2.3 (R Core Team, 2015) and RStudio version 0.99.489 (R Studio Team, 2015).

2.4. Results

BACI analysis with data from one before-year (1978) and one after-year (1983) was conducted using a two-factor ANOVA. The interaction between the site type (control, impact) and the period (before, after) was not significant with $p > 0.05$. The result also demonstrated that neither control nor impact sites have significantly different NDVI before and after construction (Table 2-2) with $p > 0.05$.

Matched pairs analysis (Wiens and Parker, 1995) assumed that the matched control and impact pairs were similar in factors that affect NDVI and any difference was due to construction activities. This analysis was conducted by comparing the NDVI values of matched impact and control sites within a single year. A paired t-test was used to detect the differences between impact and control sites. This analysis was conducted for 1978 and 1980–1983. Construction occurred during 1980–1982 and these years were included in the analysis with the expectation that impact would differ significantly from the matched control sites. A difference was not expected between impact and control sites of 1978, the year before construction. The matched impact and control sites were expected to be different in 1983, immediately after construction. However, the analysis showed no significant differences were observed between control and impact sites for 1978, 1980, 1981, 1982, and 1983 with $p > 0.05$ (Table 2-3) indicating the absence of an impact.

Pre/post pairs analysis (Wiens and Parker, 1995) looked at the differences in NDVI at impact sites before (1978) and after construction (1983). By comparing differences between time periods at the same sites, the analysis serves to minimize the effect of natural variation that could obscure the effects of construction. Differences in the natural log-transformed values of NDVI at paired impact sites from 1978 and 1983 were analyzed. The expectation was that the difference in NDVI at the paired impact sites between 1978 and 1983 would not be zero due to construction impacts. However, the analysis (Figure 2-3) indicated there were no significant differences between the impact sites of 1978 and 1983. This analysis was repeated with the paired control sites from 1978 and 1983. Since control sites were not impacted by construction, the differences between the control sites of 1978 and 1983 were expected to be close to zero. The analysis does show that there were no significant differences between the control sites of 1978 and 1983 (Figure 2-3). At both impact and control sites, the differences in NDVI did not deviate significantly from zero.

The previous analyses indicate that an impact was not detected in the Landsat images. To assess recovery after the impact, the mean ∆NDVI (mean of the 38 NDVI differences between matched control and impact sites in a single year) of all the years was plotted relative to the ∆NDVI of the baseline year of 1978. The baseline ∆NDVI was set to 0 to make the plot easier to read (Figure 2-4). The expectation was that the difference between control and impact in the construction years and immediately after construction, would be significantly greater than zero, since the NDVI at control sites would be greater than the NDVI at the impact sites. Over time, as vegetation reestablished in the impact sites, the difference between the control and impact sites would be closer to zero. While the difference between the control and impact sites was greater than zero for the construction years, there was a lot of variability and thus no discernible pattern was observed over time (Figure 2-4). Interestingly, the ∆NDVI observed in 2014 was the greatest relative to the baseline year. To test the significance of these observations, the linear mixed model conducted individual z-tests to determine if the ∆NDVI observed in any single year was significantly different from the ∆NDVI observed in 1978. The resulting p-values indicated no significant differences were observed (Table 2-4).

Mean NDVI of all 38 control sites and all 38 impacts sites from every year studied is shown in Figure 2-5. The plot shows that NDVI values recorded at control and impact sites in each year were similar to each other. This was apparent even during construction (1980–1982) when a drop in NDVI values were observed at both control and impact sites. The mean NDVI at both control and impact sites in 2014 was greater than the respective mean NDVI observed in 1978. To test the significance of this observation, a linear mixed model was utilized to analyze if the change in NDVI at impact sites over time is different from the change in NDVI at control sites over time. The result indicated no statistical significant difference in the change in NDVI at control and impact sites through time with $p > 0.05$ further indicating that impact and control sites are indistinguishable through time.

2.5. Discussion

The results consistently show no significant difference in NDVI before and immediately after construction, indicating that impacts of transmission power line construction are not evident in the Landsat imagery used.

There are several reasons why the NDVI values of the impact and control sites are mirroring each other through time. First, desert vegetation may not be green enough for the software to detect discernible signals in the Landsat images to distinguish between bare land and the sparse vegetation typically observed in the lower Colorado Desert, thus making the impact and control sites indistinguishable.

Figure 2-5 shows a drop in NDVI values during the construction years (1980–1982) but a difference in NDVI between control and impact sites within each year is not discernible. It could be that the impacts from transmission power line construction are not detectable by the Landsat imagery in the early years because of low resolution of the images. Natural or other anthropogenic factors may have had a stronger impact on both control and impact sites in those years. The average annual precipitation (Figure 2-2) recorded at the two weather stations located closest to the study area, shows relatively low rainfall in the early- to mid-1970s but rainfall is abundant at least 4 years prior to construction and during construction implying that precipitation may not be a factor in the drop observed in NDVI during the construction years at both the control and impact sites. Furthermore, a similar drop in precipitation is apparent in the late 1990s to the early 2000s, but the NDVI does not drop like it did in the early 1980s. The two weather stations are located approximately 80 km from the western end of the study area and 30 km from the eastern end of the study area respectively.

Second, construction requirements and methodologies may have been different from what occurs now in the field. A discussion with a construction supervisor involved in the construction of DCR1 revealed that crews only cleared vegetation if it was necessary for staging equipment and installation (Rorabaugh, 2013). In other words, there weren’t established areas of impact associated with the type of construction activity as observed in more recent projects (California Public Utilities Commission, 2006). Comparatively, recent construction strategy can involve clearing of designated areas by a crew different from the installation crew several months prior to actual staging and installation. While there are several reasons why this is done, this strategy is beneficial to projects that may be required to work through certain restricted biological seasons (e.g. nesting season) because in the absence of vegetation, the likelihood for a bird to nest and disrupt the schedule is very low. This is an important point, because the disturbance area assumption (30 m x 30 m) is based on information from recently constructed projects and may not accurately represent the area impacted during construction of DCR1.

Third, construction of transmission lines along such long linear corridors occurs in phases rather than simultaneously at all sites, and it is likely that DCR1 followed this approach. While the 38 paired locations were chosen to reduce variation in terms of anthropogenic and natural factors, they are still spread over 60 km. Though the likelihood is low given the rate of natural recovery in desert habitats (Bainbridge, 2012), it is possible that some of the 38 towers may have been constructed long before the rest of the towers and this may be why a significant difference in NDVI is not observed before and after construction. But the likelihood is very low since construction of the entire transmission line including the segment in this study was completed in two years.

The results demonstrate an overall increase in NDVI from 1978 to 2014. A recent study (Potter, 2016) focusing on the lower Colorado desert, looked at changes in NDVI over 30 consecutive years (1985–2015). The study demonstrated that the three periods of significant decrease in NDVI were detected during the drought periods of 1989-1990, 2002-2003, and 2013-2015 indicating that annual precipitation largely influences NDVI. Weiss et al., (2004) conducted a time-series of NDVI (1990-2000) and also demonstrated that the NDVI variability corresponds to precipitation variability. Schmidt and Karnieli (2000) observed increases in NDVI coinciding with vegetation responses to rainfall events in a semi-arid environment in the Negev Desert in Israel. A study conducted in the semi-arid regions of Africa where an increase in greening has been observed since the mid-1980s indicated that the overall increase is likely due to increases in rainfall in the region, but that it is likely not the only cause (Olsson et al., 2005). Increase in anthropogenic nitrogen deposition is probably another factor influencing plant community structure in deserts (Allen et al., 2009; Báez et al., 2007; Brooks, 2003; Rao and Allen, 2010). Moreover, studies suggest that nitrogen deposition is increasing the occurrence of nonnative annual plants in desert habitats (Brooks, 2003; Rao and Allen, 2010). Studies focusing on the combined effects of precipitation, increases in CO_2 levels and nitrogen deposition, and temperature on the southern California desert habitats are required. Further analysis employing a larger study area and 30 m (higher resolution than 60 m) Landsat imagery, independent of anthropogenic land disturbances, may help ascertain the long-term greening of the deserts of southern California and if it is indeed a significant occurrence.

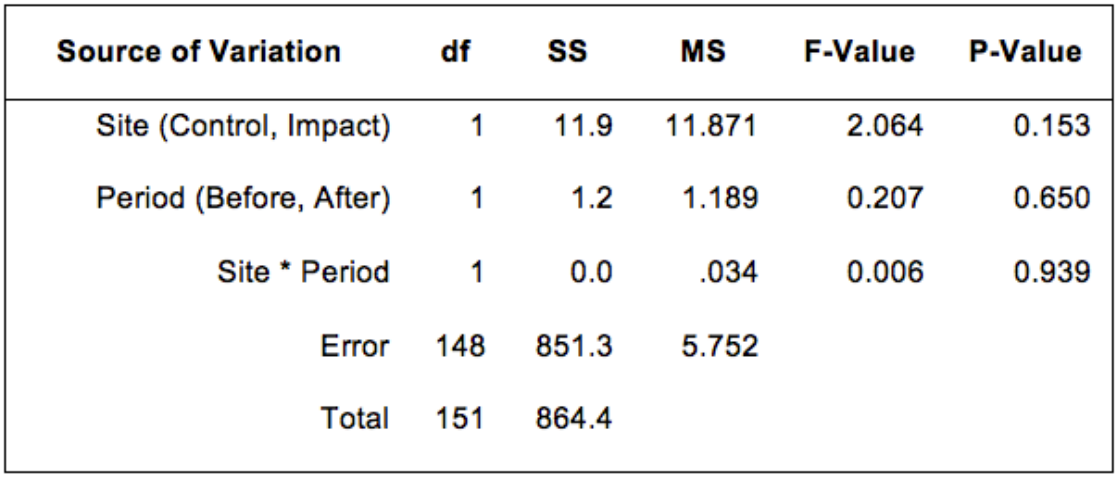
Though the results of this study do not demonstrate the effect of the impact on NDVI extracted from Landsat imagery, the technique has been successfully implemented to detect significant long-term observations, albeit on larger impact areas, in arid and semi-arid ecosystems (Anderson et al., 1993; Potter, 2016; Schmidt and Karnieli, 2000; Weiss et al., 2004). The results do, however, point to a general resiliency of the desert habitat and its ability to recover indicated by the overall increase in NDVI over time. Due to the relatively small impact areas associated with transmission towers construction, future long-term studies on effects to vegetation and recovery in desert habitats would be better served to utilize remote sensing techniques on images with higher resolution.

2.6. Tables

Table 2-1. Landsat images processed in this study. MSS is Multispectral Scanner and TM is Thematic Mapper.

Image ID	Date	Sensor	Resolution
LM30420371978225	Aug. 14, 1978	MSS	60 m
LM20420371980224	Aug. 13, 1980	MSS	60 m
LM20420371981218	Aug. 06, 1981	MSS	60 m
LM30420371982186	Jul. 05, 1982	MSS	60 m
LM40390371983237	Aug. 26, 1983	MSS	60 m
LM50390371984216	Aug. 04, 1984	MSS	60 m
LT50390371985234	Aug. 22, 1985	TM	30 m
LT40390371990208	Jul. 27, 1990	TM	30 m
LT50390371995214	Aug. 02, 1995	TM	30 m
LT50390372000260	Sep. 17, 2000	TM	30 m
LT50390372005225	Aug. 13, 2005	TM	30 m
LT50390372010239	Aug. 27, 2010	TM	30 m
LC80390372014218	Aug. 06, 2014	TM	30 m

Table 2-2. Two-factor ANOVA results for a Before-After-Control-Impact (BACI) analysis with data from 1978 (before construction) and 1983 (after construction).



Source of Variation	df	SS	MS	F-Value	P-Value
Site (Control, Impact)	1	11.9	11.871	2.064	0.153
Period (Before, After)	1	1.2	1.189	0.207	0.650
Site * Period	1	0.0	.034	0.006	0.939
Error	148	851.3	5.752		
Total	151	864.4			

Table 2-3. Results of matched pairs analyses comparing the NDVI of the control sites to their matched impact sites for each year using a paired t-test.

Year	T-value	P-Value
1978	-0.78	0.44
1980	-1.19	0.24
1981	0.47	0.64
1982	0.24	0.81
1983	-0.54	0.60

Table 2-4. Results of individual z-tests comparing ∆NDVI (Control-Impact) of each year to the ∆NDVI of 1978.

Year	P-Value	Z-Value
1980	0.96	-0.05
1981	0.65	-0.46
1982	0.56	-0.58
1983	0.90	-0.13
1984	0.92	-0.10
1985	0.79	-0.27
1990	0.59	-0.54
1995	0.47	-0.72
2000	0.72	-0.36
2005	0.79	-0.27
2010	0.69	-0.39
2014	0.30	-1.05

2.7. Figures

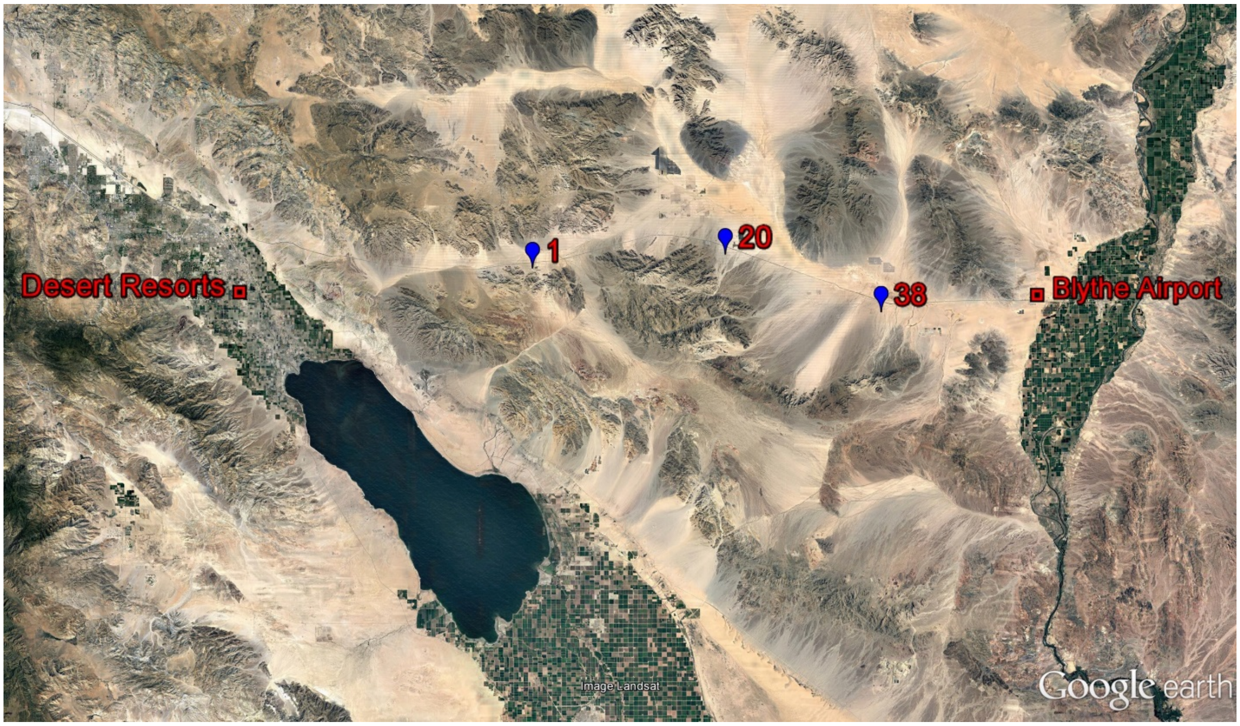


Figure 2-1. Study area in the lower Colorado desert. Desert Resorts Regional Airport and Blythe Airport weather station locations (NOAA) are shown relative to the sites sampled in this paper. Only sites 1, 20, and 38 are pointed out in this figure for clarity, but all 38 sites are located between 1 and 38.

Map data: Google, Landsat.

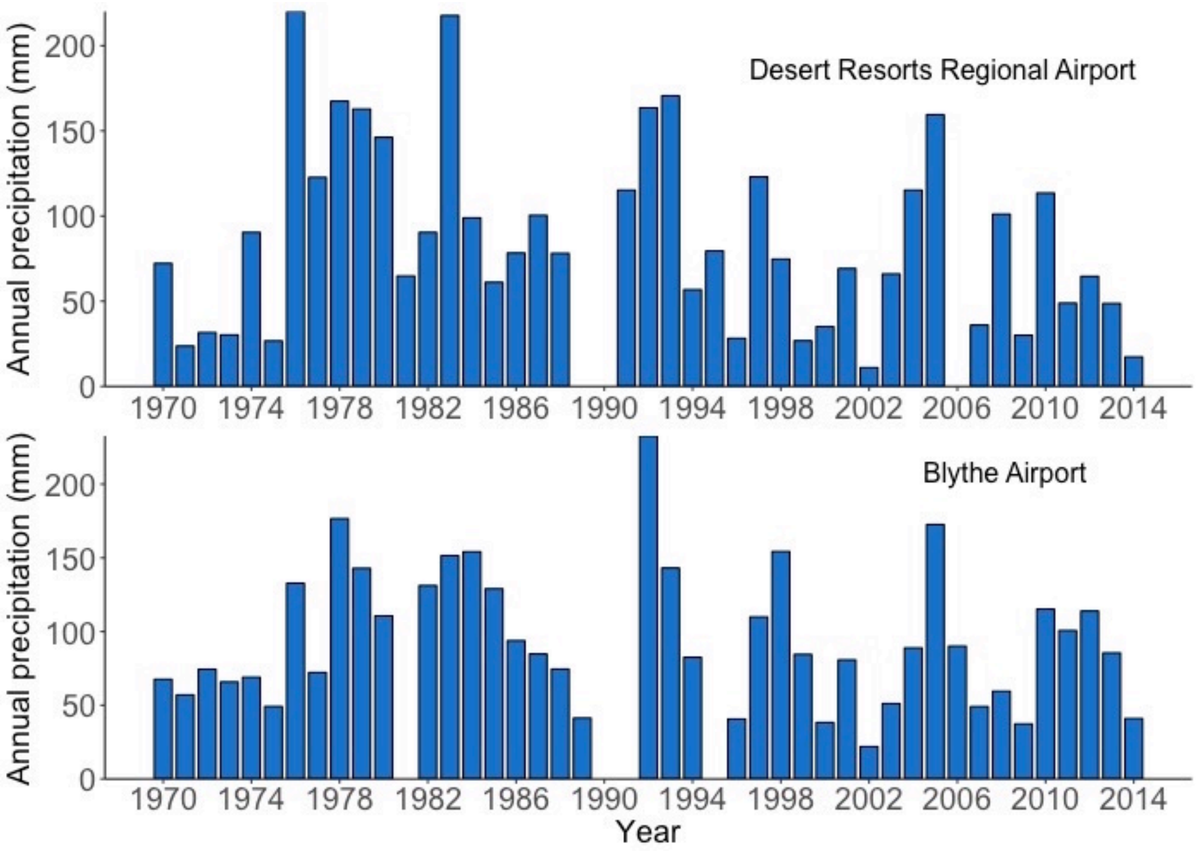


Figure 2-2. Average annual precipitation from 1970-2014 recorded at the Desert Resorts Regional Airport and Blythe Airport stations (NOAA).

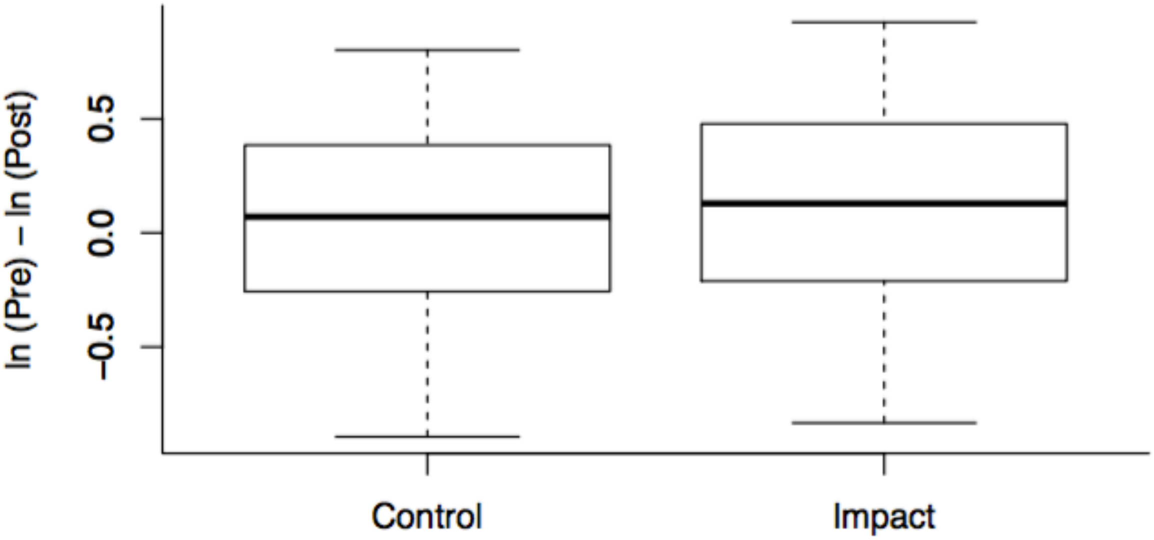


Figure 2-3. Pre/post pairs analysis with natural log-transformed mean NDVI differences of control and impact sites between 1978 and 1983.

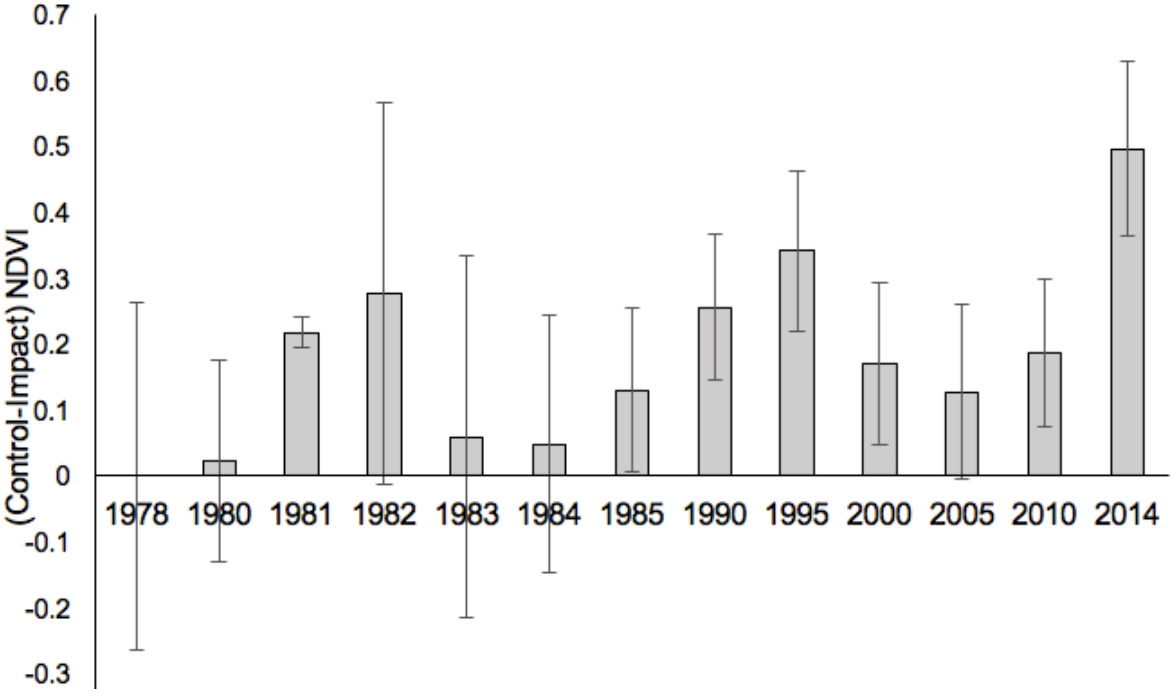


Figure 2-4. Mean NDVI difference between control and impact sites for all years. The error bars are standard error of the mean difference.

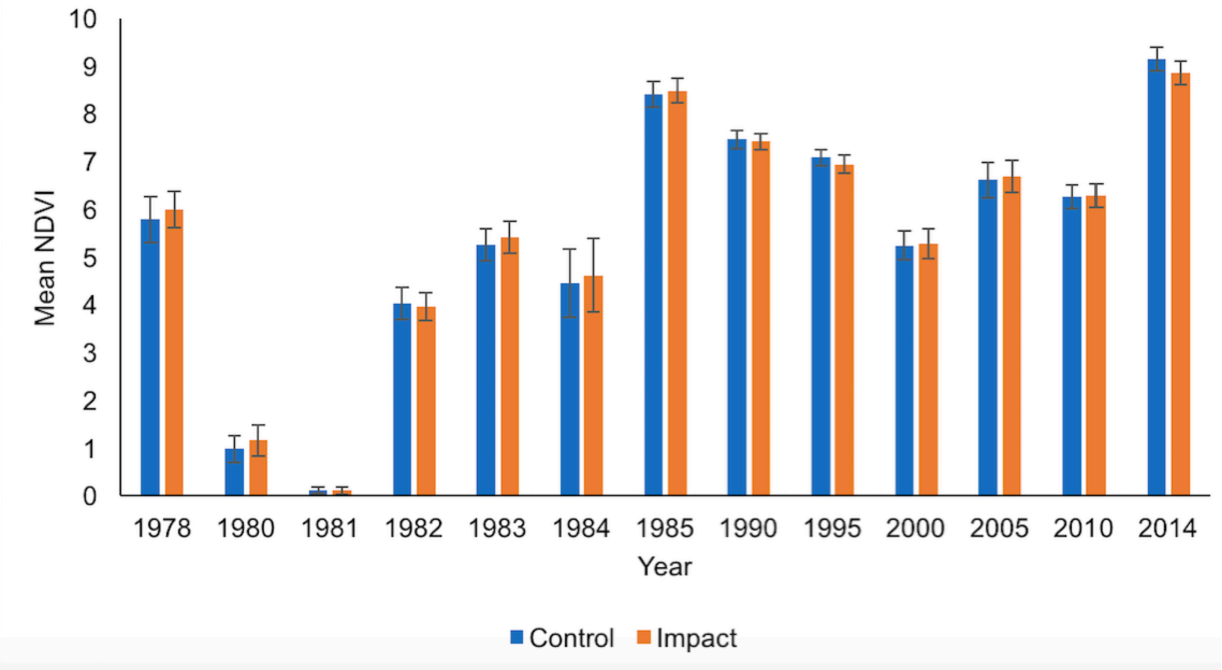


Figure 2-5. Mean NDVI measured at all control and all impact sites from 1978–2014. Error bars represent the standard error of the mean.

2.8. Appendix

The appendix has 38 figures showing the trends in NDVI at both the impact and control sites of each location through time.

2.8.1. Figures

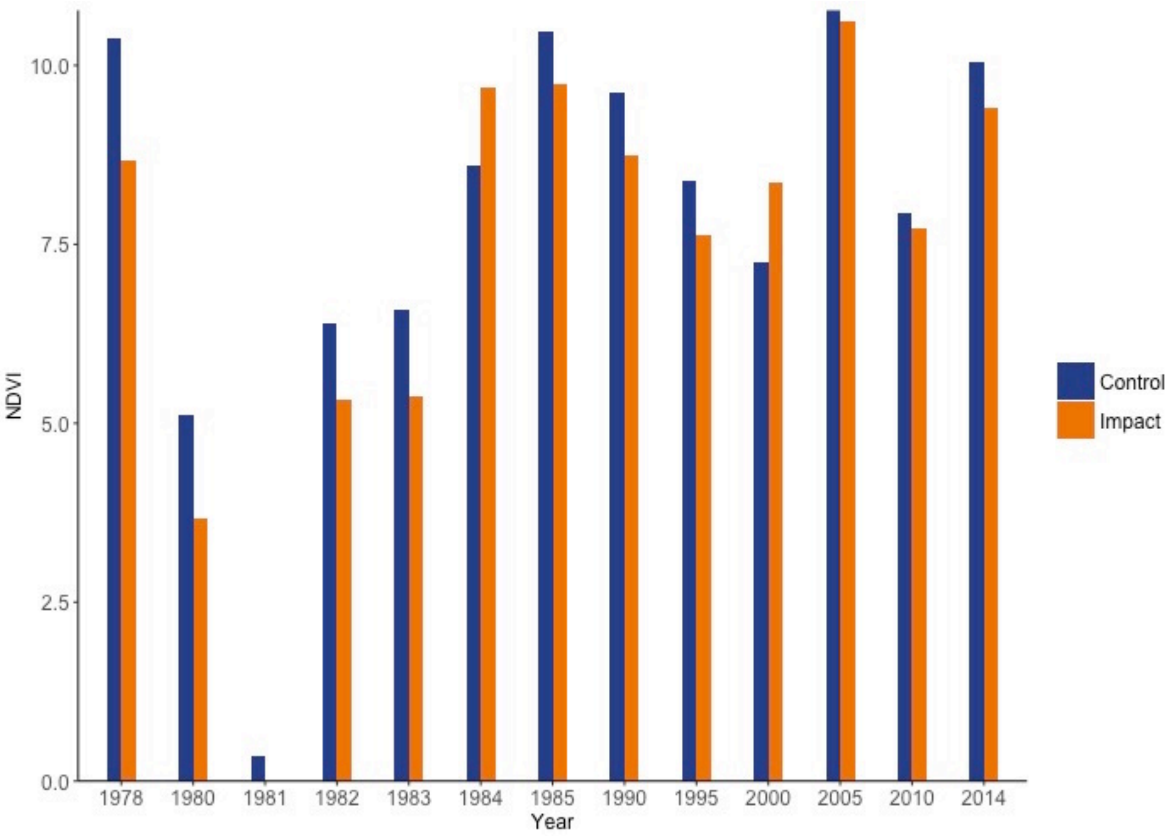


Figure A2-1. NDVI at control and impact sites at location 1.

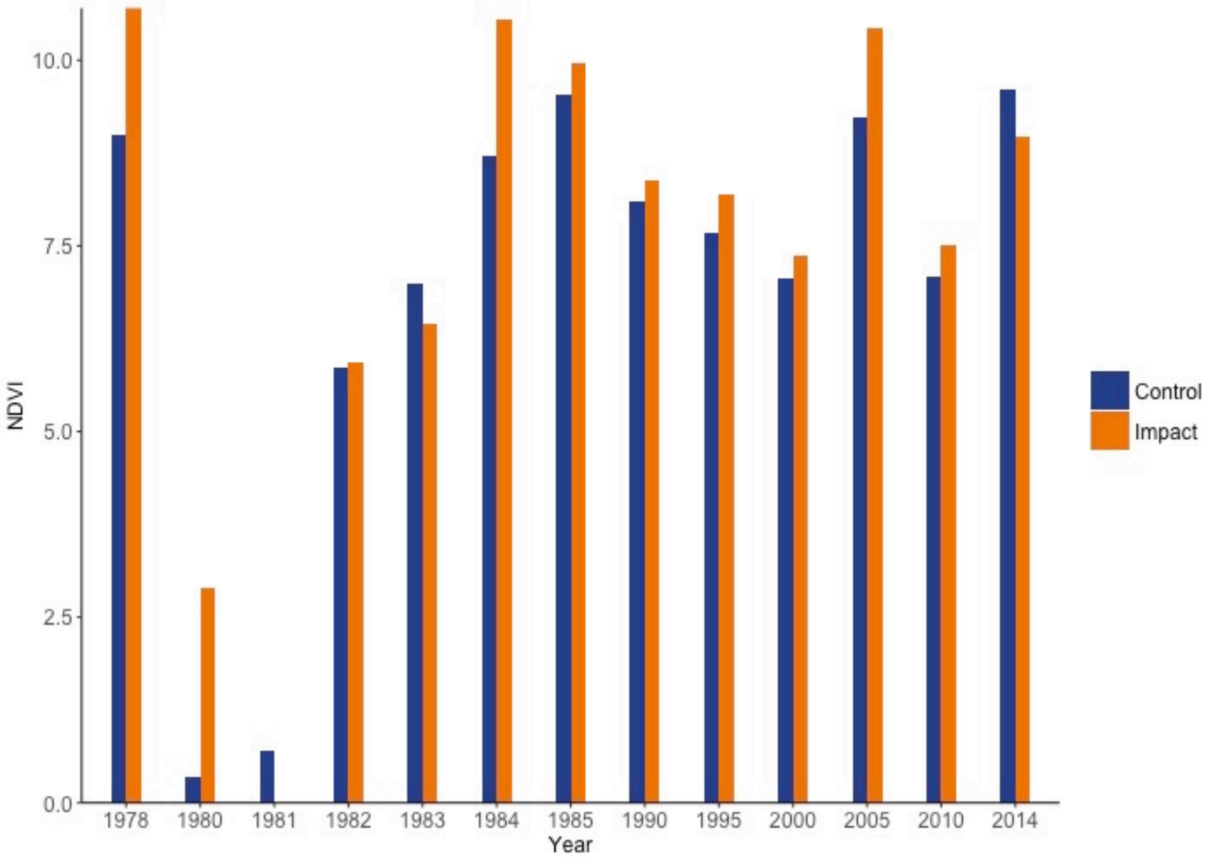
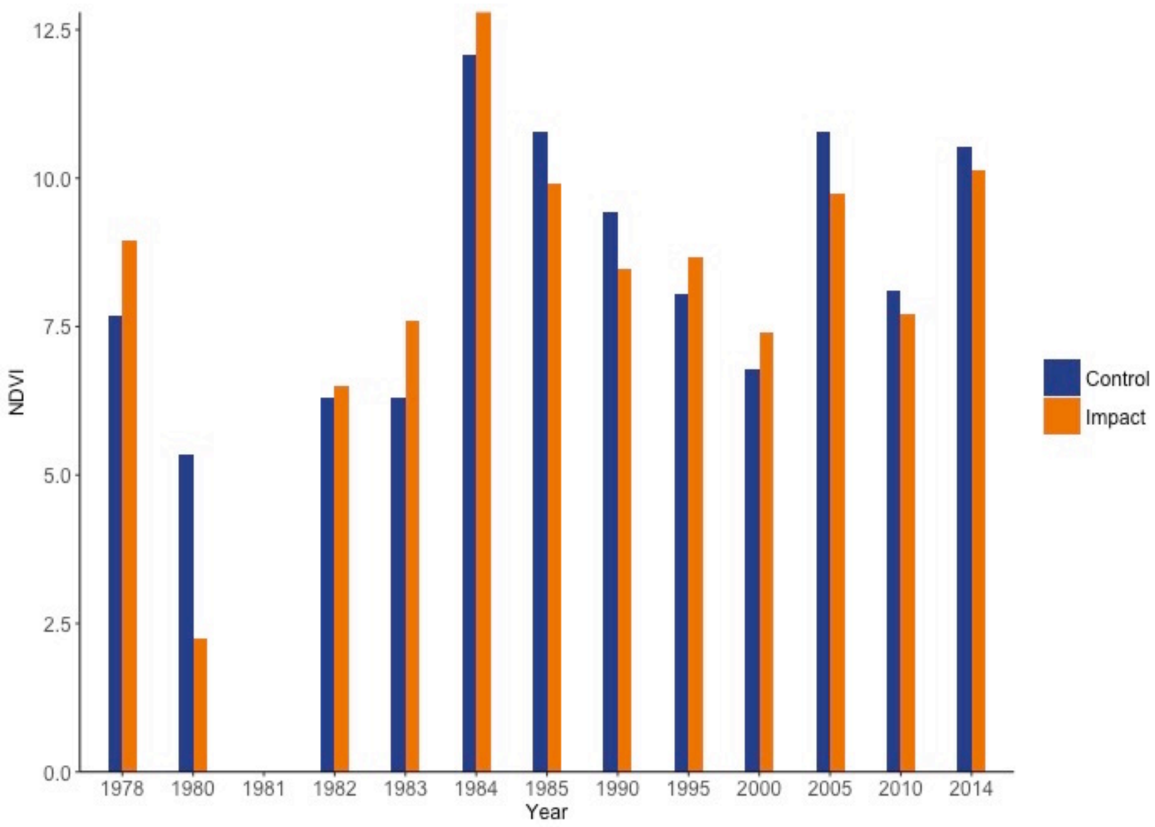


Figure A2-2. NDVI at control and impact sites at location 2.



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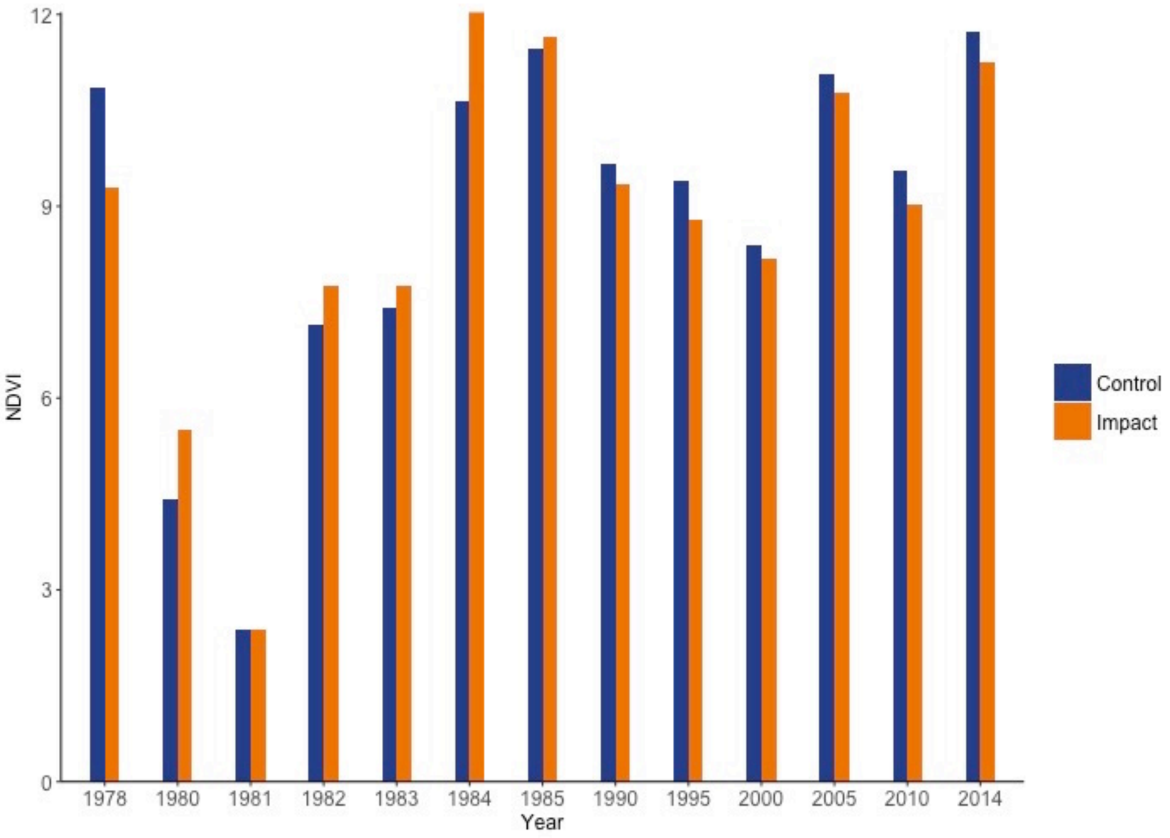

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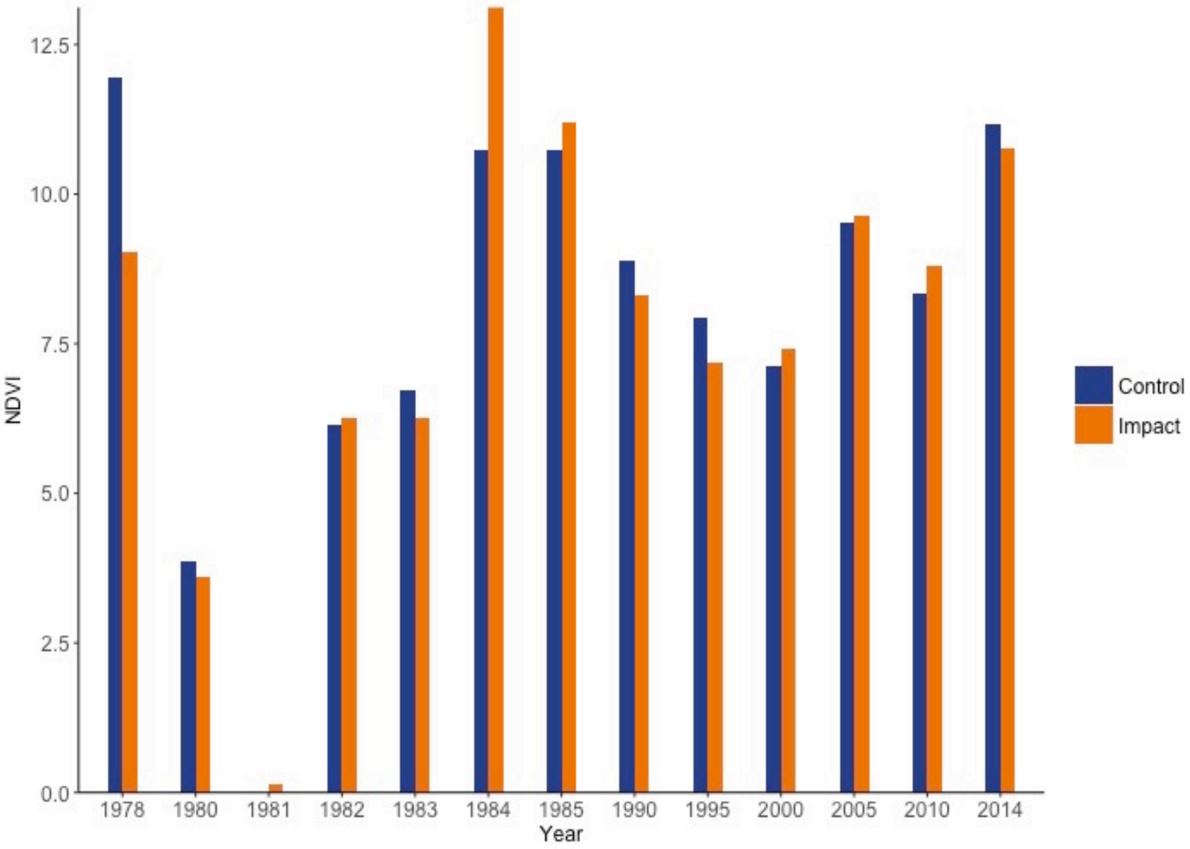

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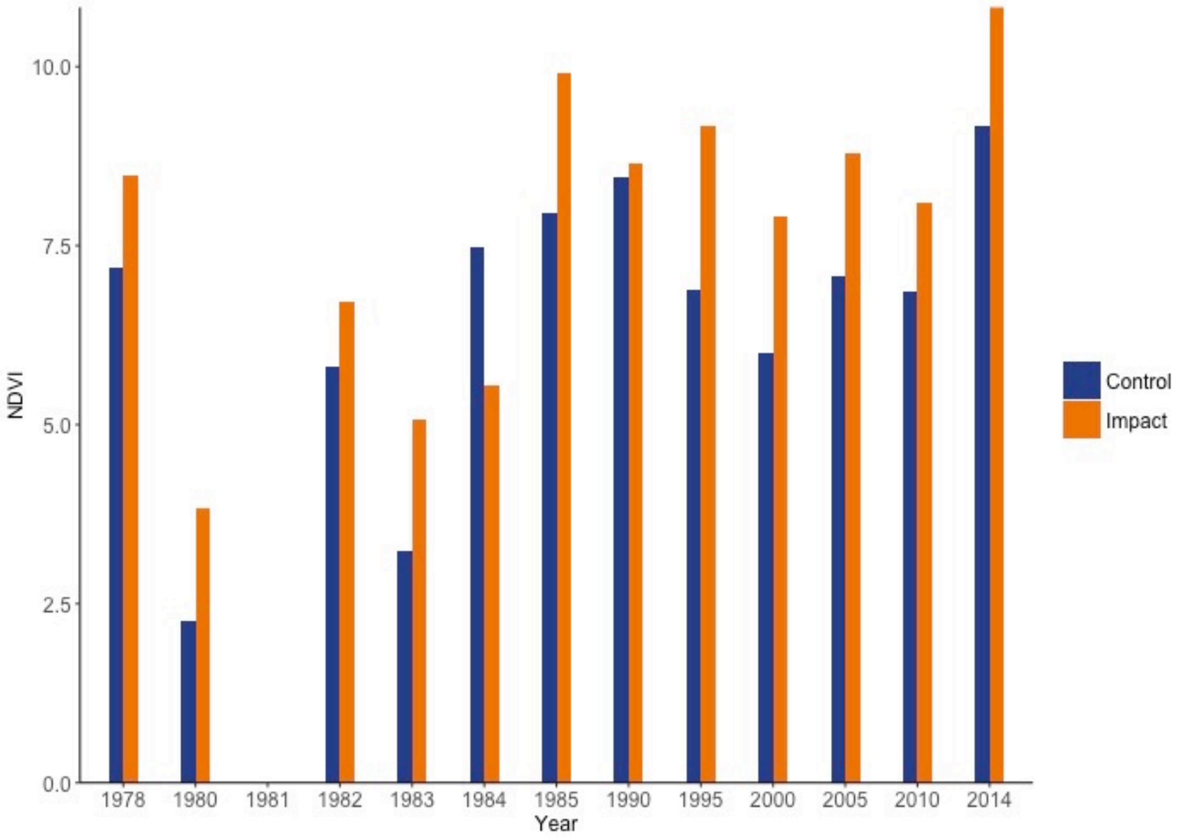

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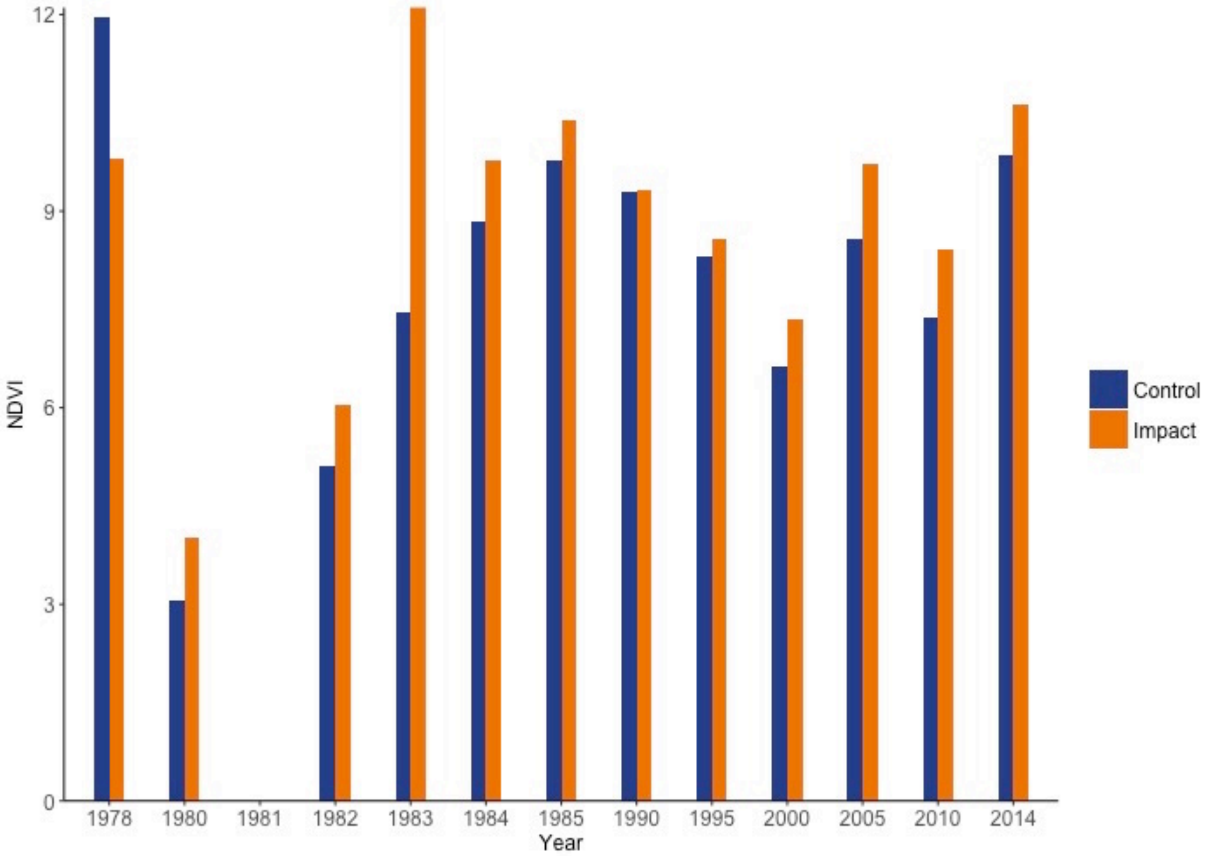


Figure A2-7. NDVI at control and impact sites at location 7.

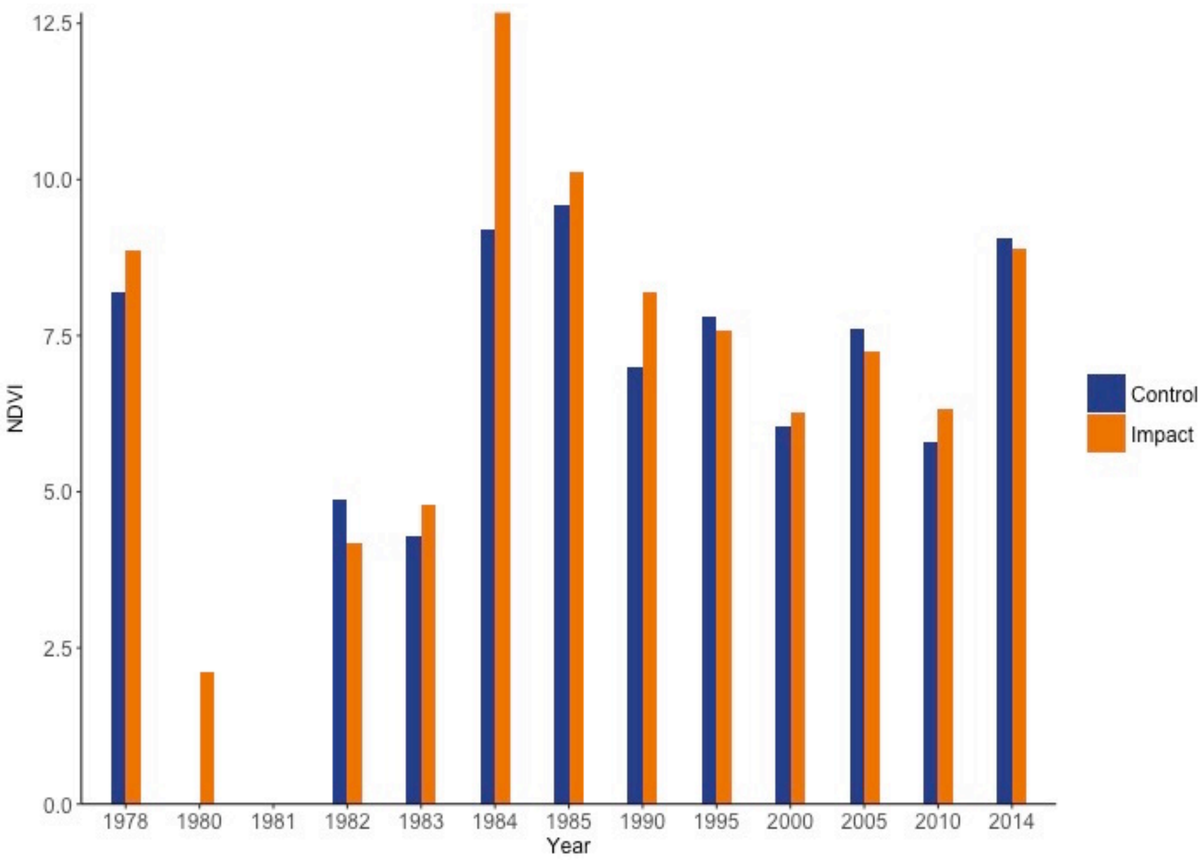


Figure A2-8. NDVI at control and impact sites at location 8.

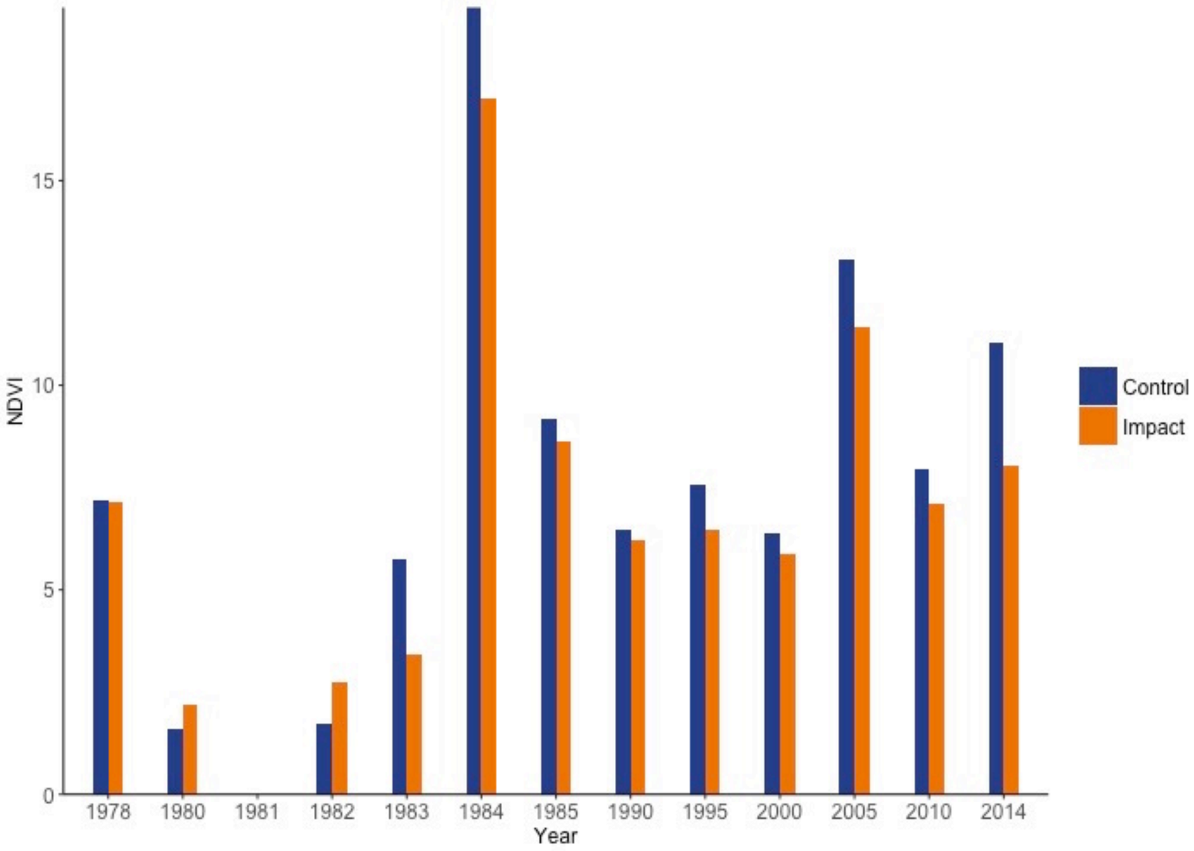


Figure A2-9. NDVI at control and impact sites at location 9.

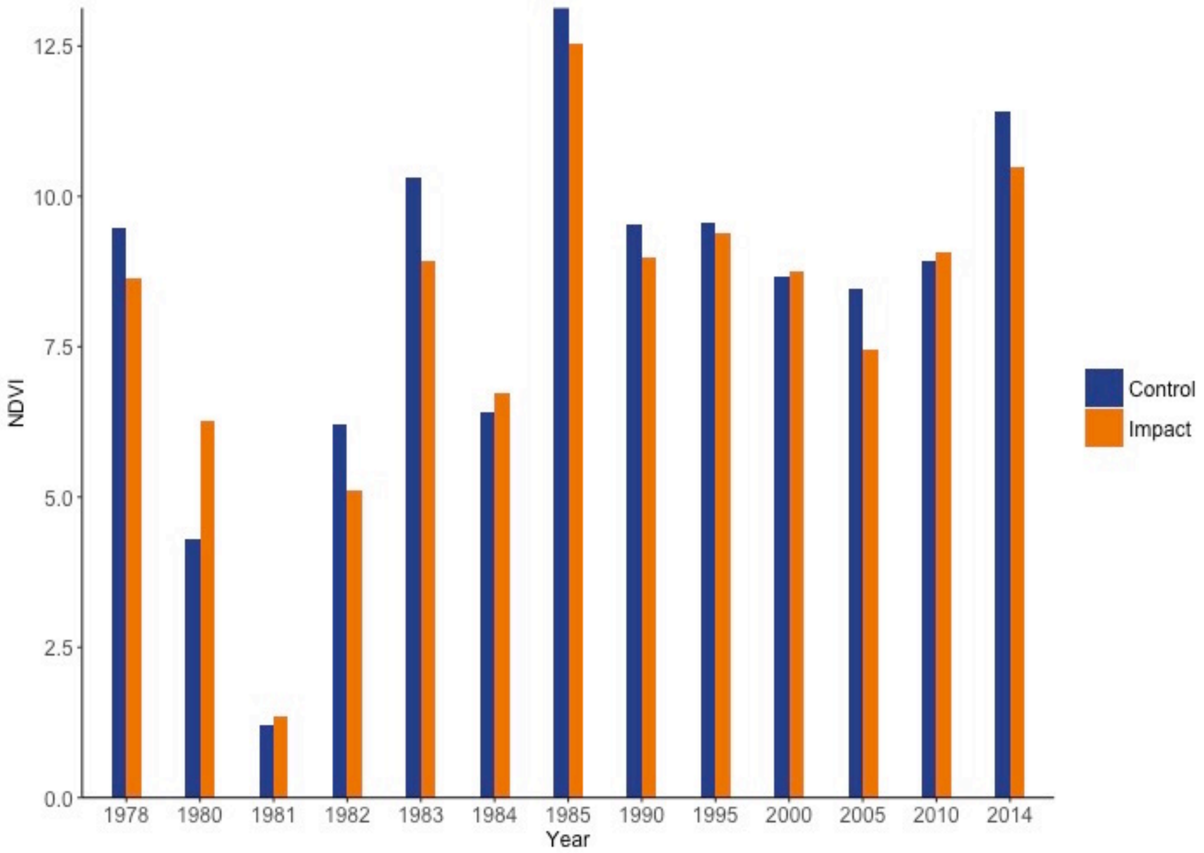
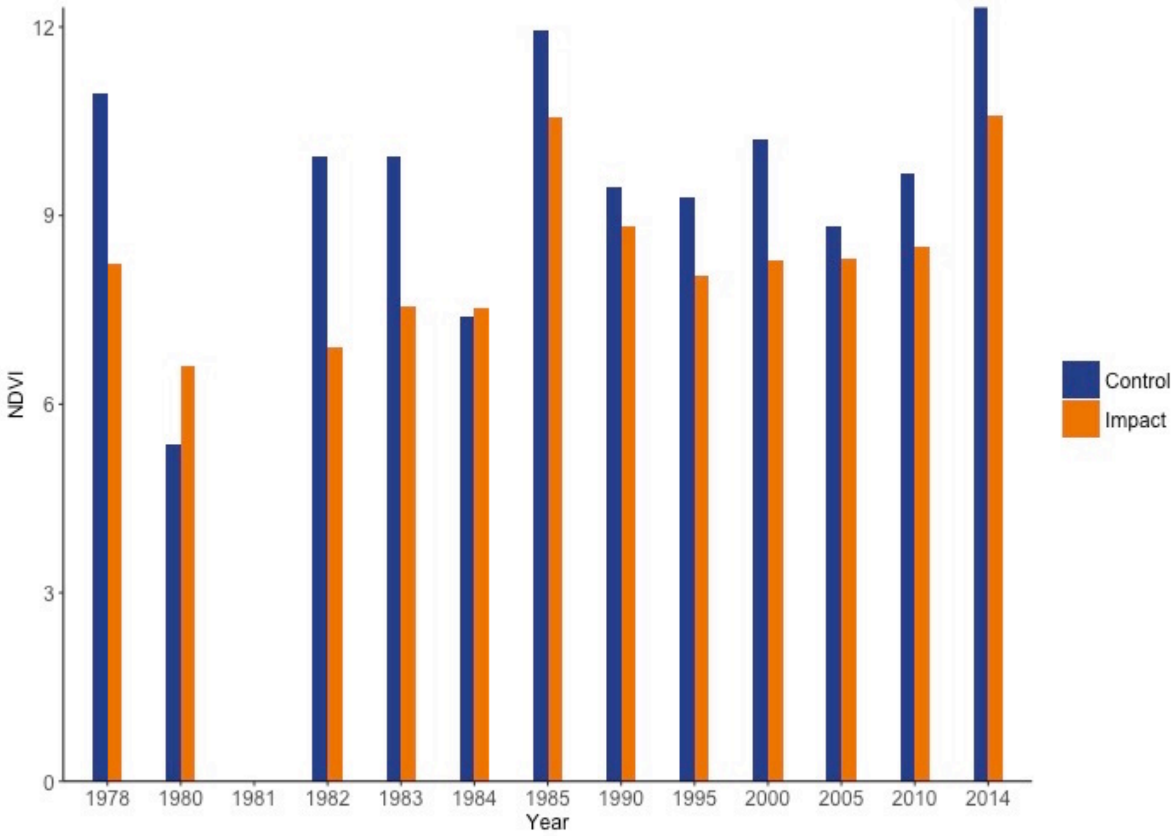


Figure A2-10. NDVI at control and impact sites at location 10.



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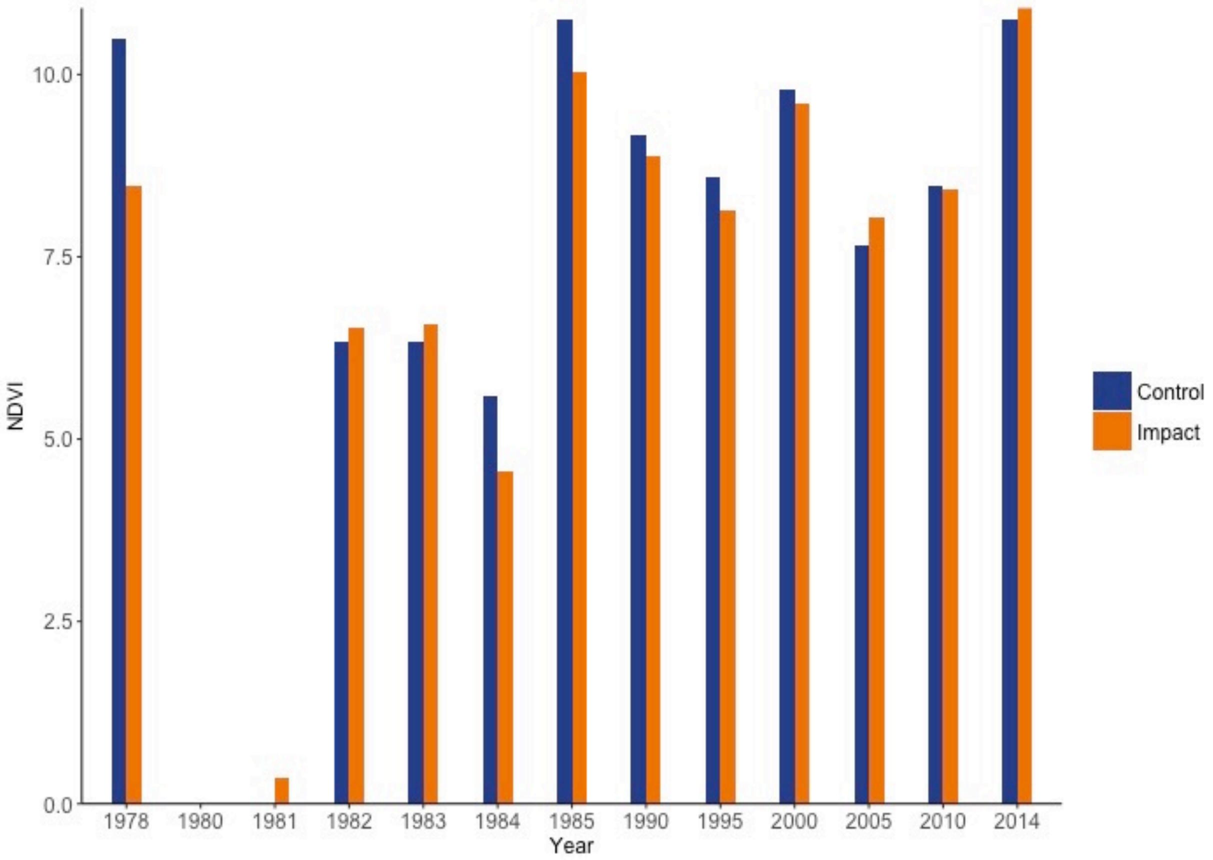

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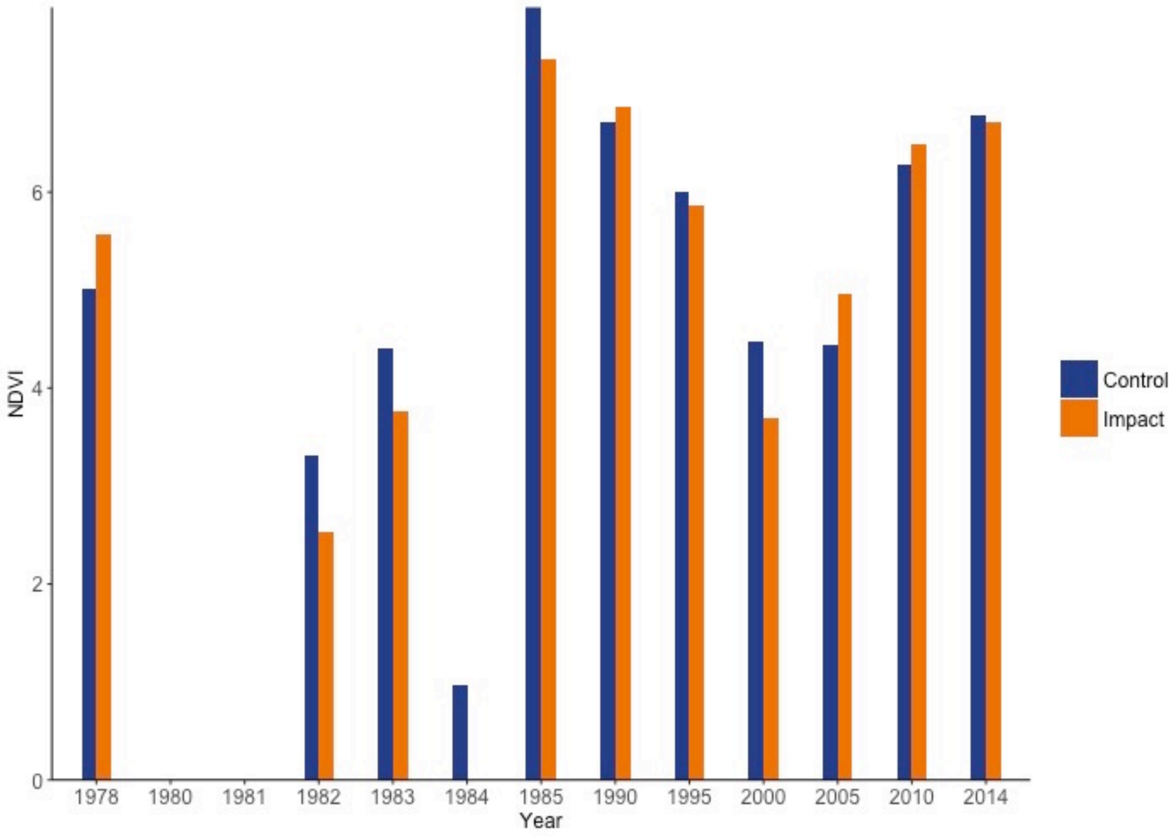
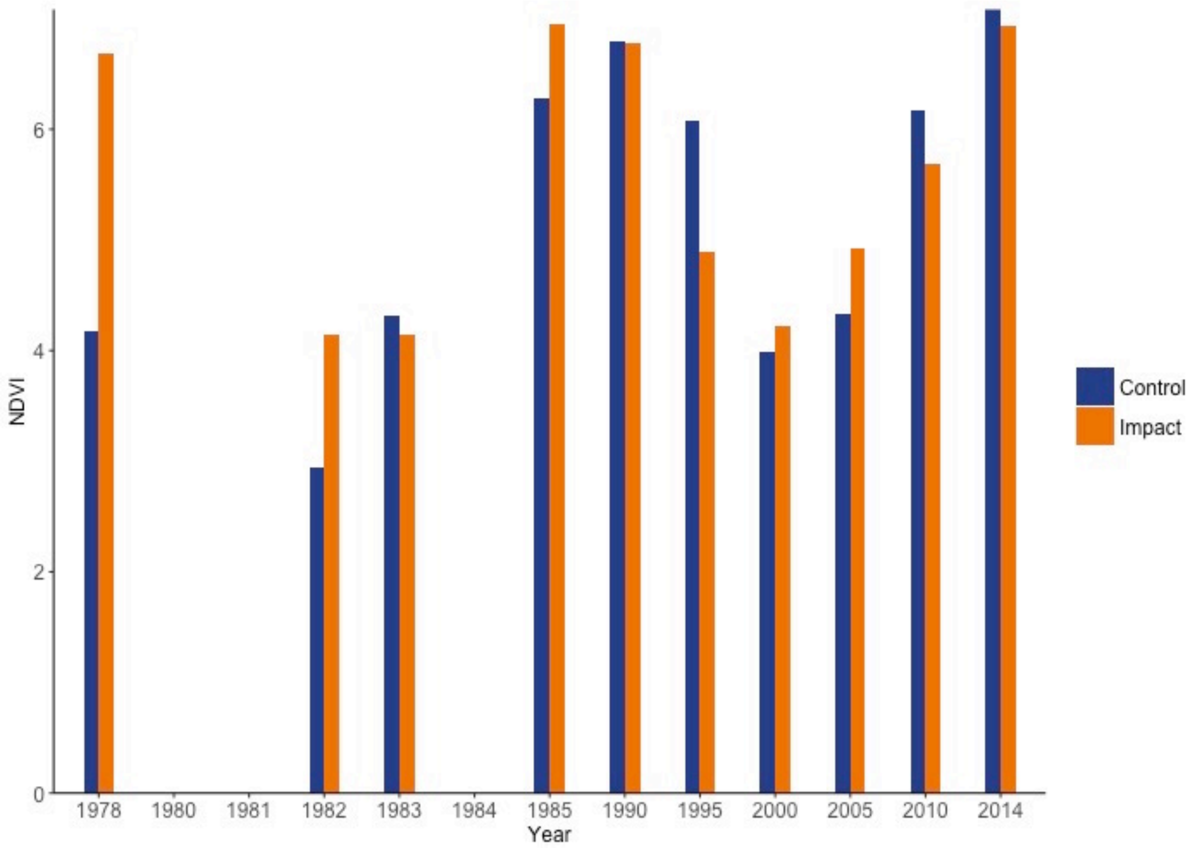


Figure A2-13. NDVI at control and impact sites at location 13.



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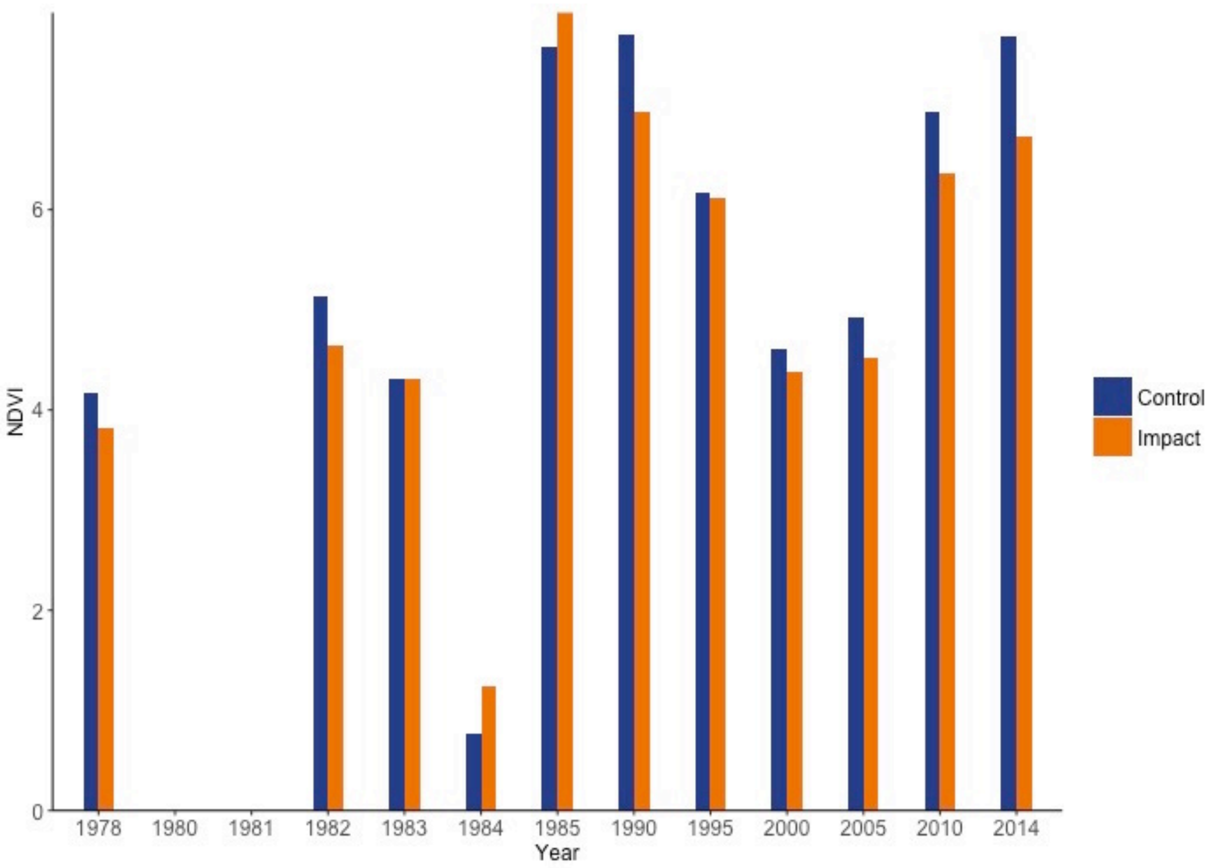

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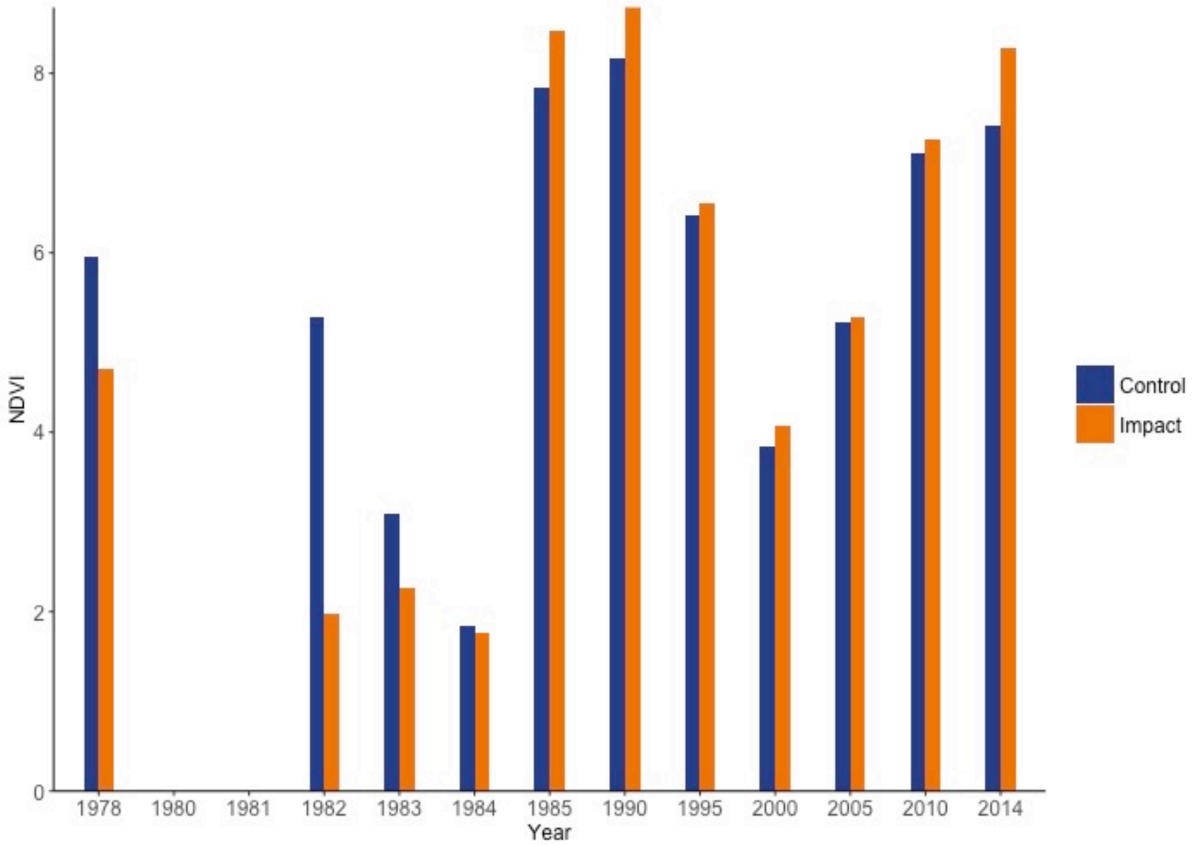

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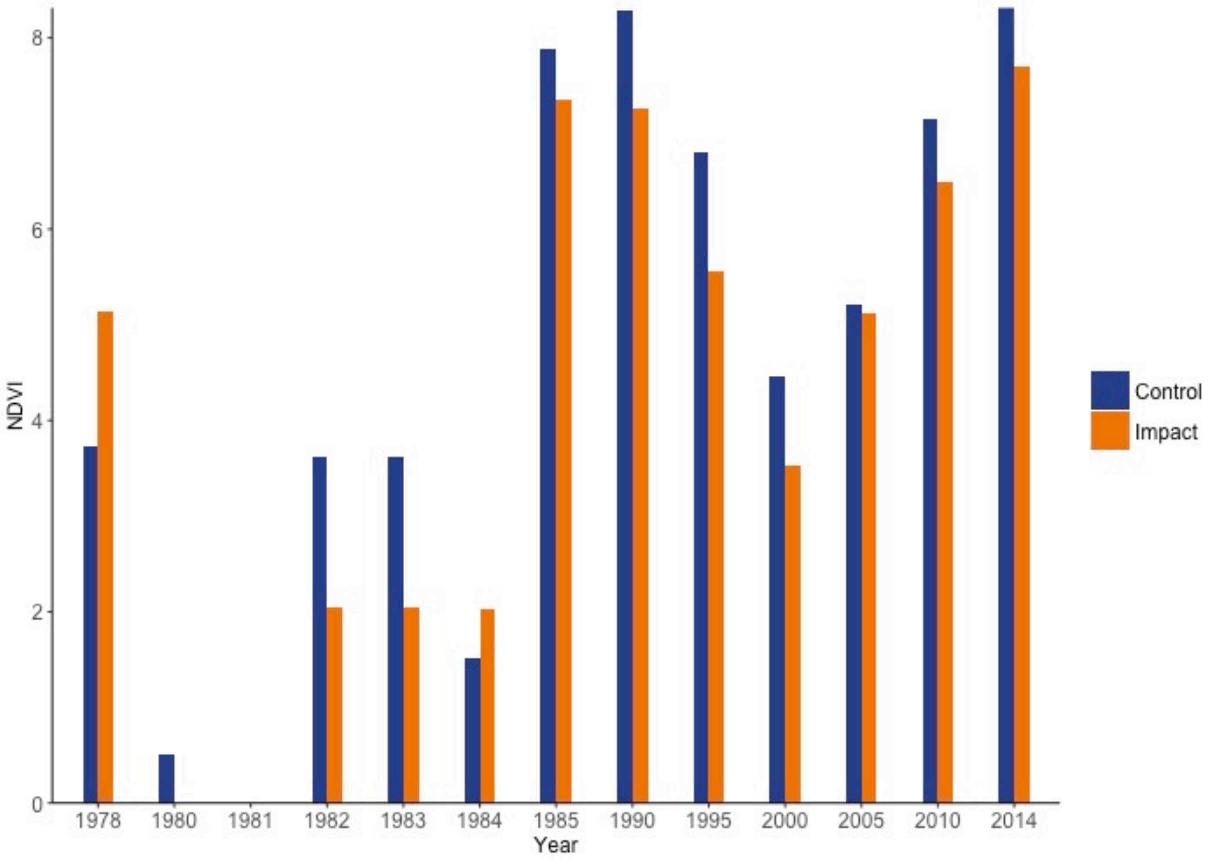

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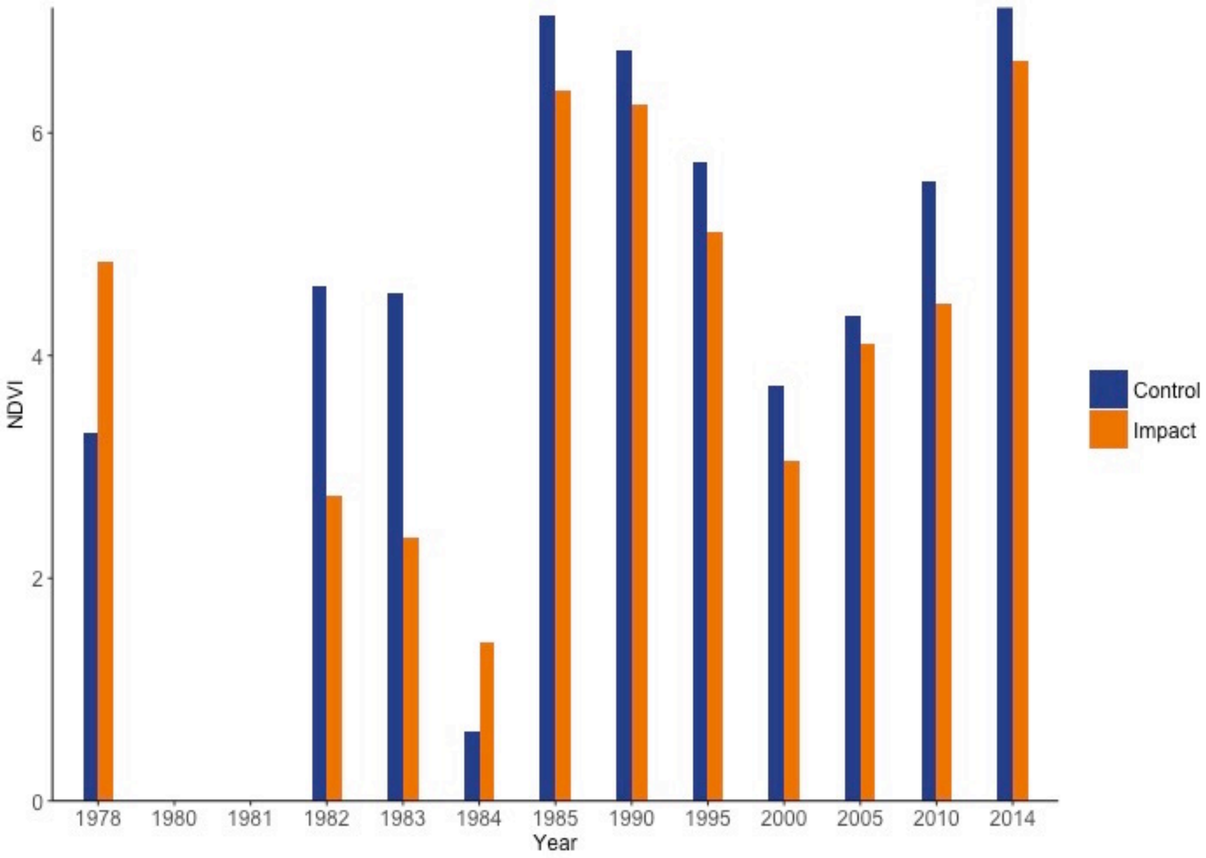

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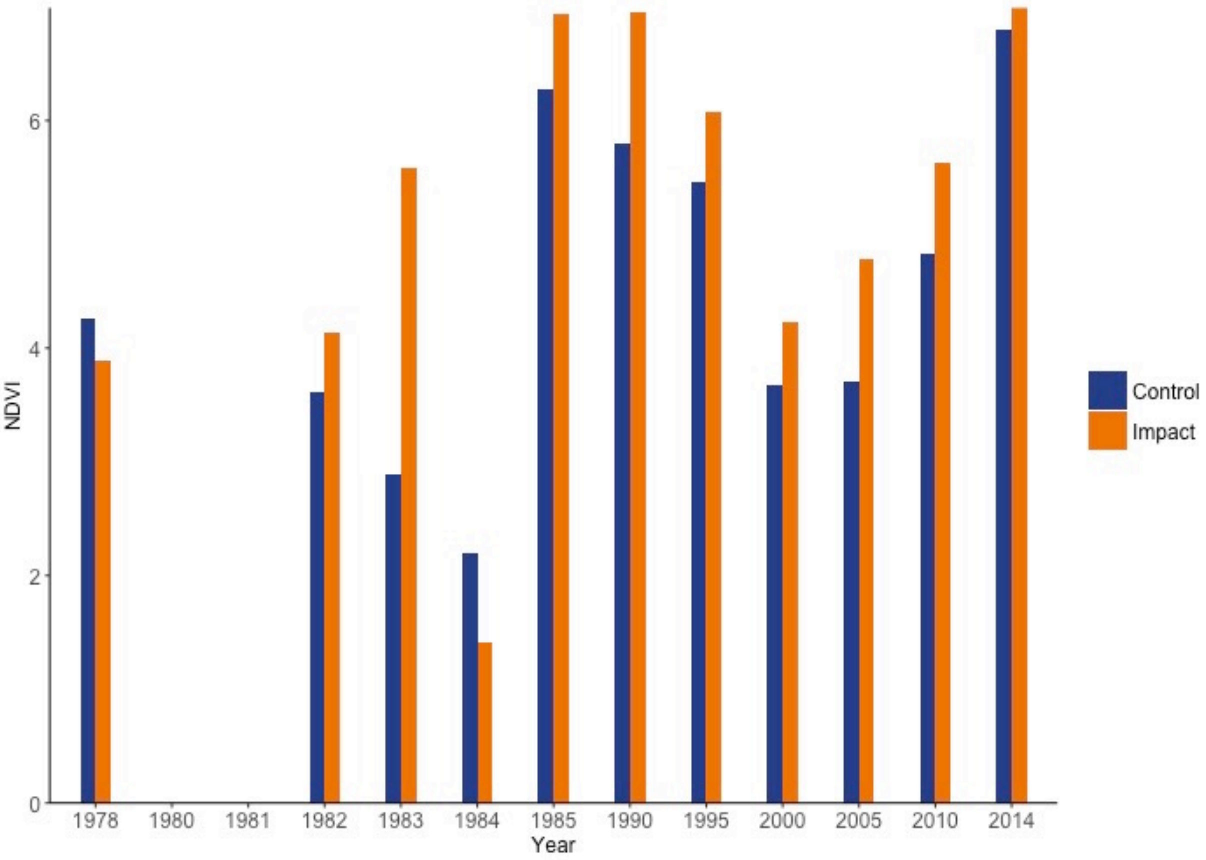

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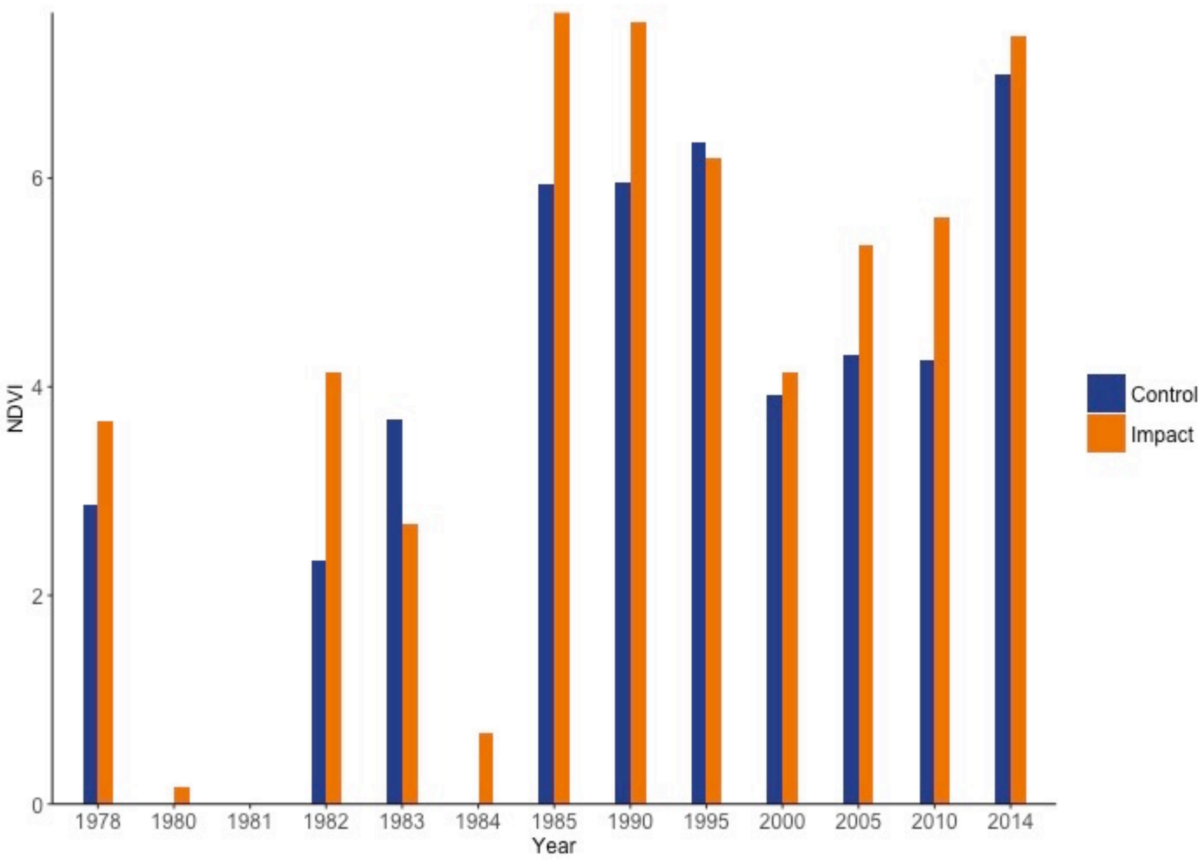

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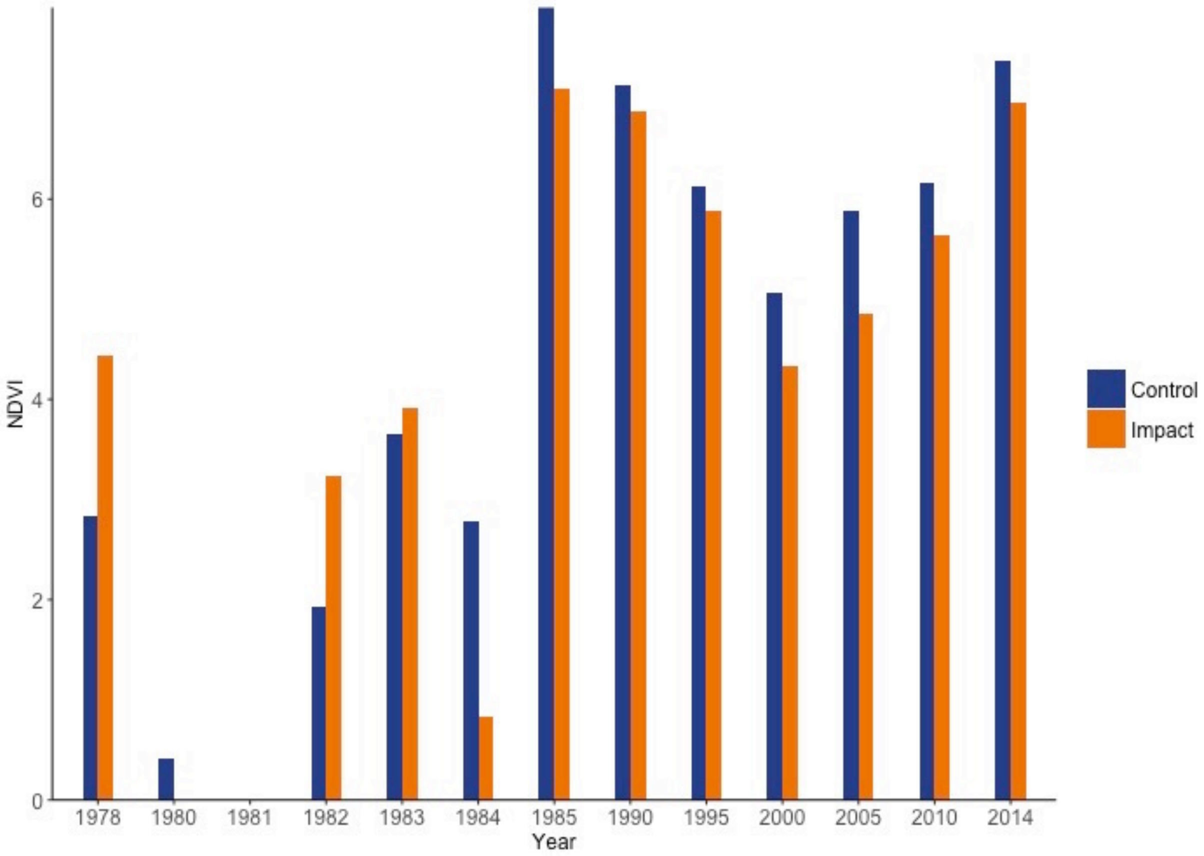

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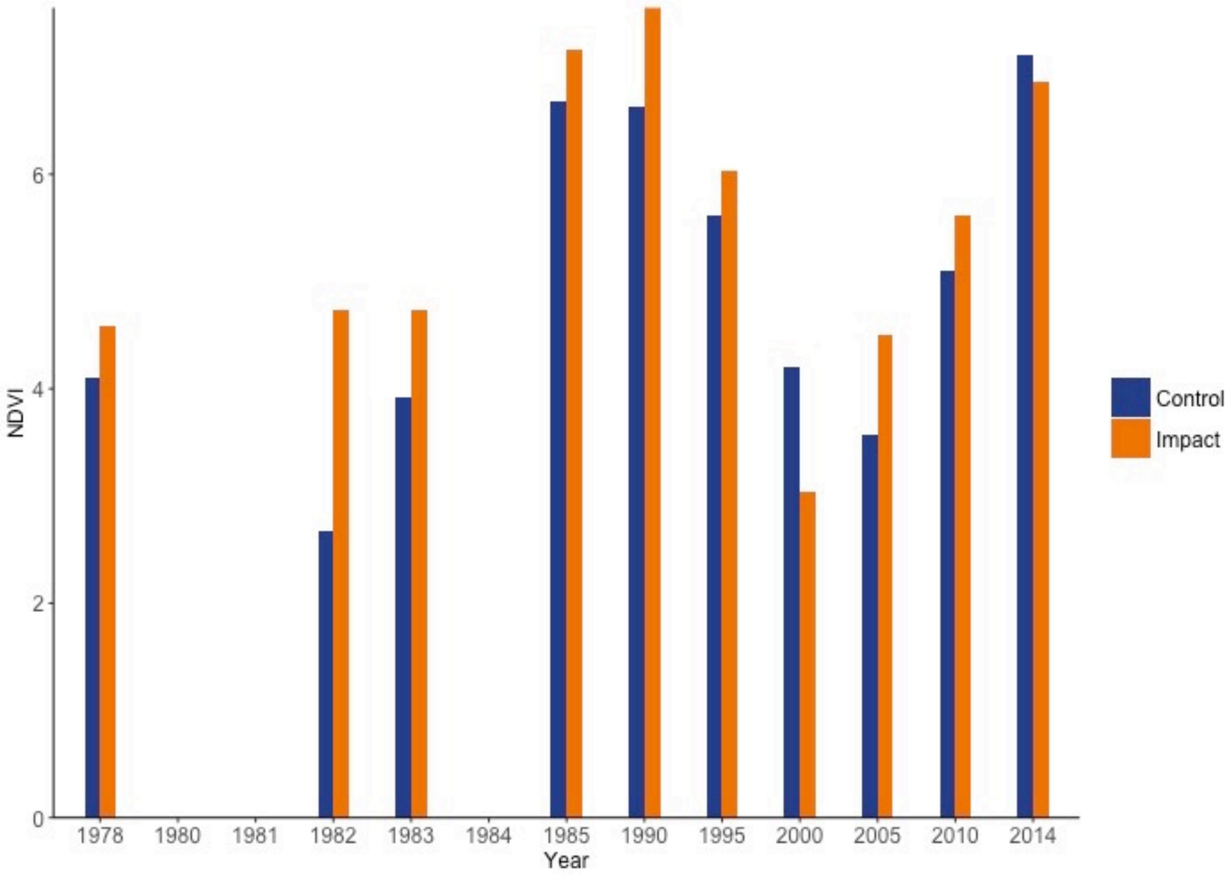

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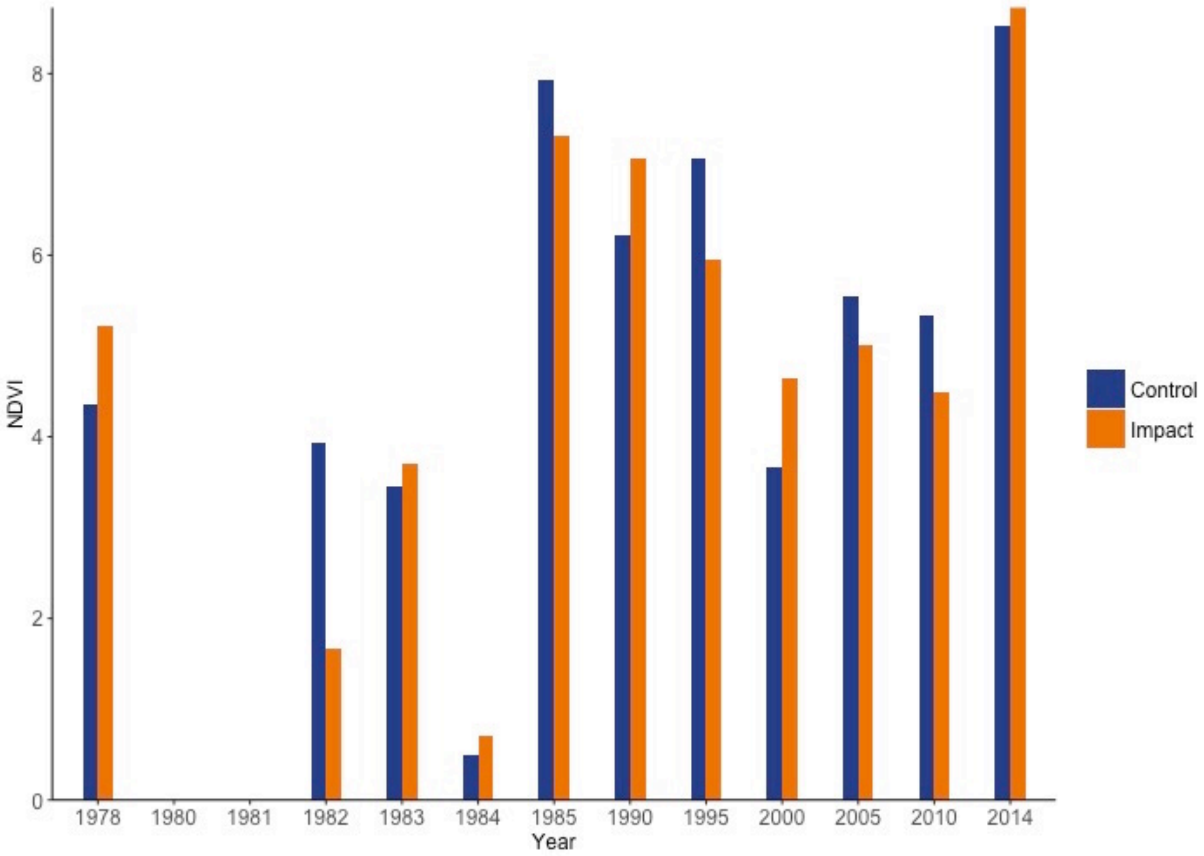

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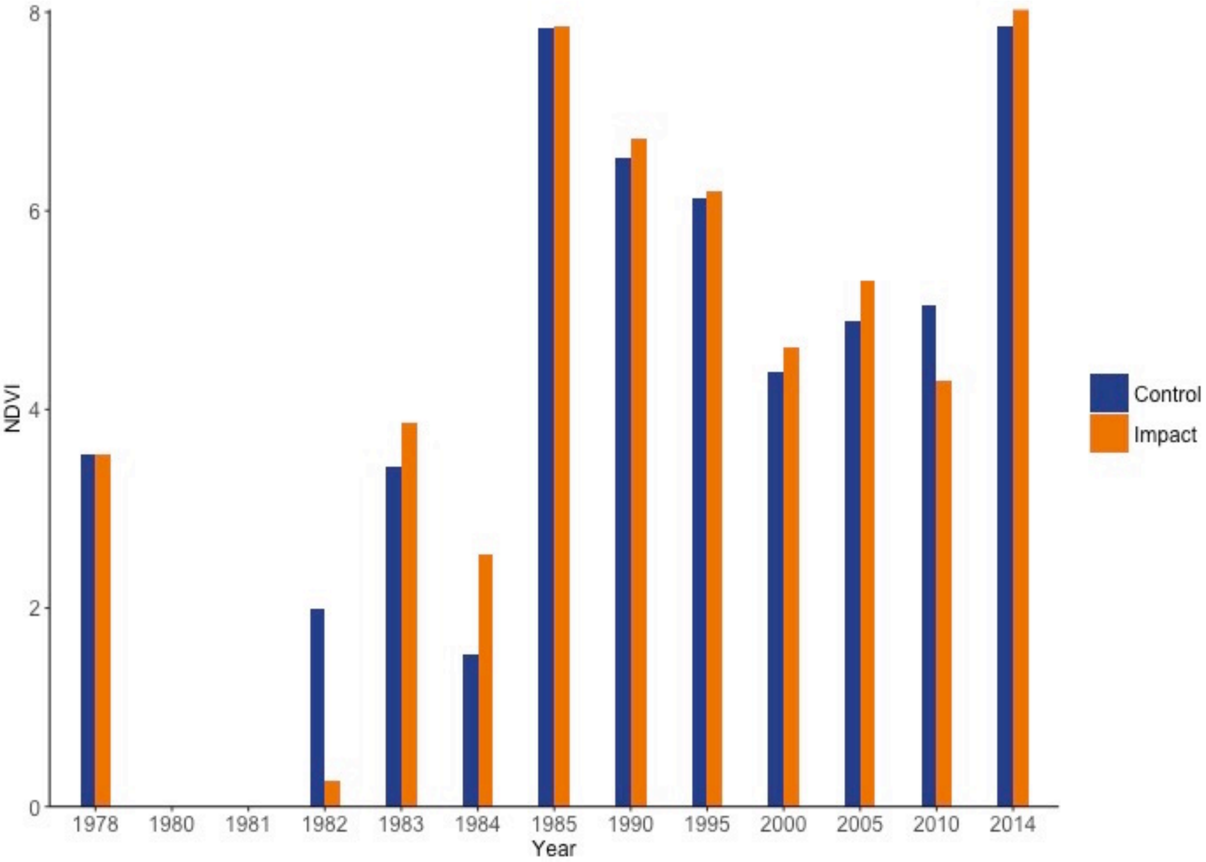

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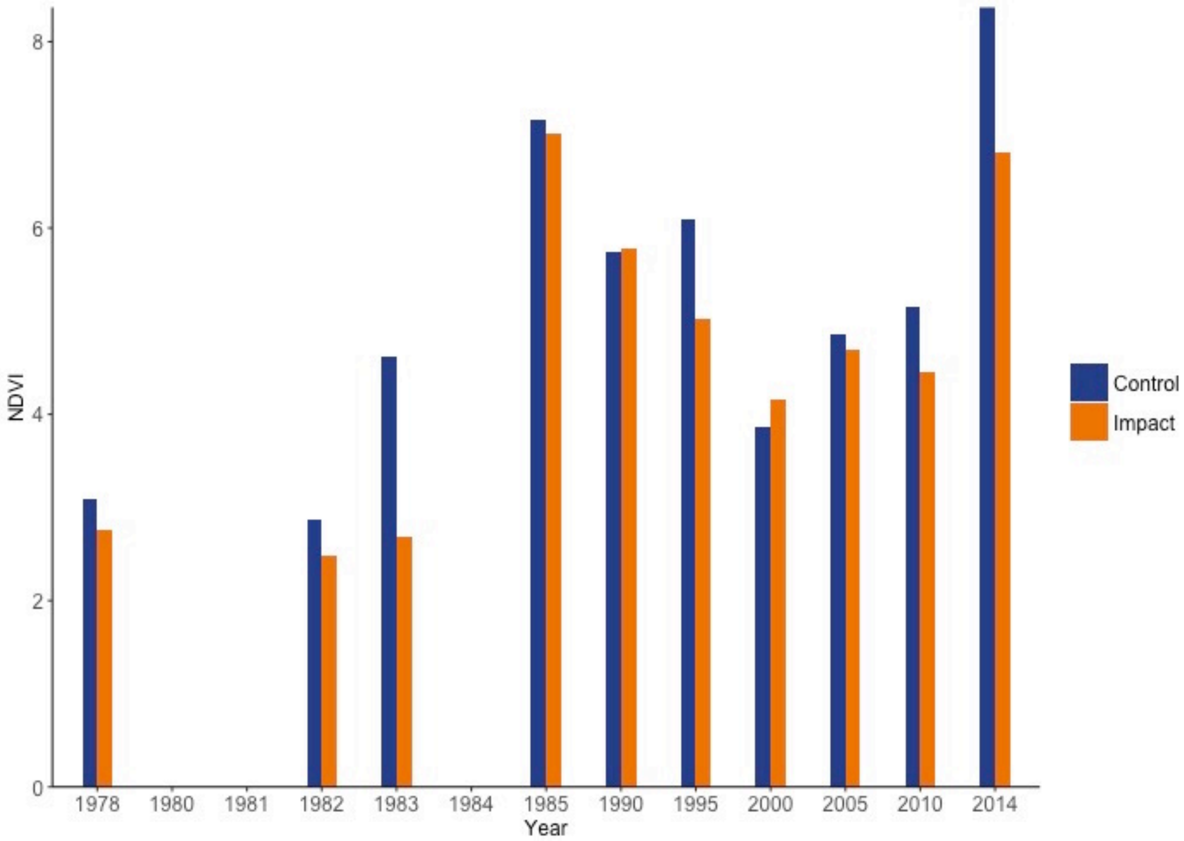

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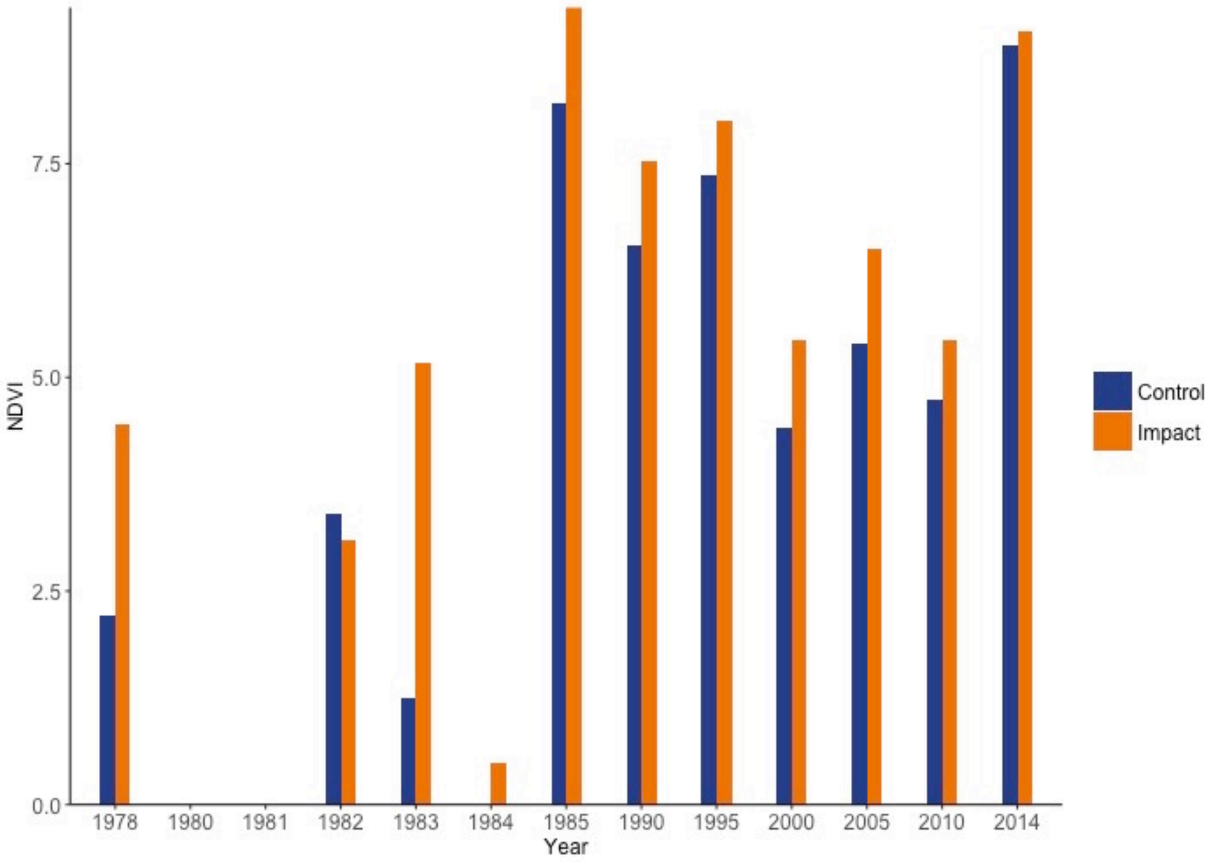

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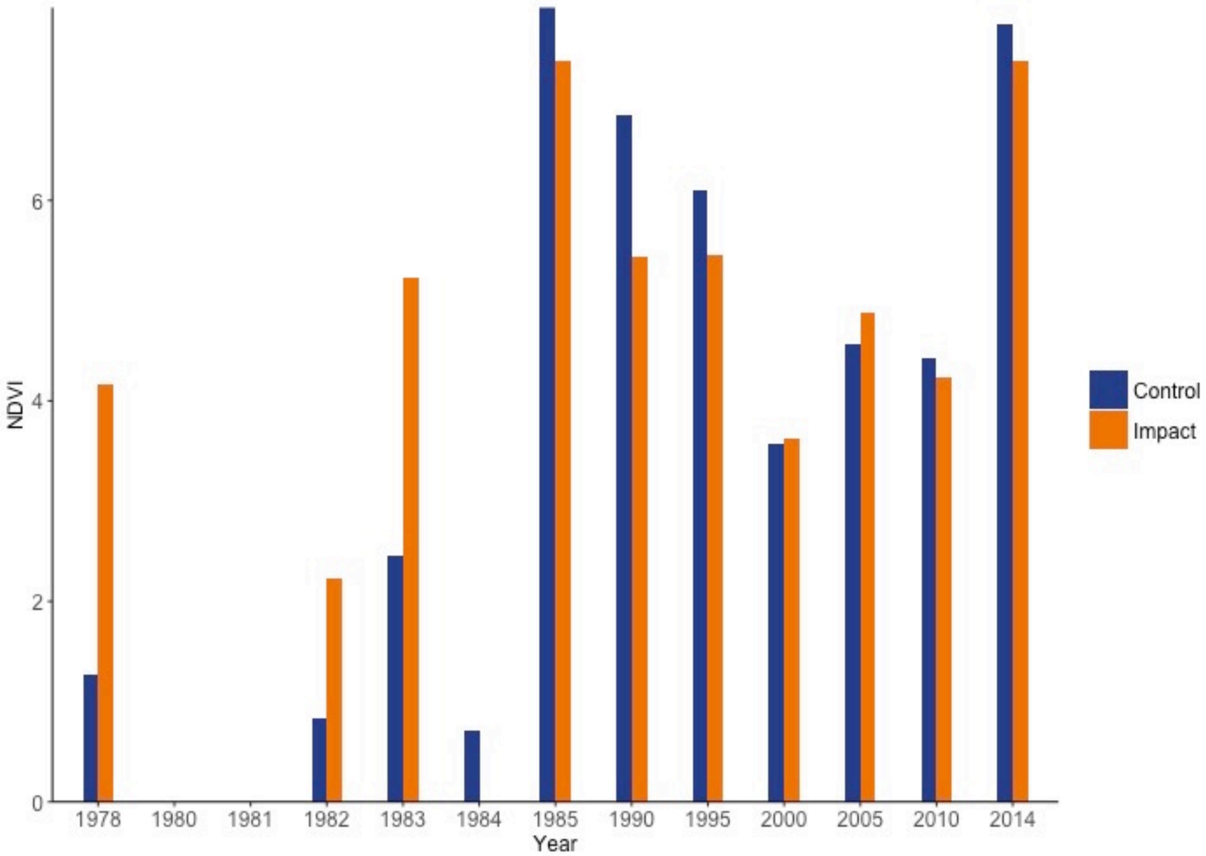

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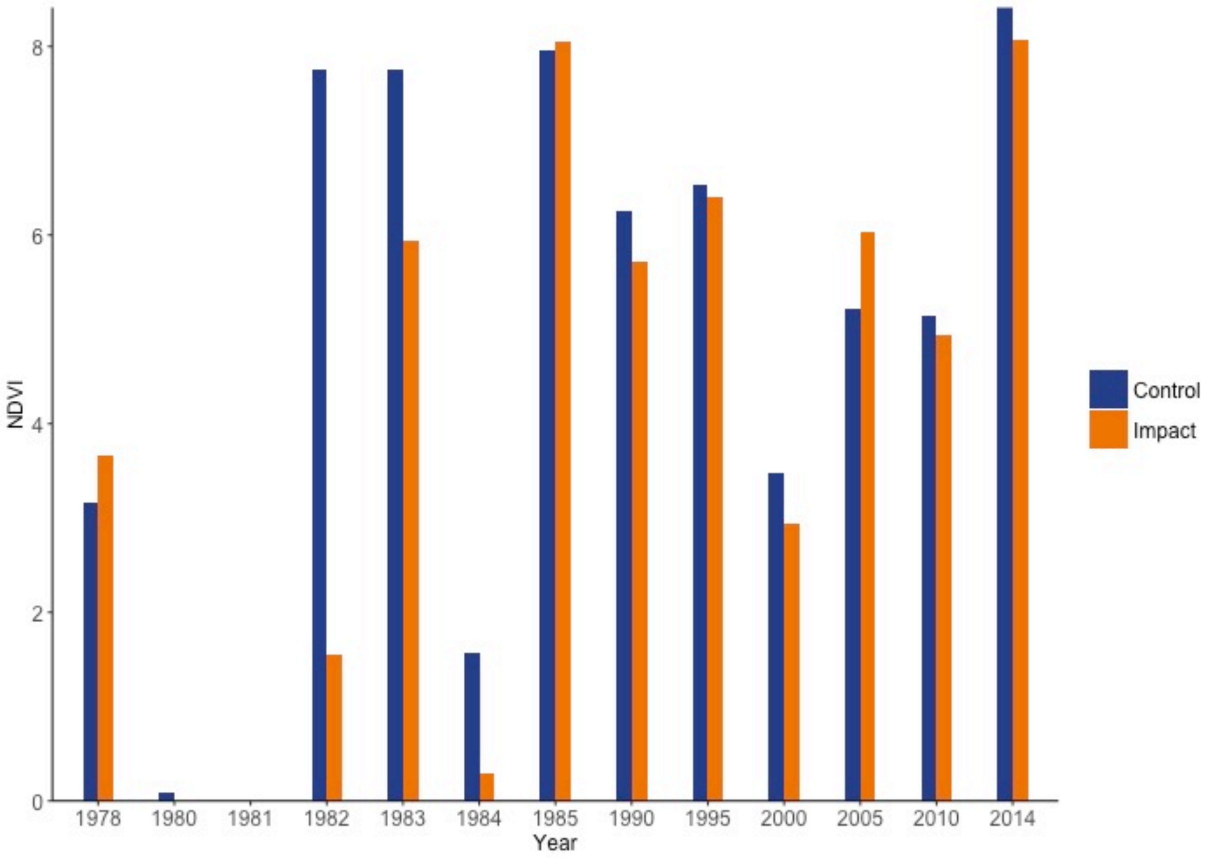

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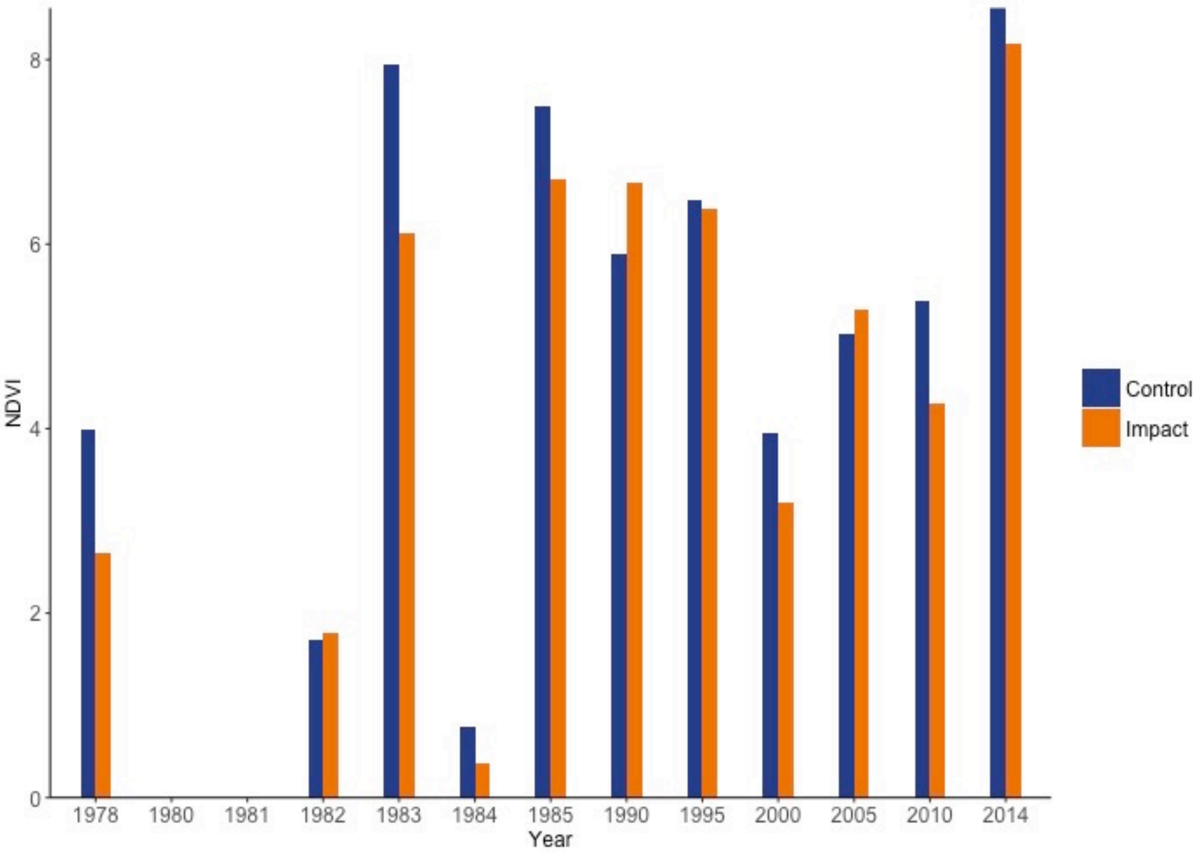

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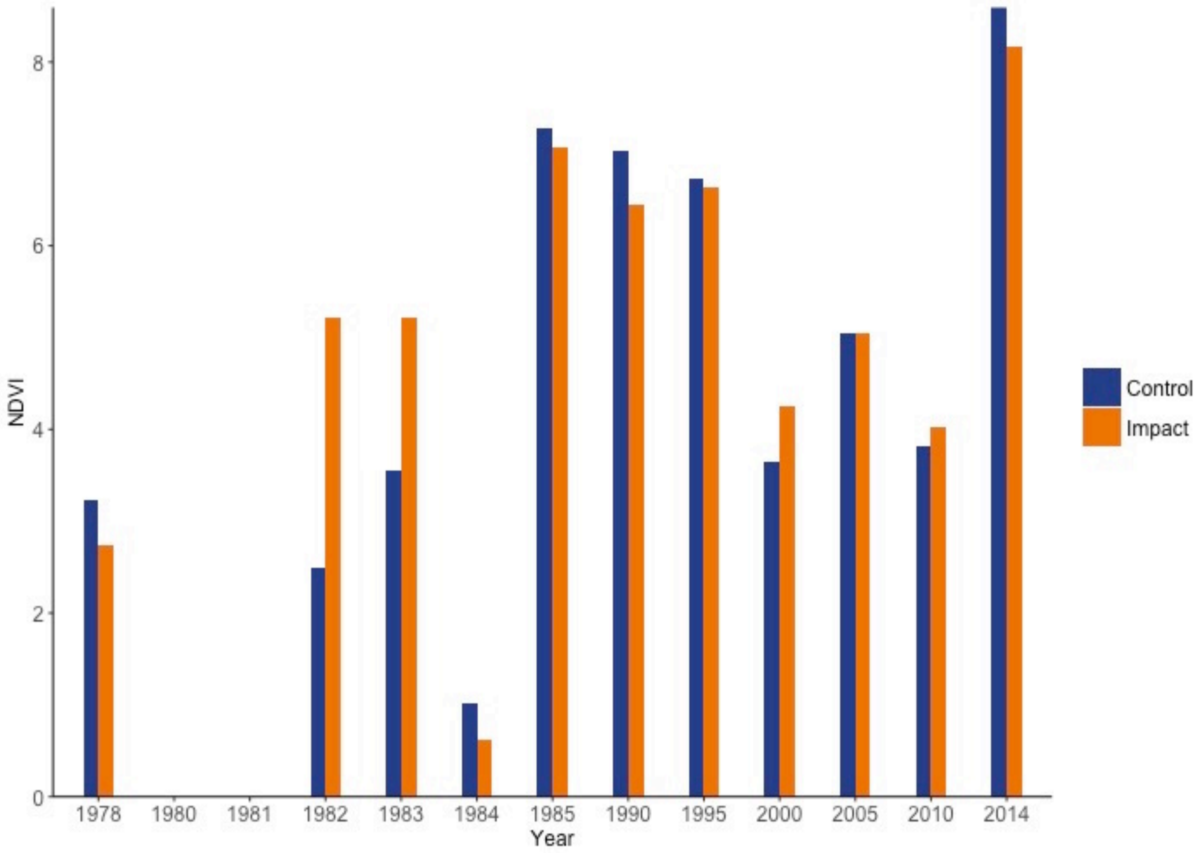

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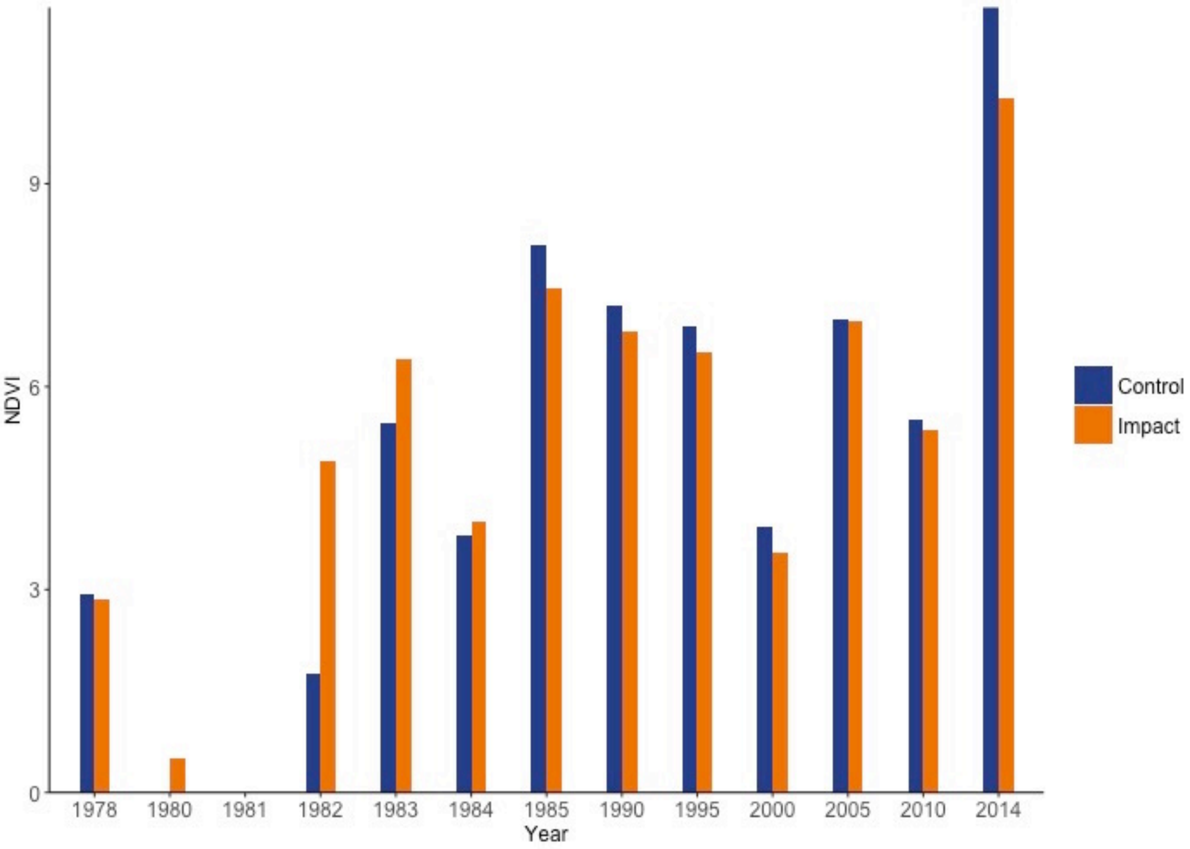

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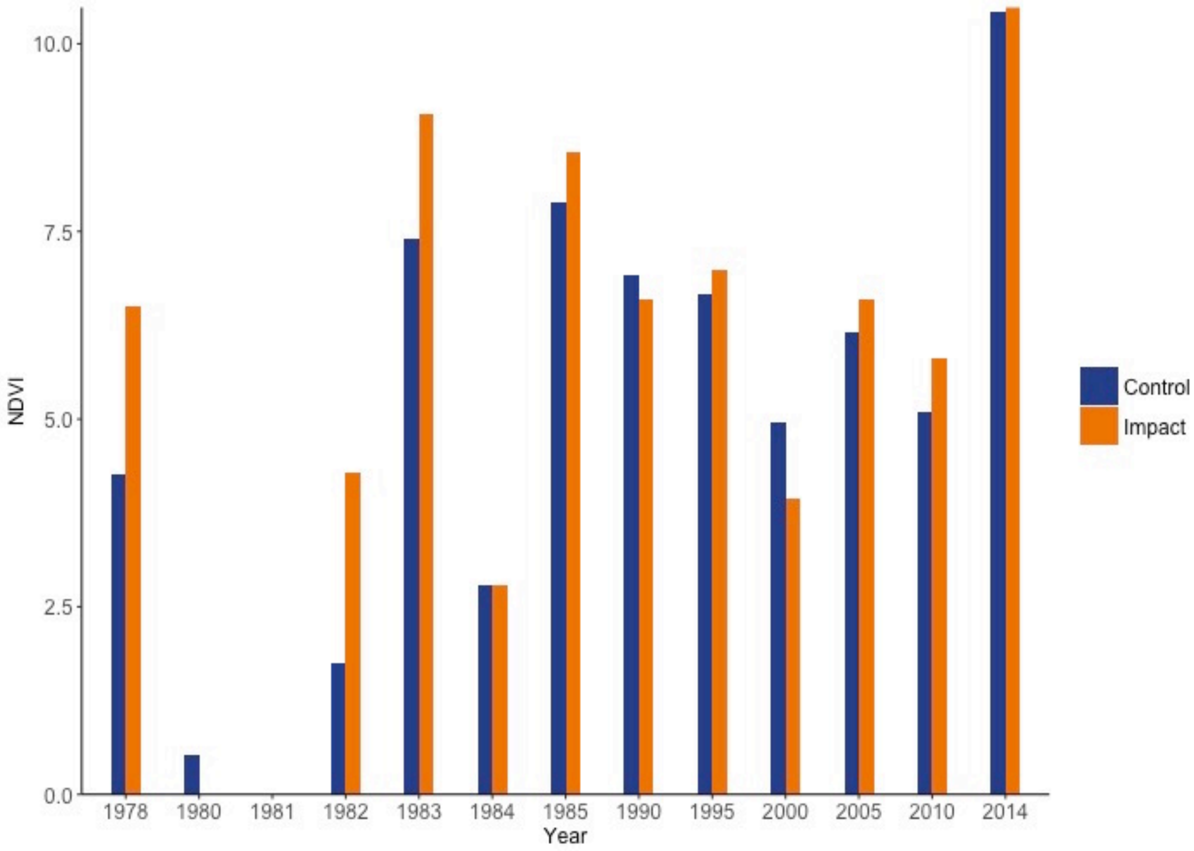

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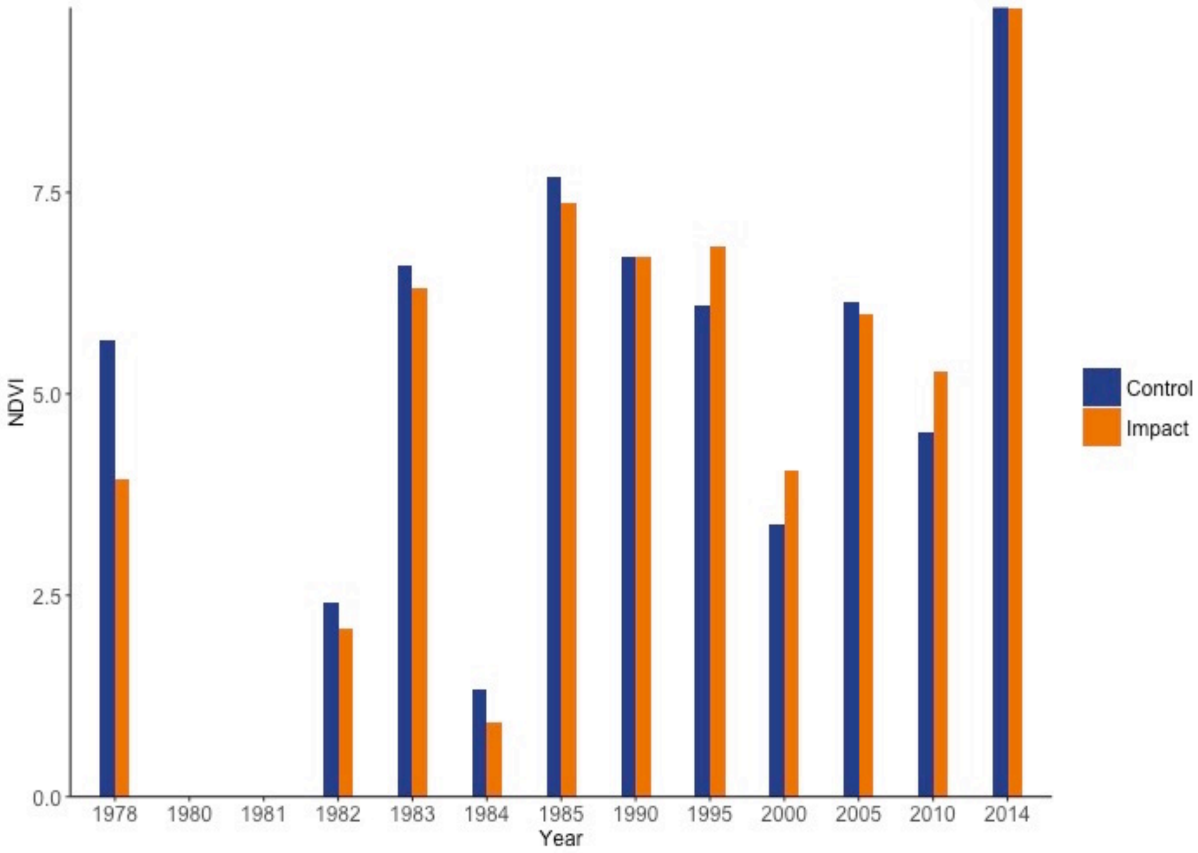

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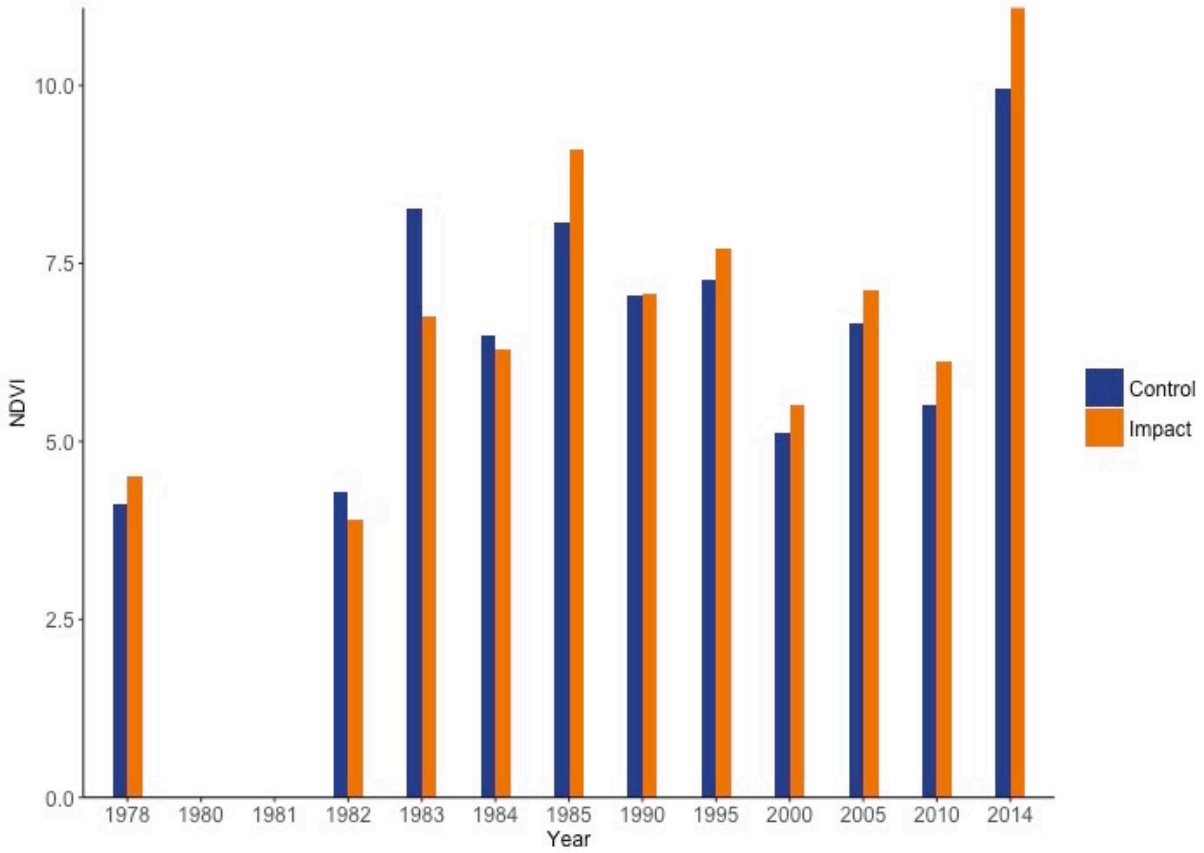

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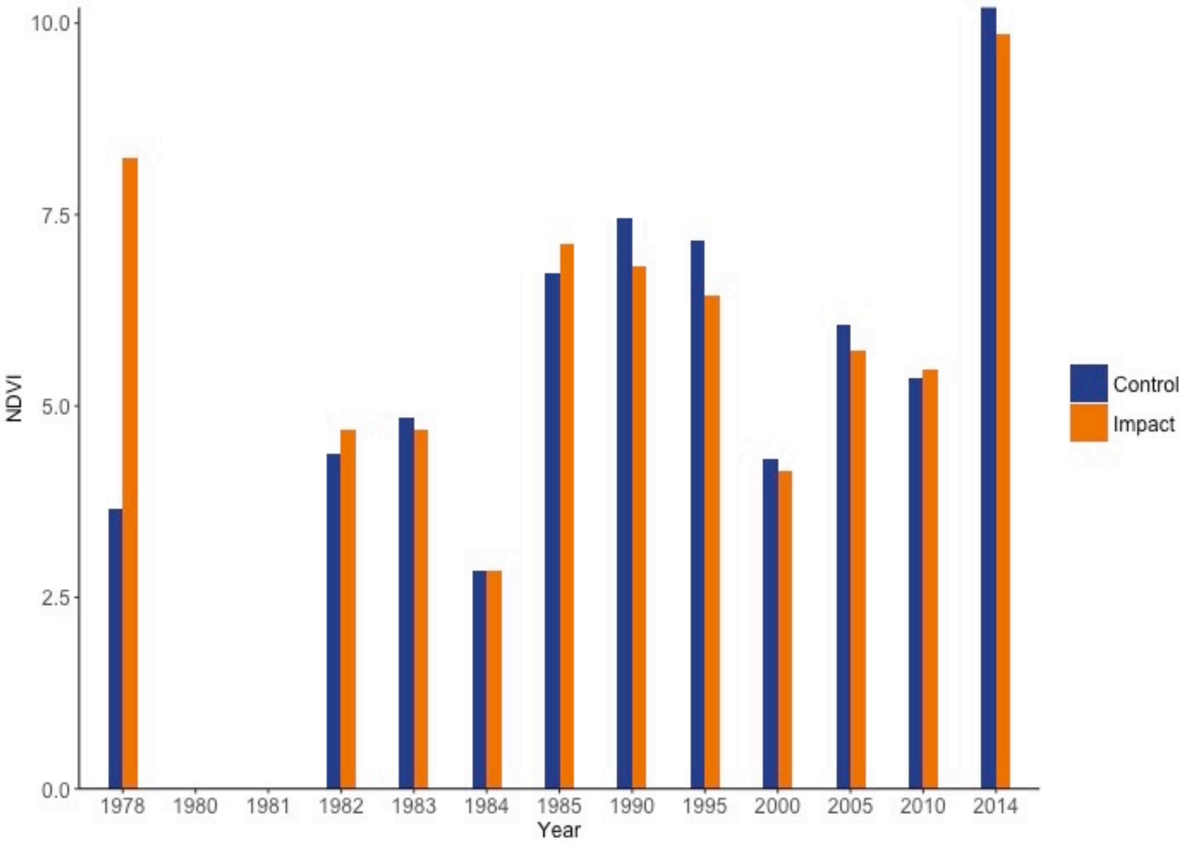

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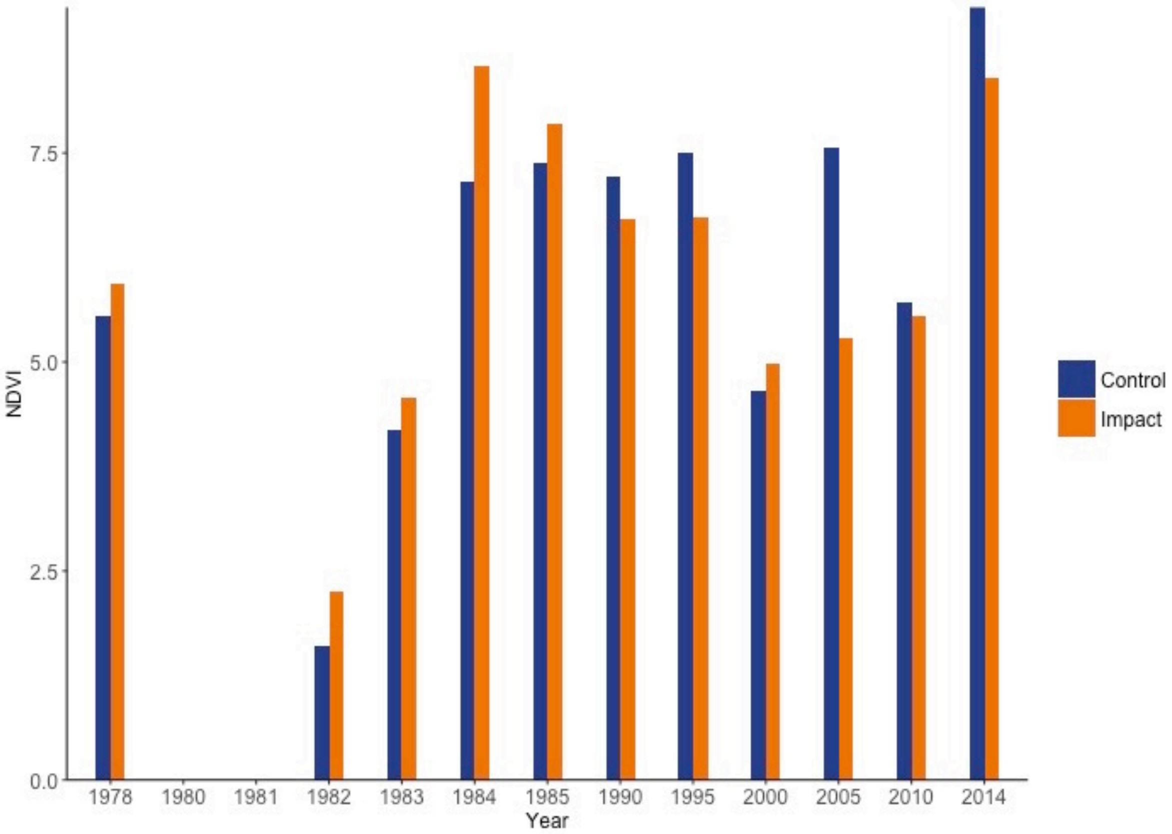

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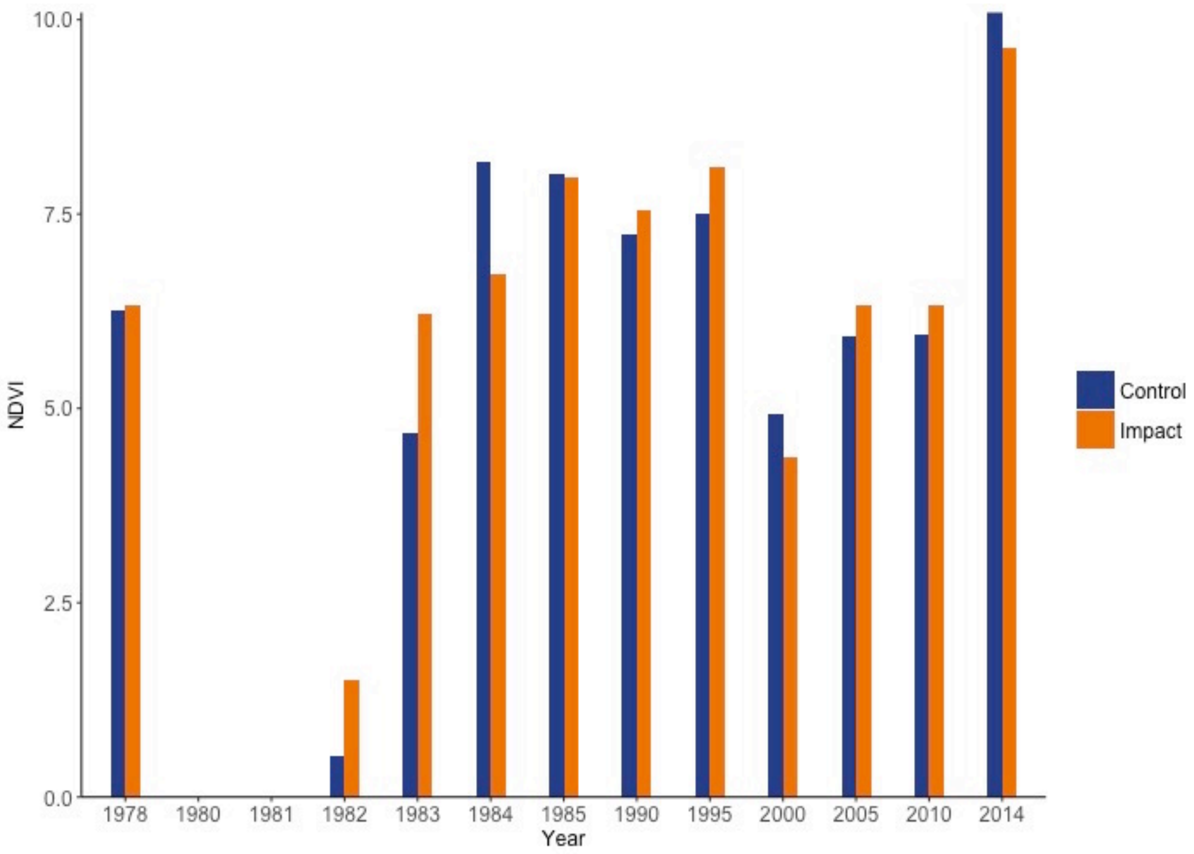

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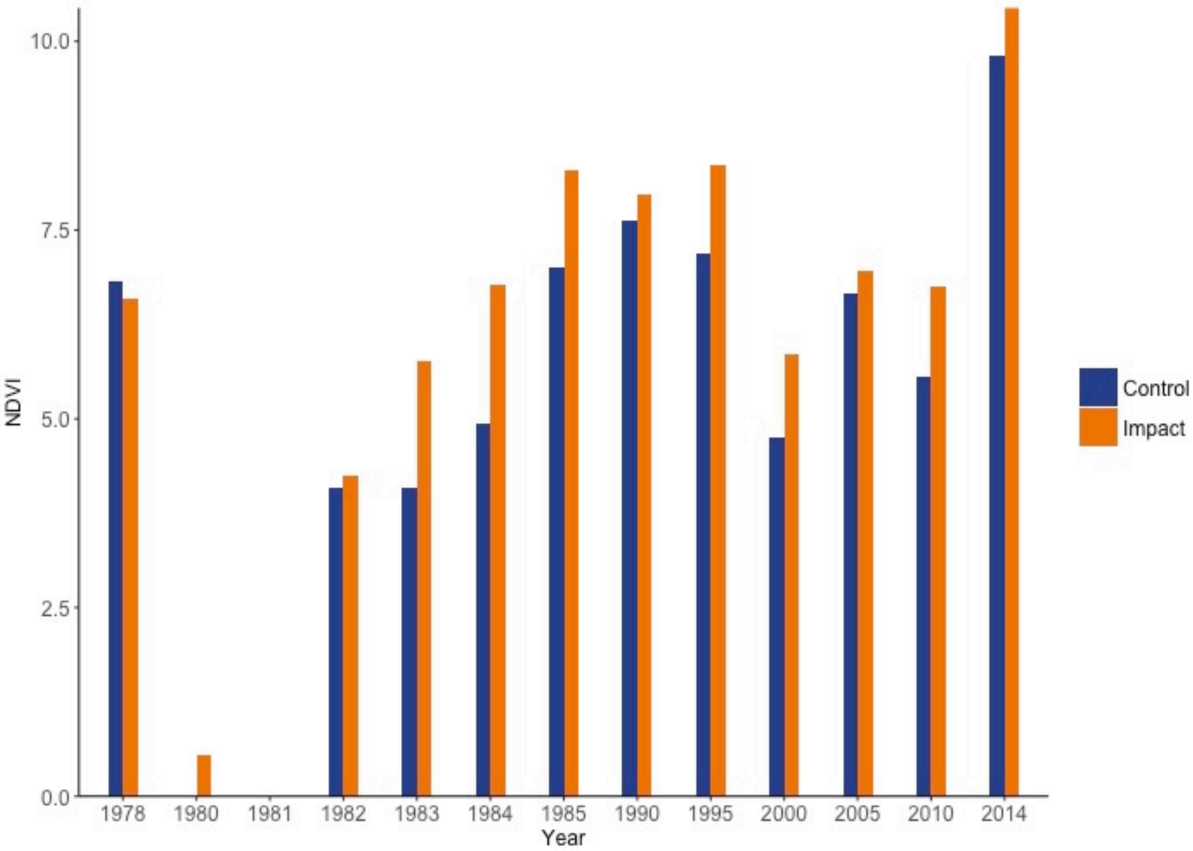

Figure A2-38. NDVI at control and impact sites at location 38.

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CHAPTER 3

Recovery of Perennial and Annual Vegetation 33 Years After the Construction of a Transmission Power Line in the Colorado Desert of Southern California

3.1. Abstract

This study examined the recovery of perennial and annual plant species on sites impacted during transmission power line construction 33 years ago. The survey area, dominated by creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*), was in the lower Colorado Desert of southern California. The impact sites were areas impacted during transmission tower construction. Belt transects (2 m x 30 m) were established at 0 m, 2 m, 4 m, 6 m, 8 m, and 10 m, from the transmission towers. The control belt transect was located 100 m away from the tower in undisturbed habitat. Larger species consisting of perennial shrubs and grasses were surveyed in the entire 60 m^2 area of each belt transect. Smaller herbaceous species consisting mainly of annual species and one perennial species (*Ditaxis lanceolata*) were sampled using five 1 m x 1 m quadrats within each belt transect. Recovery was assessed by comparing species richness (total number of species), plant density (total number of plants within area surveyed), and percent cover between the impact and control transects. In addition, species were categorized as native and nonnative. The results showed no significant differences in the species richness, plant density, and percent cover between all belt transects, including control, for both perennial and annual species. No nonnative perennials were observed in any of the tower locations at any distance. Three annual nonnative species were observed. *Erodium cicutarium* was observed at two towers but not in the transect closest to the impact or the control transect. *Schismus barbatus* was

observed at two towers and was present at all distances. *Tribulus terrestris* was observed at only one tower and only in the transect closest to the impact and the control transect. The results indicate sites impacted during construction approximately thirty years ago have recovered to levels indistinguishable from the adjacent control sites located in undisturbed habitat in terms of species richness, plant density, and percent cover.

3.2. Introduction

Increases in population and urbanization in southern California have resulted in growing utility demand. To support this demand, infrastructure construction of public utilities such as electric power, natural gas, and water is growing and has resulted in impacts to the desert landscape (Abella, 2010; Lathrop and Archbold, 1980a, 1980b; Lovich and Bainbridge, 1999; Reible et al., 1982; Vasek et al., 1975b, 1975a; Walsh and Hoffer, 1991). Land is cleared of vegetation during transmission power line, gas pipeline, and aqueduct construction for trenching, piling, refilling, grading, campsites, storage areas, tower sites, service roads, and conductor pulling and splicing sites (Brum et al., 1983; Lathrop and Archbold, 1980a, 1980b; Vasek et al., 1975a, 1975b). Besides direct effects to vegetation, removal can also affect desert wildlife species (Berry et al., 2016; Esque et al., 2003), increase soil erosion (Artz, 1989; Lovich and Bainbridge, 1999; Webb, 2002) and fugitive dust release (Grantz et al., 1998), alter fire events (Abella, 2010; Lovich and Bainbridge, 1999), and facilitate the establishment of invasive nonnative species (Bainbridge, 2012; Berry et al., 2016, 2015; Brooks, 1999).

Plant growth and establishment are naturally slow in the extreme conditions of the desert due to high temperatures, intense sunlight, limited moisture availability, variability in rainfall events, herbivory, and low soil fertility (Bainbridge and Virginia, 1990; Brooks, 2012; Brooks and Berry, 2006; Brooks and Pyke, 2001; Prose and Wilshire, 2000; Sassi et al., 2009). Utility construction, abandoned towns and roads, military activities, grazing, fires, and recreational activities such as off-road vehicle usage can exacerbate the severity of these conditions affecting natural recovery (Abella, 2010; Bainbridge, 2012; Bainbridge and Virginia, 1990, 1990; Bolling and Walker, 2000; Guo and Pärtel, 2004; Lathrop and Archbold, 1980a, 1980b; Vasek et al., 1975a, 1975b; Webb et al., 1983; Webb and Wilshire, 1983). Historically, impacted areas in the desert were mostly left to recover via natural processes.

Recovery of impacted lands has been an important topic of discussion and research in ecology (Walker, 2012). Research has focused on describing impacts, recovery of vegetation and soils, recovery time, and whether active restoration enhances recovery (Abella, 2010, 2009, Berry et al., 2016, 2015; Bolling and Walker, 2000; Brooks, 2012; Brum et al., 1983; Denslow, 1980; Guo and Pärtel, 2004; Lathrop and Archbold, 1980a, 1980b, Vasek et al., 1975a, 1975b; Webb, 2002; Webb et al., 1983; Webb and Wilshire, 1983). Post-impact recovery is defined as the return of vegetation characteristics to levels observed in adjacent undisturbed habitats (Abella, 2010; Lathrop and Archbold, 1980a, 1980b; Vasek et al., 1975a, 1975b). The time estimated for desert perennial plant species to reestablish in impacted areas naturally can range from a few decades to centuries depending on the metric of recovery, severity of impact, time since impact, soil type and quality, landform, climate, and presence of nonnative invasive species (Abella, 2010; Berry et al., 2016, 2015, Lathrop and Archbold, 1980a, 1980b; Lovich and Bainbridge, 1999; Vasek et al., 1975b, 1975a; Webb et al., 1983). Metrics of vegetation recovery can be plant density, biomass, percent cover, species richness and composition relative to adjacent undisturbed habitat (Abella, 2010; Berry et al., 2016, 2015; Lathrop and Archbold, 1980b; Vasek et al., 1975a). Abella (2010) reviewed 47 studies looking at various types of disturbances in both the Mojave and Sonoran Deserts and synthesized the results to estimate the time required for complete recovery. Studies used in the analysis included research on impacts from military activity, abandoned towns, roads, and agricultural fields, and utility (powerline, pipeline, aqueduct) construction on vegetation recovery. Using data from 29 studies, he estimated 76 years were necessary for perennial cover recovery. Similarly, using data from 31 studies, he estimated 215 years for perennial species composition recovery. Depending on the metric, the time to complete recovery can be wide-ranging.

Roads, transmission power lines, aqueducts, and pipelines are the most pervasive anthropogenic elements in the deserts of southern California and they are all characterized by long and relatively narrow corridors of disturbance (Lovich and Bainbridge, 1999). These corridors can also be a source of invasive plants inadvertently brought in during construction and during subsequent use (Lovich and Bainbridge, 1999). Previous studies on recovery of lands from linear impacts associated with pipelines and transmission lines in the Mojave and Sonoran Deserts have primarily focused on perennial shrub and grass species (Abella, 2010, 2010; Abella et al., 2007; Berry et al., 2016; Hessing and Johnson, 1982; Johnson et al., 1975; Kay, 1988, 1979; Kay and Graves, 1983; Lathrop and Archbold, 1980a, 1980b, Vasek et al., 1975a, 1975b). Only one study looked at annual species recovery from the effects of pipeline construction (Berry et al., 2015).

Impacts associated with the construction of utility transmission power lines can be classified as temporary and permanent impacts. Permanent impacts include eradication of vegetation and impacts to soils associated with the construction of the service road used for repair and maintenance purposes, and that is maintained throughout the life of the line, along with short spur roads connecting each tower to the service road. Temporary impacts include vegetation clearing/mowing associated with tower installation, campsites, staging areas, and heavy ground equipment usage to complete all activities associated with construction (Brum et al., 1983; Lathrop and Archbold, 1980b; Rorabaugh, 2013). This study focuses on recovery of vegetation from the temporary impacts associated with tower installation (tower sites) in the Colorado Desert.

The objective of this study is to determine the status of natural recovery of perennial and annual vegetation in a creosote bush dominant habitat approximately 30 years after the construction of a transmission power line in the Colorado Desert. Natural recovery will be assessed based on: 1. Whether the species richness of perennial species and annual herbaceous species differ at impact and control sites; 2. Whether the plant density of perennial shrub species and annual herbaceous species differ at impact and control sites, and; 3. Whether the percent cover of perennial shrubs species and annual herbaceous species differ at impact and control sites.

3.3. Methods

The study area was along an approximately 60 km segment of transmission power line owned and operated by the Southern California Edison Company (SCE) in the lower Colorado Desert between 33°39’47” N, 115°58’23” W and 33°35’34” N, 114°50’45” W in Riverside County. The transmission line was constructed in the early 1980s (1980–1982) and is called Devers-Colorado River No.1 or DCR1. DCR1 is composed of numerous lattice steel towers conducting electricity over a distance of 250 km including the study area (Figure 3-1). The Colorado Desert is the western part of the Sonoran Desert and is located mostly in California’s Riverside and Imperial Counties (Burk, 1977). It is located at a lower elevation than the Mojave Desert to the north and much of the land lies below 1,000 feet in elevation. The climate is very arid, with as little as 127 mm (5 inches) of precipitation per year (California Public Utilities Commission, 2006). There is a biseasonal rainfall pattern with winter frontal systems and summer convectional storms (Burk, 1977; Lovich and Bainbridge, 1999). The sampling area is composed of broad alluvial valley floors dominated by creosote bush (*Larrea tridentata*) in alliance with white bursage (*Ambrosia dumosa*) on rocky mountain slopes, bajadas or intergraded slopes, and desert washes (personal observation and California Public Utilities Commission, 2006). This study area was selected because of the uniformity observed in terms of the dominant vegetation type, soil type, distance from slopes, and distance from anthropogenic impacts such as camping grounds and the old Highway 10. Within the area surveyed, sites affected by significant desert washes and sites in proximity to other anthropogenic impacts unrelated to transmission line maintenance (such as berms for gas lines) were excluded. The construction of DCR1 in 1980 included the creation of a service road located on the north side of the DCR1 towers. The service road is maintained for the life of DCR1 and is used to access and repair not only DCR1 but also adjacent and parallel transmission lines. This road is also used for recreation and access by the public. A small clearance connecting the tower to the service road (spur road) is also maintained near each tower to ensure easy access for repair and maintenance. All belt transects in this study were located on the south side of the DCR1 towers.

The specific sites sampled in this study were associated with the construction of the transmission towers. Impacts associated with tower construction involve clearing of vegetation for the foundations of the tower and soil compaction caused by construction equipment (drill rigs, cranes, trucks, etc.). The area underneath the transmission tower enclosed by four concrete footings is about 6 m x 6 m. The total impacted area that is typically associated with tower construction is about 30 m x 30 m (California Public Utilities Commission, 2006). This can vary depending on the tower type, the topography, and the ability to use the service road as part of the construction impact area. The site-specific plans and construction details were not available for DCR1 and the assumption of the size of the impact area was based on a transmission line recently constructed parallel to DCR1 (California Public Utilities Commission, 2006).

Due to natural variation in topography, soil type, and the presence of other anthropogenic impacts along the transmission line, only 23 towers were sampled to minimize these differences. Starting at the south side of the tower, six 2 m x 30 m (length x breadth) belt transects were established at 0 m, 2 m, 4 m, 6 m, 8 m, and 100 m distances parallel to the service road. The 100 m transect represented control and was in located in an area with no observable anthropogenic impacts. This design was used to study the effect of distance from the impact on vegetation recovery. Sampling was conducted from April 24th to May 13th in 2015. Within each transect, species composition (species present), plant abundance (number of individual plants), and plant diameter were recorded. Species richness (number of species) at each distance was calculated using the species composition information.

The GPS coordinates of the center-point locations and two diameter measurements along the large and small axes were recorded for the larger plants consisting of trees, perennial shrubs, and grass species (collectively referred to as perennials in this manuscript). The canopy cover area was calculated using the average of the two diameter measurements and creating a circle centered at the GPS center-point in ArcGIS (www.esri.com; version 10.2.2). In instances where there were overlapping canopies with multiple individuals of the same species, one set of GPS coordinates was used to document the group of individuals and the canopy measurements were grouped. The number of individuals was also noted in this situation. Additionally, individuals with canopy cover within, but centered outside the belt transects were also recorded. The canopy of many individuals was not contained within one belt transect. Often the location of the plant caused the canopy cover to be split between multiple transects or not be entirely contained within the transect. Therefore, a single individual may have coverage in multiple belt transects. To avoid duplication when determining richness and density information, the center-point GPS position of the individual plant was used to determine the location within the associated belt transect. Even though the canopy spanned more than one transect, only the transect containing the center-point GPS position received richness and density information. If the center-point of a plant was located outside the boundaries of the belt transects, the plant was not counted for density and richness. Cover data was calculated as absolute cover within the transect. Absolute cover was defined as the proportion of the ground surface covered by plant canopy. Absolute cover including unvegetated areas summed up to 100%. In areas of canopy overlap with a taller and shorter species, only the canopy cover of the taller species was captured.

Within each 2 m x 30 m belt transect, five 1 m x 1 m quadrats were utilized to sample the shorter plants consisting of annual, herbaceous perennial, and lichen species (collectively referred to as annuals in the rest of this manuscript). The quadrats were positioned along the breadth of the transect at the 5 m, 10 m, 15 m, 20 m, and 25 m intervals. The quadrats were placed on the north side of the belt transect at the 5 m, 15 m, and 25 m locations and on the south side at the 10 m and 20 m locations.

Individual plants from genera *Atriplex*, *Camissonia*, *Cryptantha*, and *Lupine* were not identified to the species level and for ease of analysis the plants are categorized as *Atriplex* sp., *Camissonia* sp., *Cryptantha* sp., and *Lupine* sp. respectively. A perennial herb *Ditaxis lanceolata* was analyzed as part of the annuals data set because of its short size. Lichen species were also analyzed as part of the annuals data set and did not occur in every sampling site. These were recorded as lichen spp. for ease of analysis. Within each quadrat, the cover was estimated visually such that the total including bare ground added up to 100%. During analysis, the vegetated percent cover of the quadrats for each belt transect was calculated as a percent of the total area sampled (5 m^2).

Perennials were present at every tower that was sampled. The number of individuals and species varied, but data recorded from all 23 towers were analyzed. Annuals were not consistently present at every tower or at every distance. Towers without annuals at any distance were excluded from the analysis. Towers with annuals occurring in extremely low abundance (less than 10 individuals in total across all 6 distances at a tower) were excluded from the analysis as well to avoid skewing the results. Thus, only 10 out of the 23 towers sampled qualified for further analysis.

Species richness was defined as the total number of species within each belt transect. The number of perennial species within each belt transect was recorded at all 23 towers. The number of annual species contained within each of the 6 belt transects was represented by counts within the five quadrats. For both annual and perennial species, a single-factor Analysis of Variance (ANOVA) was conducted to determine if the differences in species richness observed at all distances were statistically significant.

Plant density was defined as the number of individual plants present within the surveyed area. The number of perennial plants within all six belt transects was recorded at all 23 towers. Perennial plant density was calculated by dividing the number of perennials observed by the area of the belt transect (60 m^2) surveyed. The number of annual plants observed in the five quadrats in each of the six belt transects was recorded at the 10 towers. Annual plant density was calculated by dividing the total number of annuals observed in each transect by the total area sampled (5 m^2). A single-factor ANOVA was conducted to determine if differences in plant density observed at all distances were statistically significant.

Percent cover was defined as the percent of the sampling area covered by plant canopy such that the total including the unvegetated area was 100 percent. The canopy cover of the perennials calculated using the two measurements of diameter was divided by 60 m^2 and multiplied by 100 to determine the cover as a percent of the total sampling area. The cover of the annuals was visually estimated within each quadrat and the percent cover in the belt transect was obtained by calculating the percent of vegetated cover in all five quadrats relative to the total area sampled (5 m^2). The percent cover values for both the perennials and the annuals in each of the six belt transects were used to conduct a single-factor ANOVA to identify if differences observed at each distance were statistically significant.

The survey area and all sampling sites were located on public land administered by the U.S. Department of the Interior, Bureau of Land Management (BLM). All data and statistical analysis were conducted using R version 3.2.3 (R Core Team, 2015) and RStudio version 0.99.489 (R Studio Team, 2015). The ANOVA tables are available in the appendix.

3.4. Results

All the perennial species observed were native species. The stretch of the desert sampled for this study was a *L. tridentata* dominant habitat in close association with *A. dumosa*. *Larrea* was observed at most of the towers, but it was not present at all 23 towers (Table 3-1). Most other species, while native, were not always present at all 23 sampling locations (towers). *Croton californicus*, *Cylindropuntia echinocarpa*, *Cylindropuntia ramosissima*, *Encelia farinosa*, *Fouquieria splendens*, and *Opuntia* *basilaris* were present only at one tower and only at one distance. A total of 8 species were observed in the 0–2 m and 8–10 m transects, followed by 7 species in the 100–102 m transect, 6 species in the 2–4 m and 4–6 m transects, and 5 species in the 6–8 m transect (Table 3-1). Average species richness was highest in the 0–2 m and 100–102 m transects, and a pattern with distance was not discernible (Figure 3-2A). Statistically, species richness of perennials was similar ($p > 0.05$) across all distances. The data were reorganized and analyzed five other ways (e.g., removing towers with low counts of species, averaging information from multiple transects, and only comparing three transects, presented in the appendix), but no significant differences were detected in species richness of perennials between the transects closest to the impact (tower) and the control transect.

Atriplex sp., *Camissonia* sp., *Eremalche rotundifolia*, *Lepidium lasiocarpum*, and *Lupine* sp. were only observed at one distance at one tower (Table 3-2). The distribution of the annual species and number of individual plants observed were generally sparse. Only *Aristida adscesionis* and *Euphorbia micromeria* were observed at five towers or more. *Chaenactis fremontii* and lichen spp. were observed at three towers or more. The species observed were further classified as native or nonnative. *Atriplex sp*. was categorized as unknown since the specific species was not determinable. Nonnative species were observed at four out of the ten towers. The nonnative species were *Erodium cicutarium*, *Schismus barbatus*, and *Tribulus terrestris. Erodium cicutarium* was only present at two towers within the first 10 m from the transmission towers, but not in the control transect. *Schismus,* observed at two towers, occurred at every distance when present, and *T. terrestris,* observed at just one tower, occurred at only two distances, closest to the tower (0–2 m) and in the control transect (100–102 m). The mean species richness in the 8–10 m transect was the highest, but a pattern with distance was not discernible (Figure 3-2B). No statistically significant differences were observed between the different distances ($p > 0.05$) in terms of annual species richness. The annuals data were reorganized and analyzed two other ways (see the appendix), with similar results. In short, there were no significant differences in species richness of annuals in the transects closest to the impact and the control transect.

Plant density indicated the productivity within the belt transects without considering species composition. The transect located at 4–6 m and the control transect 100 m away from the tower on average had the highest perennial plant density (Figure 3-3A). There was no pattern detected with distance from impact for perennial plant density. A large wash was present along the entire 4–6 m transect at one tower, likely the reason why this transect has plant density similar to the control transect. While the number of plants was generally fewer than 10 per belt transect at other towers, at this tower at the 4–6 m distance, the total number of plants was 26. Whether using all 23 towers or just 22 towers (excluding the tower with the wash at 4–6 m), there was no statistically significant difference ($p > 0.05$) in perennial plant density across all transects. The data were reorganized and analyzed five other ways (see the appendix), with no significant differences in perennial plant density between the transects closest to the impact and the control transect.

Plant density of annual species was lowest at the distance closest to the impact and highest at the control transect (Figure 3-3B). While there appeared to be a trend with plant density increasing with increasing distance from impact, there were no statistically significant differences (p > 0.05) between the densities observed at all distances. The data were reorganized and analyzed two other ways (see the appendix), with no significant differences in annual plant density between the transects closest to the impact and the control transect.

The average percent cover of perennial species was highest in the control transect and lowest in the two transects closest to the impact and the transect located at 8 m (Figure 3-4A). A pattern with distance from impact is not apparent and statistically the cover did not differ significantly across the transects (p > 0.05). The data were reorganized and analyzed five other ways (see the appendix) with similar results.

The average percent cover of annuals was lowest in the transect closest to the impact and highest in the control transect (Figure 3-4B). There appeared to be a trend with distance with cover increasing with increasing distance from the impact. However, statistically, the cover did not differ significantly across transects (p > 0.05). The data were reorganized and analyzed two other ways (see the appendix) with similar results.

3.5. Discussion

The results of this study strongly suggest that in the region examined, vegetation characteristics in sites disturbed by transmission power line construction 33 years ago are indistinguishable from control sites in the adjacent undisturbed habitat. While this study does not examine recovery directly, by using a comparative analysis between impact and control, it implies that the impacted sites have recovered. Abella (2010) estimated a recovery time of at least 76 years for reestablishment of total perennial plant cover and 215 years for perennial species composition recovery; intervals of much longer duration than observed in this study. The analysis (Abella, 2010) combined different intensities of impacts and this likely affected the time estimated for recovery (Bainbridge and Virginia, 1990; Lovich and Bainbridge, 1999). Temporary impacts associated with transmission tower construction are not long-sustained impacts such as those associated with road usage, military training, or settlements. The temporary impact areas studied here were not disturbed after the initial act of construction and were left to recover naturally. In other words, transmission line construction may not be as impactful as other anthropogenic disturbances in the deserts including other utility construction because trenching is not necessary (Lovich and Bainbridge, 1999). It is therefore possible that impacts associated with transmission tower construction are not as intense and vegetation can reestablish quicker than estimated by Abella (2010).

Few previous studies have focused specifically on annual plant recovery (Berry et al., 2015). This study was designed to determine if distance from impact can affect vegetation. I expected there to be more nonnative species closer to the towers relative to the control transect since the towers are along a well-traveled service road that is likely a source of nonnative species. However, nonnatives, when present, do not appear to be influenced by distance from the tower. Berry et al. (2015) studied the recovery of annual species in an aqueduct pipeline corridor 36 years after construction in the Mojave Desert by establishing transects at 0 m, 20 m, 40 m, and 100 m from the road (impact). They determined that native species richness increased with increasing distance from impact (highest at 100 m which served as control), but density and cover did not significantly differ along the distance gradient. Oddly, they observed nonnative species significantly increased in richness, density, and cover with increasing distance from the impact. The study designs of both studies, though not identical, are similar but the results are varied. This may be due to differences in the intensity of the original impact (pipeline versus overhead transmission power line), other unrelated anthropogenic disturbances, and desert location.

Another factor that could be affecting the results of this study, is the location of the control transect. I made two assumptions regarding the control transect: 1. That it is in an area that has remained undisturbed since construction; and 2. That 100 m is sufficient distance from the tower to not be affected by construction. I avoided areas influenced by other obvious anthropogenic (berms from gas lines, other transmission lines, old highway 10) and natural (slopes) factors for the impact and control transects in this study, so the likelihood that the control transects were affected by a unique disturbance is low. Previous studies focusing on impacts to perennial species from utility construction placed control transects at least 50 m away from impact (Lathrop and Archbold, 1980a, 1980b, Vasek et al., 1975a, 1975b) and more recent studies placed it at least 100 m away from the impact (Berry et al., 2016, 2015). Berry et al., (2016) observed significant trends with perennial species richness, plant density, and cover, with all three increasing with increasing distance from impact, indicating that the location of the control may be satisfactory for the larger long-lived plant species. On the contrary, Berry et al., (2015) observed an unexpected trend with nonnative annual species increasing in biomass, density, richness, and cover with increasing distance from the impact. The current study does not show significant trends with either perennial or annual species in terms of richness, density, and cover. Future studies may clarify this uncertainty with control transect located farther than 100 m from impact especially for herbaceous annual species.

The lack of regular precipitation over the five years prior to this study likely influenced the abundance of the annuals. Even though sampling was conducted approximately three weeks after a short bout of rainfall in spring 2015, scant annual herbaceous species were observed at only 10 towers. While the low density of both native and nonnative annuals may be attributable to low rainfall, the observations are still likely representative of the naturally occurring species in the survey area. The low density of shrubs appears to be characteristic of the area.

Previous studies on ground-disturbing impacts in deserts have estimated vegetation recovery requiring several decades (Abella, 2010; Bolling and Walker, 2000; Lathrop and Archbold, 1980a, 1980b, Vasek et al., 1975a, 1975b; Webb et al., 1983). This study suggests that the impact sites are similar to control sites in terms of species richness, plant density, and percent cover, suggesting recovery has occurred. However, the study does not determine the time taken to achieve recovery other than it likely took less than 33 years; shorter than the duration estimated in previous studies. While natural recovery appears to be a feasible long-term option for mitigating temporary ground disturbance associated with transmission power line construction, projected increases in other developmental and recreational access to the desert regions (California Energy Commission, 2017) may justify requiring more rapid rehabilitation of the temporarily impacted lands. Active restoration emphasizing shrub salvage and weed control promoting the establishment of native species and deterring nonnative species may expedite vegetation recovery on impacted lands. Studies focused on identifying specific active restoration techniques pertinent to impact types and impact locations may help with future land management decisions.

3.6. Tables

Table 3-1. List of perennial species and the number of towers where they were observed. *Larrea tridentata* and *Ambrosia dumosa* are the dominant species.

Scientific Name	**Distance from Impact Site**					
	0–2 m	**2–4 m**	**4–6 m**	**6–8 m**	**8–10 m**	**100–102m**
Ambrosia dumosa	9	9	9	9	9	13
Ambrosia salsola	0	1	1	1	0	1
Circidium floridum = Parkinsonia florida	0	0	0	0	1	1
Croton californicus	1	0	0	0	0	0
Cylindropuntia echinocarpa	1	0	0	0	0	0
Cylindropuntia ramosissima	0	0	0	0	2	0
Encelia farinosa	1	0	0	0	0	0
Fouquieria splendens	1	0	0	0	0	0
Hilaria rigida	3	1	2	4	1	4
Krameria erecta	2	1	3	1	2	2
Larrea tridentata	19	16	13	12	14	18
Olneya tesota	0	1	2	0	1	1
Opuntia basilaris	0	0	0	0	1	0
Number of species	**8**	**6**	**6**	**5**	**8**	**7**

Table 3-2. List of annual species and the number of towers where they were observed. Species with asterisk (*) are nonnative species.

Scientific Name	**Distance from Impact Site**					
	0–2 m	**2–4 m**	**4–6 m**	**6–8 m**	**8–10 m**	**100–102 m**
Allionia incarnata	1	1	0	1	2	1
Aristida adscesionis	8	6	7	6	5	6
Atriplex sp.	0	0	1	0	0	0
Camissonia sp.	0	0	0	0	0	1
Chaenactis fremontii	5	3	2	3	4	6
Chorizanthe brevicornu	1	1	0	2	2	1
Chorizanthe rigida	1	0	0	0	1	0
Chylismia claviformis	0	0	0	1	0	1
Cryptantha angustifolia	1	1	2	2	2	0
Cryptantha sp.	2	3	2	0	4	1
Ditaxis lanceolata	0	1	0	1	1	0
Ditaxis neomexicana	2	1	0	0	0	0
Eremalche rotundifolia	0	0	0	0	1	0
Eriogonum thomasii	2	2	3	2	1	3
*Erodium cicutarium**	0	1	1	1	2	0
Euphorbia micromeria	6	7	6	6	7	7
Lepidium lasiocarpum	1	0	0	0	0	0
Lupine sp.	0	0	0	0	1	0
Pectocarya heterocarpa	0	1	0	1	0	1
Pectocarya penicillata	2	2	2	2	2	2
Pectocarya recurvata	1	0	1	1	2	2
Plantago ovata	2	1	3	3	2	2
*Schismus barbatus**	2	2	2	1	1	1
*Tribulus terrestris**	1	0	0	0	0	1
Lichen spp.	3	3	5	4	5	4
Number of Species	**17**	**16**	**13**	**16**	**18**	**16**

3.7. Figures

Figure 3-1. Lattice steel transmission towers in the lower Colorado Desert.

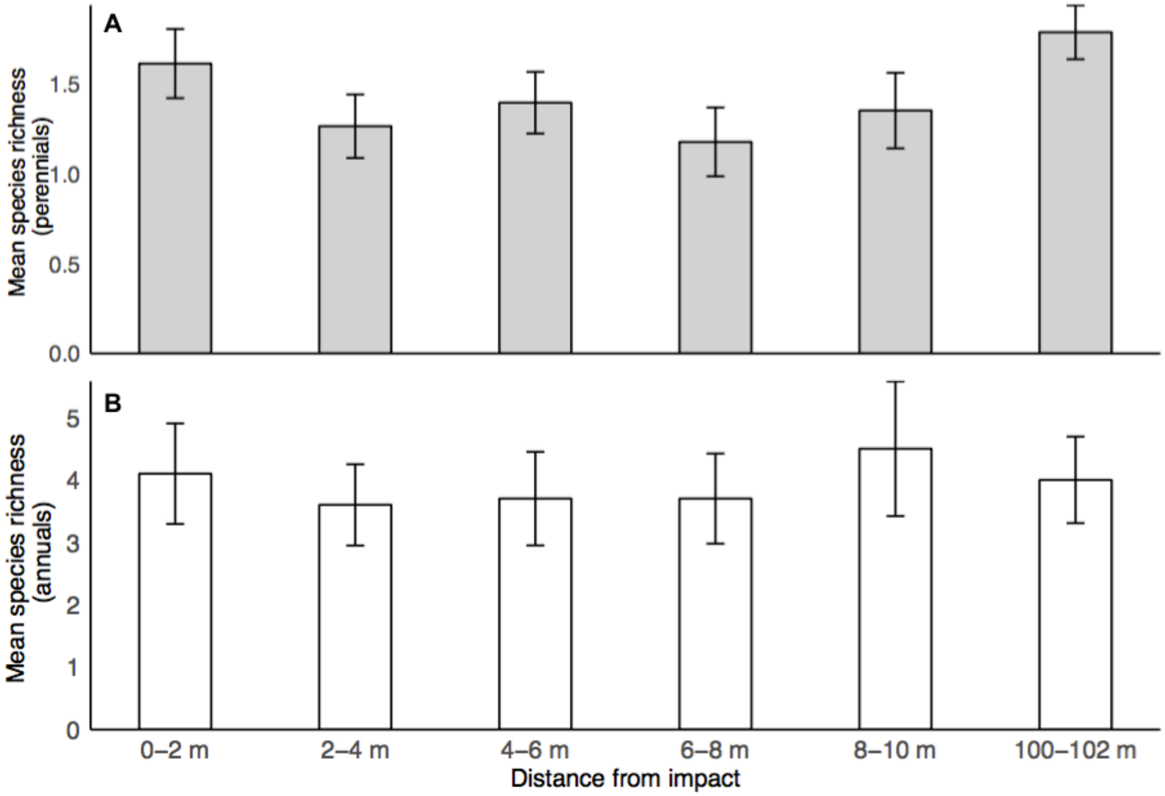

Figure 3-2. Mean species richness with distance from tower for perennial species (A) and annual herbaceous species (B). Error bars represent the standard error of the mean.

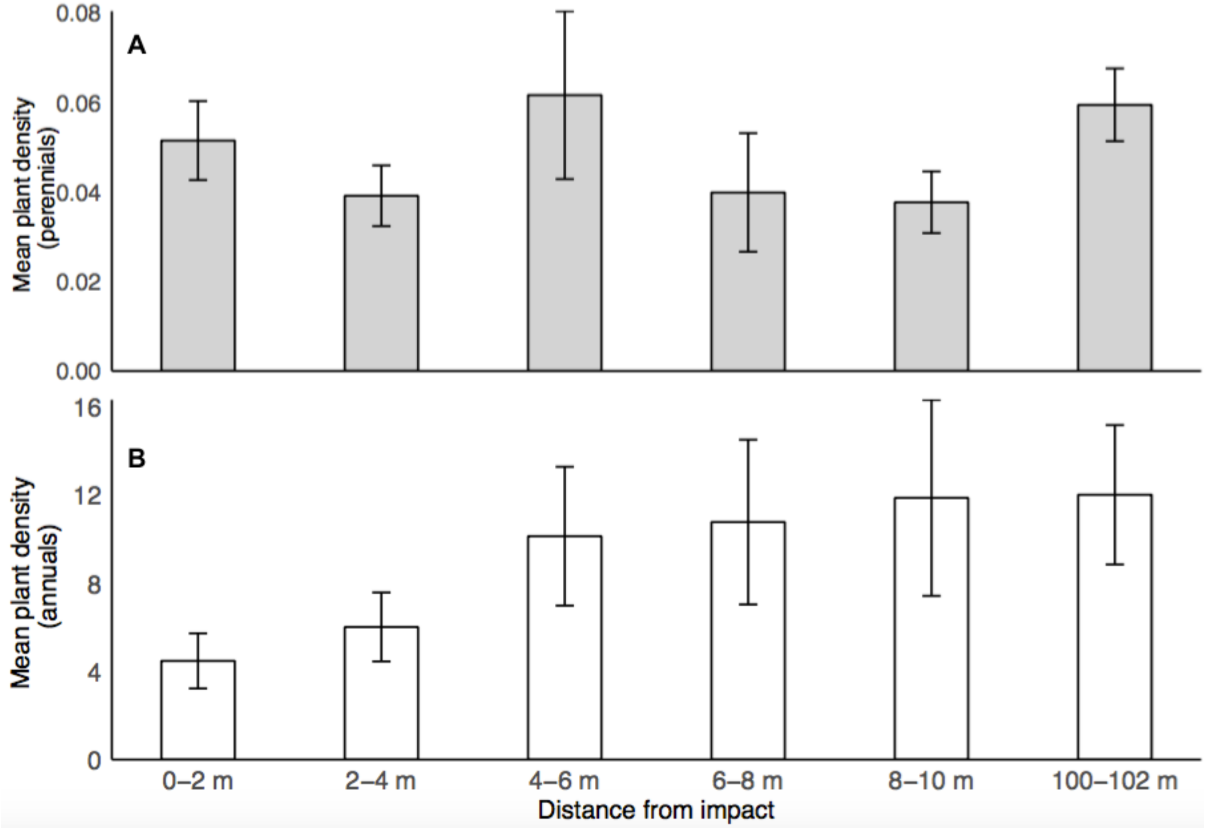

Figure 3-3. Mean plant density with distance from tower for perennial species (A) and annual herbaceous species (B). Error bars represent the standard error of the mean.

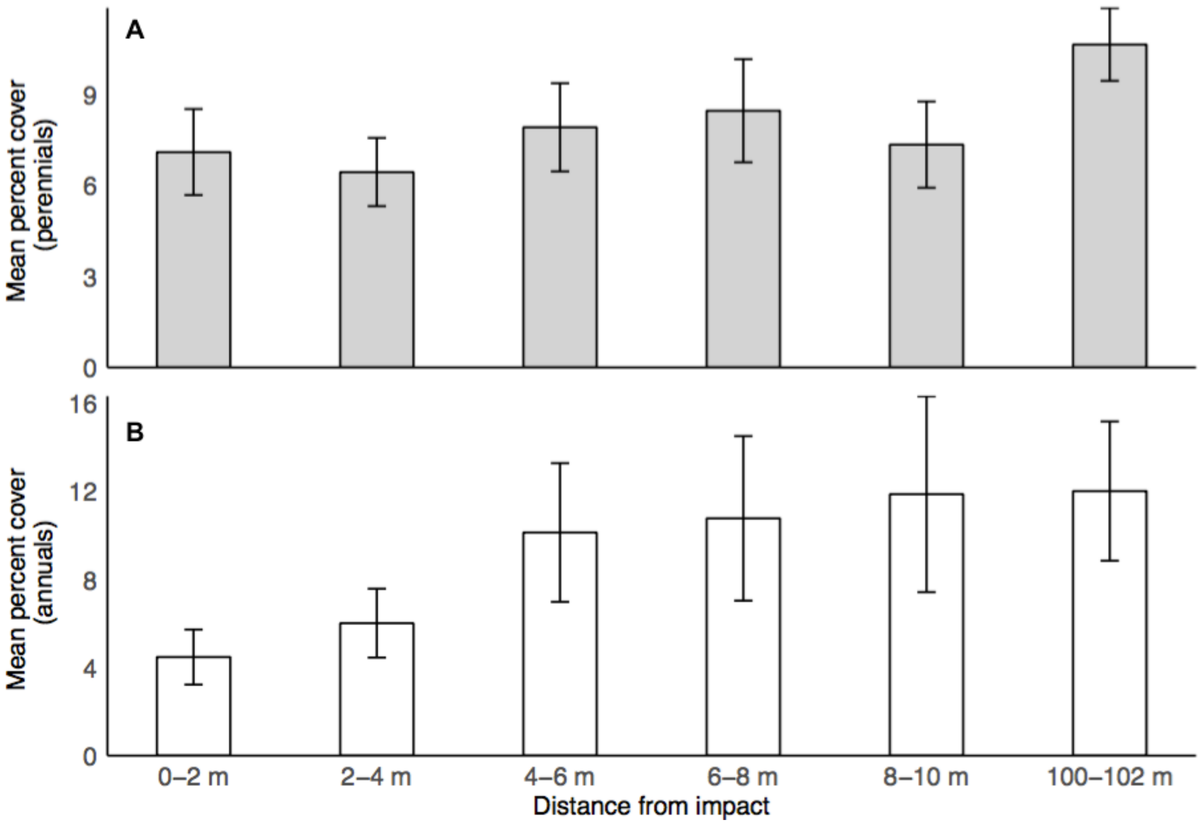

Figure 3-4. Mean percent cover with distance from tower for perennial species (A) and annual herbaceous species (B). Error bars represent the standard error of the mean.

3.8. Appendix

The ANOVA results of the analysis conducted in the main paper are presented in tables A3-1– A3-6.

In the appendix section, the data were analyzed five additional ways for the perennials and two additional ways for the annual species (Table A3-7). Out of the 23 towers sampled for this study, several towers had washes traversing through some of the belt transects. In this section, the towers with washes were excluded and a total of 10 towers were analyzed for the perennials. The data were analyzed for only 10 towers in the main paper as well as in the appendix for the annuals.

The first method of analysis in the appendix for both perennials and annuals utilized data recorded in the belt transects at 0 m, 8 m, and 100 m. For perennials, this analysis was performed with data from all 23 towers and from the 10 selected towers. For annuals, the analysis was performed with data from the same 10 towers analyzed in the main section of the paper.

In the second method of analysis for both perennials and annuals, data collected at distances 0 m and 2 m were averaged. Similarly, the data collected at distances 6 m and 8 m were averaged. The average values represented two distances, 0–4 m and 6–10 m respectively. For perennials, this analysis was conducted with data from all 23 towers and the 10 selected towers. For annuals, the analysis was conducted using the data from the same 10 towers analyzed in the main section of the paper.

Figures A3-1–3-5 show the pattern of mean species richness for perennials and annuals with distance from impact. Figures A3-6–3-10 show the pattern of mean plant density for perennials and annuals with distance from impact. Figures A3-11–3-15 show the mean percent cover trend for perennials and annuals with distance from impact.

Following the reorganization of the data, ANOVAs were conducted to determine if there was a statistically significant difference in species richness, plant density, and percent cover between the impact transects and the control transect (Table A3-8). The ANOVA comparing the species richness of perennials from the two transects with averaged data (0–4 m and 6–10 m) to the data of the control transect resulted in a p-value equal to 0.05. This is the only instance where the difference is significant. Otherwise, the results obtained in the main section of the paper are echoed in the appendix.

3.8.1. Tables

Table A3-1. ANOVA results of species richness analysis with data (perennials) from all 23 towers.

Source of Variation	SS	df	MS	F	P-value
Between Groups	5.95	5.00	1.19	1.48	0.20
Within Groups	105.83	132.00	0.80		
Total	111.78	137.00			

Table A3-2. ANOVA results of plant density analysis with data (perennials) from all 23 towers.

Source of Variation	SS	df	MS	F	P-value
Between Groups	0.01	5.00	0.00	0.87	0.50
Within Groups	0.40	132.00	0.00		
Total	0.42	137.00			

Table A3-3. ANOVA results of percent plant cover analysis with data (perennials) from all 23 towers.

Source of Variation	SS	df	MS	F	P-value
Between Groups	0.03	5	0.01	1.07	0.38
Within Groups	0.62	132	0.00		
Total	0.65	137			

Table A3-4. ANOVA results of species richness analysis with data (annuals) from 10 towers.

Source of Variation	SS	df	MS	F	P-value
Between Groups	5.73	5	1.15	0.16	0.98
Within Groups	380.00	54	7.04		
Total	385.73	59			

Table A3-5. ANOVA results of plant density analysis with data (annuals) from 10 towers.

Source of Variation	SS	df	MS	F	P-value
Between Groups	509.03	5	101.81	0.95	0.46
Within Groups	5772.62	54	106.90		
Total	6281.66	59			

Table A3-6. ANOVA results of percent cover analysis with data (annuals) from 10 towers.

Source of Variation	SS	df	MS	F	P-value
Between Groups	0.05	5	0.01	0.95	0.46
Within Groups	0.58	54	0.01		
Total	0.63	59			

Table A3-7. Table showing the different methods of analyses and the location of the results in the paper for both perennials and annuals.

Section	**Description**	**Distance from Impact Site**					
		0–2 m	2–4 m	4–6 m	6–8 m	8–10 m	100–102 m
	Perennials						
Main Paper	0–2 m, 2–4 m, 4–6 m, 6–8 m, 8–10 m, 100–102 m, 23 towers	x	x	x	x	x	x
Appendix	0–2 m, 2–4 m, 4–6 m, 6–8 m, 8–10 m, 100–102 m, 10 towers	x	x	x	x	x	x
Appendix	0–2 m, 8–10 m, 100–102 m, 23 towers	x				x	x
Appendix	0–2 m, 8–10 m, 100-102 m, 10 towers	x				x	x
Appendix	Average of (0–4 m) and (6–8 m), 100–102 m, 23 towers	x	x		x	x	x
Appendix	Average of (0–4m) and (6–8m), 100–102 m, 10 towers	x	x		x	x	x
	Annuals						
Main Paper	0–2 m, 2–4 m, 4–6 m, 6–8 m, 8–10 m, 100–102 m, 10 towers	x	x	x	x	x	x
Appendix	0–2 m, 8–10 m, 100–102 m, 10 towers	x				x	x
Appendix	Average of (0–4 m) and (6–8 m), 100–102 m, 10 towers	x	x		x	x	x

Table A3-8. ANOVA p-values for the various analyses for both perennials and annuals.

Section	Description	ANOVA P-Value		
		Plant Density	Species Richness	Percent Cover
Perennials				
Main Paper	0–2 m, 2–4 m, 4–6 m, 6–8 m, 8–10 m, 100–102 m, 23 towers	0.50	0.20	0.38
Appendix	0–2 m, 2–4 m, 4–6 m, 6–8 m, 8–10 m, 100-102 m, 10 towers	0.66	0.92	0.78
Appendix	0–2 m, 8–10 m, 100–102 m, 23 towers	0.17	0.27	0.14
Appendix	0–2 m, 8–10 m, 100–102 m, 10 towers	0.75	0.83	0.86
Appendix	Average of (0–4 m) and (6–8 m), 100–102 m, 23 towers	0.13	**0.05**	0.10
Appendix	Average of (0–4 m) and (6–8 m), 100–102 m, 10 towers	0.49	0.55	0.61
Annuals				
Main Paper	0–2 m, 2–4 m, 4–6 m, 6–8 m, 8–10 m, 100–102 m, 10 towers	0.46	0.98	0.45
Appendix	0–2 m, 8–10 m, 100–102 m, 10 towers	0.22	0.92	0.22
Appendix	Average of (0–4 m) and (6–8 m), 100–102 m, 10 towers	0.29	0.58	0.27

3.8.2. Figures

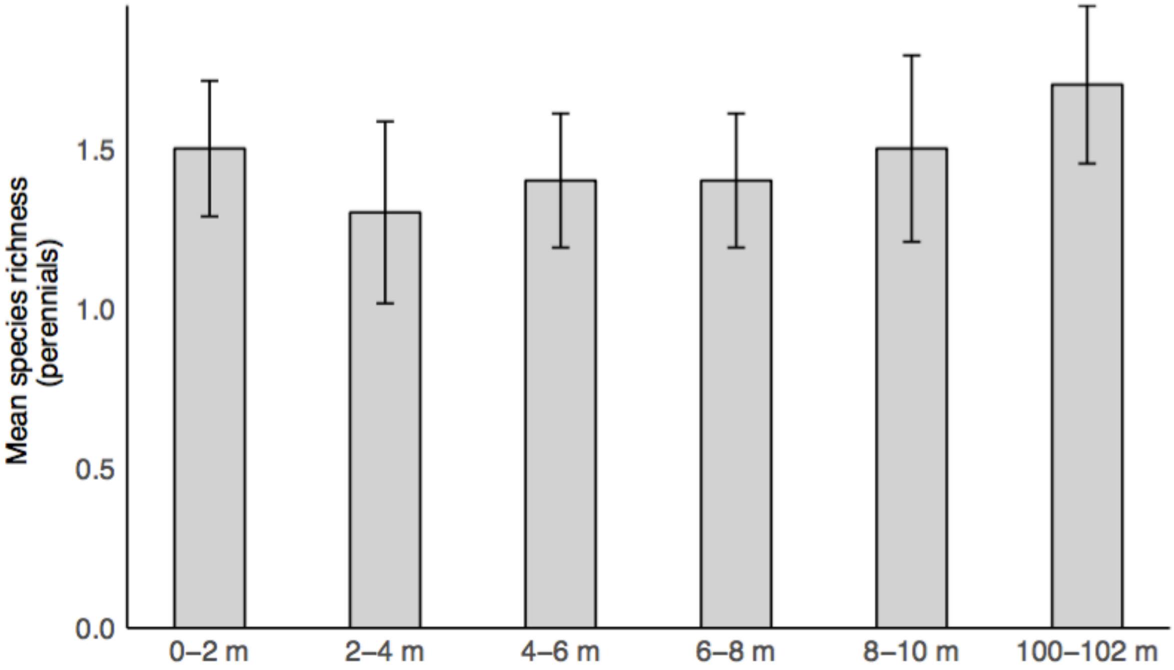

Figure A3-1. Pattern of mean species richness with distance from tower for perennial species at 10 towers. Error bars represent the standard error of the mean.

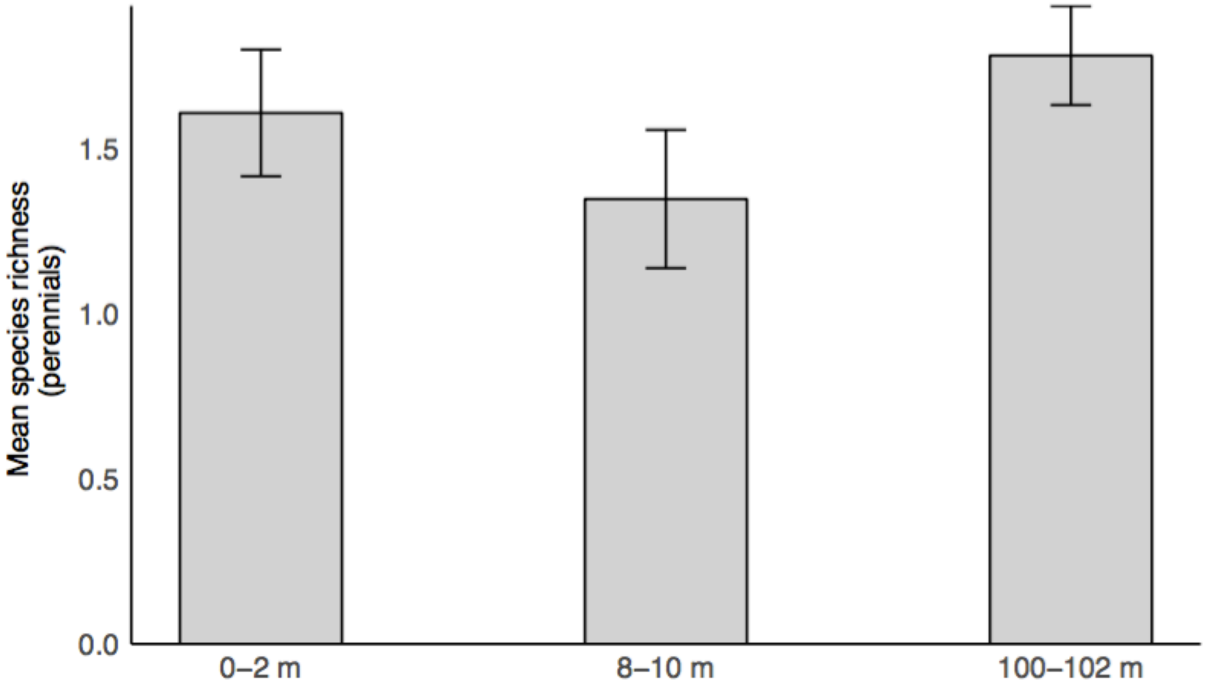

Figure A3-2. Pattern of mean species richness with distance from tower for perennial species at 23 towers. Error bars represent the standard error of the mean.

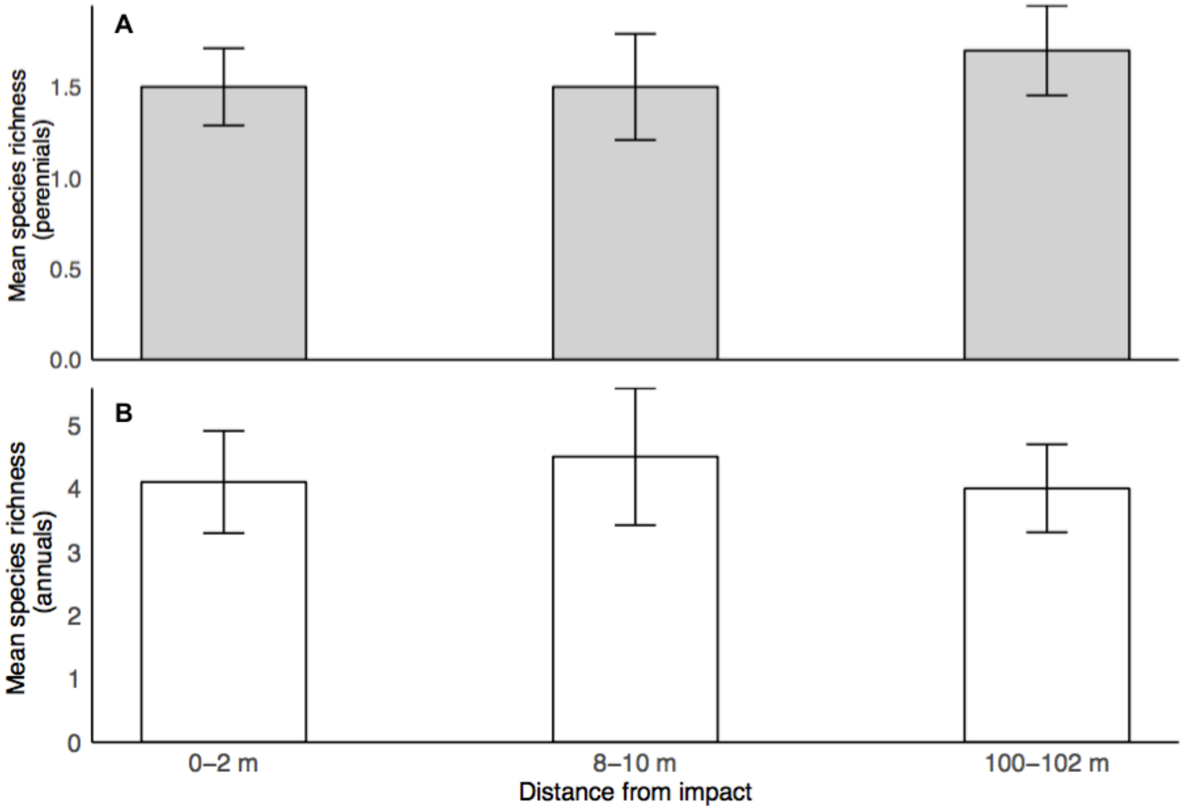

Figure A3-3. Pattern of mean species richness with distance from tower for perennial species (A) and annual herbaceous species (B). Data are from 10 towers for both perennials and annuals. Error bars represent the standard error of the mean.

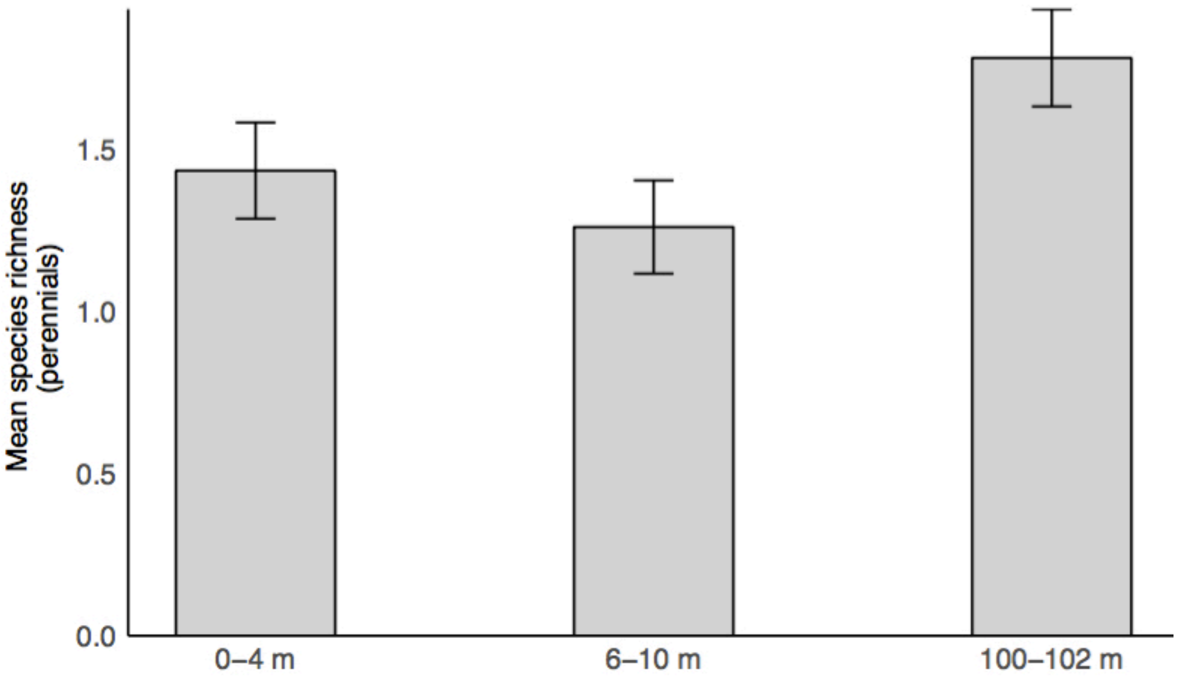

Figure A3-4. Pattern of mean species richness with distance from tower for perennial species at 23 towers. Error bars represent the standard error of the mean. The first and second bars are averages of the data of the transects traversing 0–4 m and 6–10 m respectively.

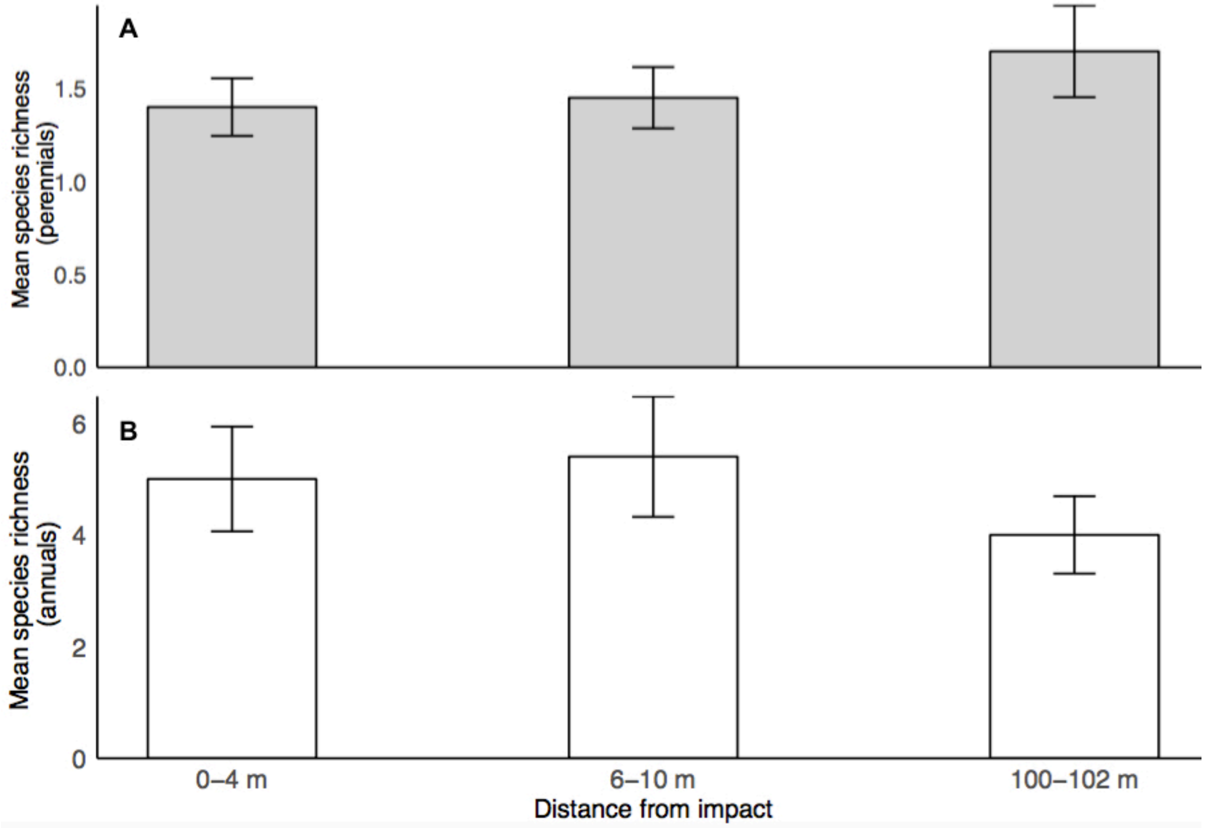

Figure A3-5. Pattern of mean species richness with distance from tower for perennial species (A) and annual herbaceous species (B) at 10 towers. Error bars represent the standard error of the mean. The first and second bars are averages of the data of the transects traversing 0–4 m and 6–10 m respectively.

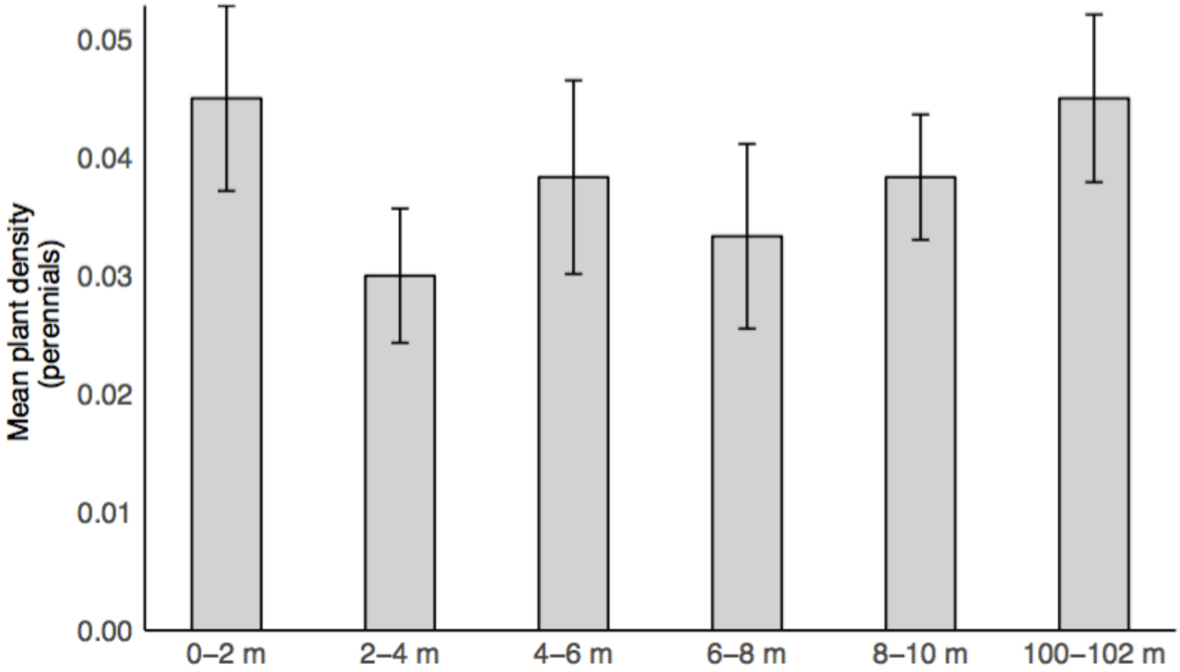

Figure A3-6. Pattern of mean plant density with distance from tower for perennial species at 10 towers. Error bars represent the standard error of the mean.

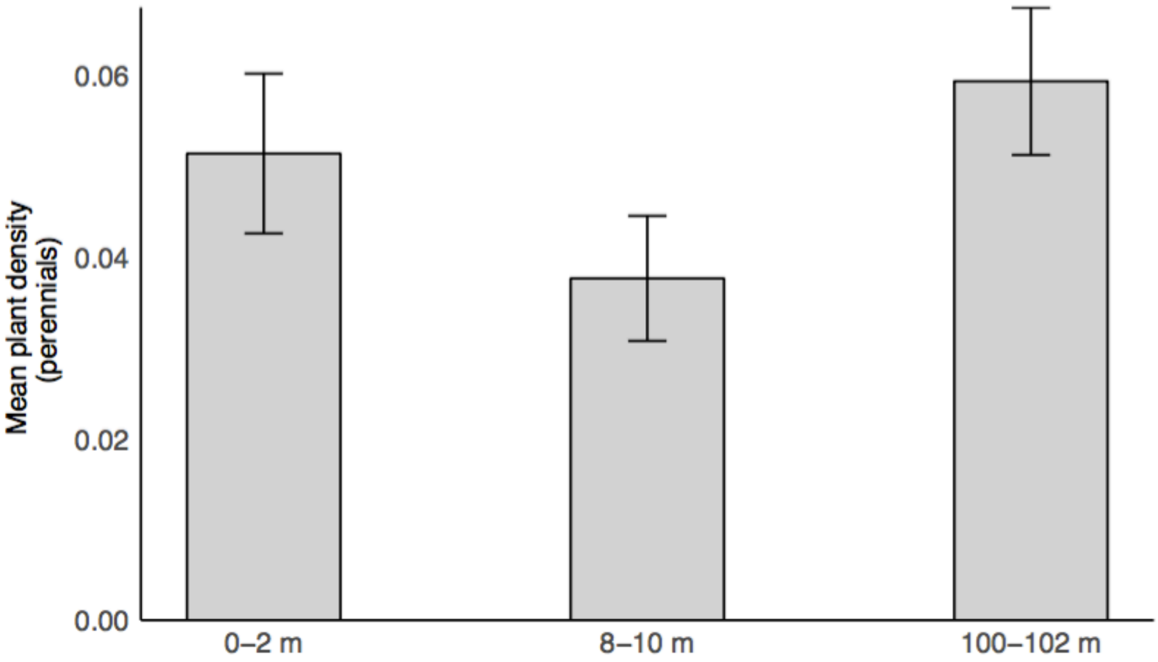

Figure A3-7. Pattern of mean plant density with distance from tower for perennial species at 23 towers. Error bars represent the standard error of the mean.

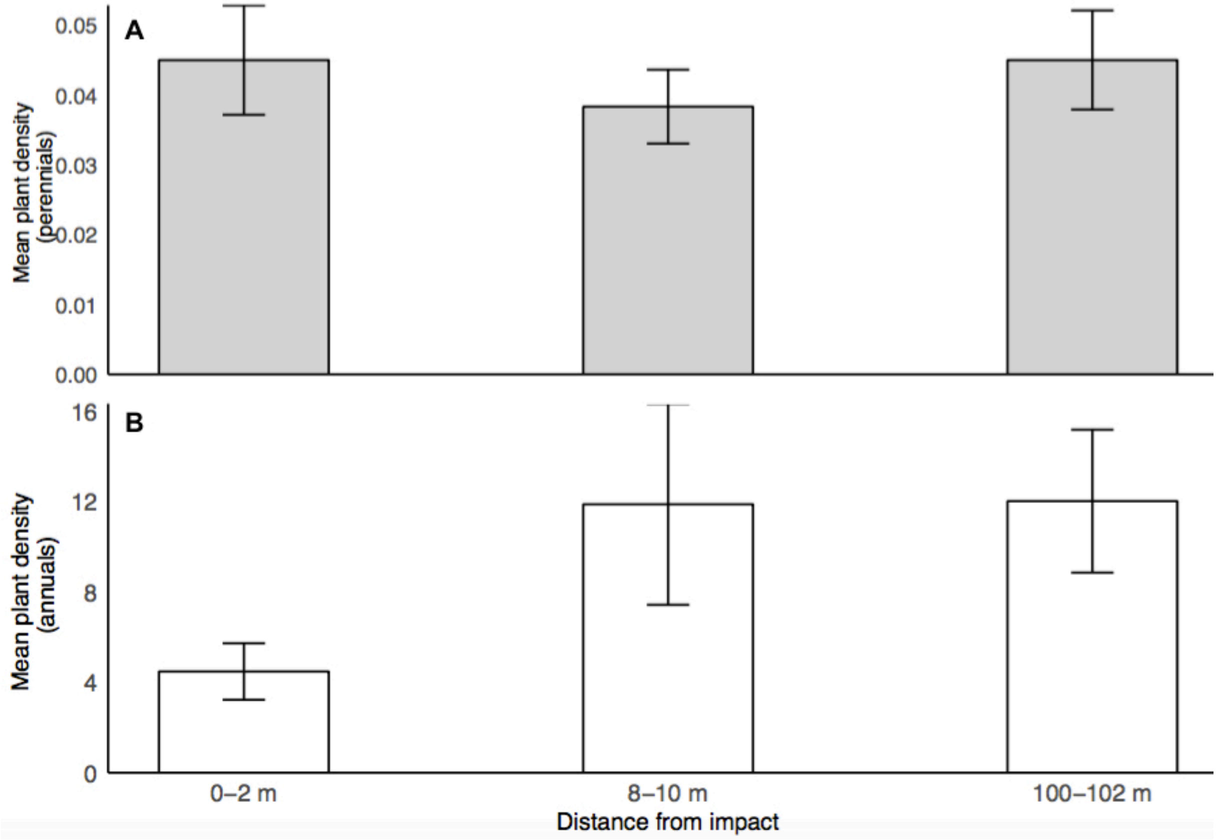

Figure A3-8. Pattern of mean species richness with distance from tower for perennial species (A) and annual herbaceous species (B). Data are from 10 towers for both perennials and annuals. Error bars represent the standard error of the mean.

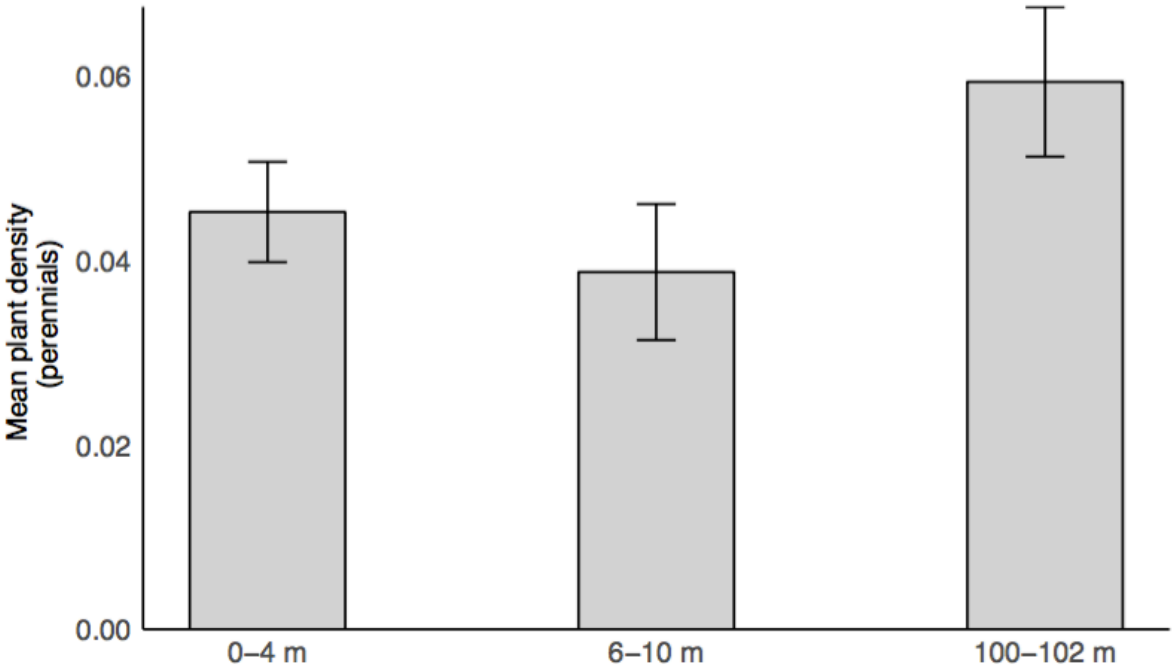

Figure A3-9. Pattern of mean plant density with distance from tower for perennial species at 23 towers. Error bars represent the standard error of the mean. The first and second bars are averages of the data of the transects traversing 0–4 m and 6–10 m respectively.

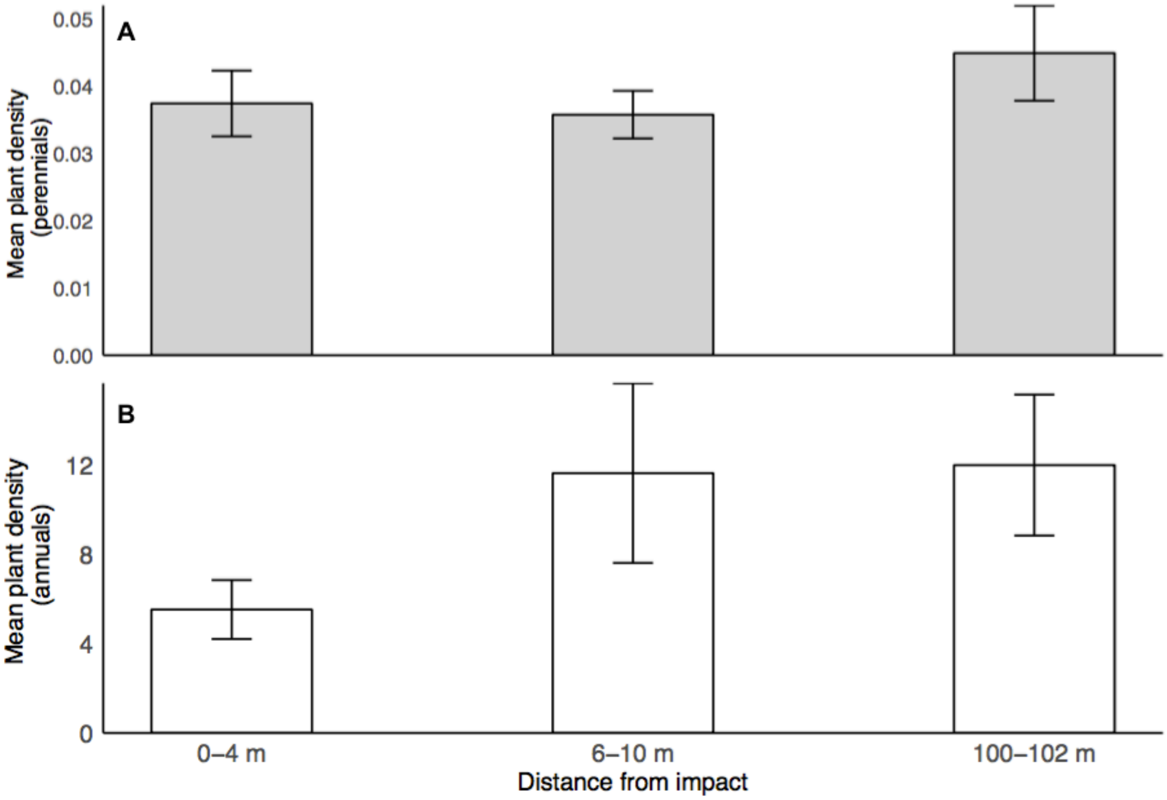

Figure A3-10. Pattern of mean plant density with distance from tower for perennial species (A) and annual herbaceous species (B) at 10 towers. Error bars represent the standard error of the mean. The first and second bars are averages of the data of the transects traversing 0–4 m and 6–10 m respectively.

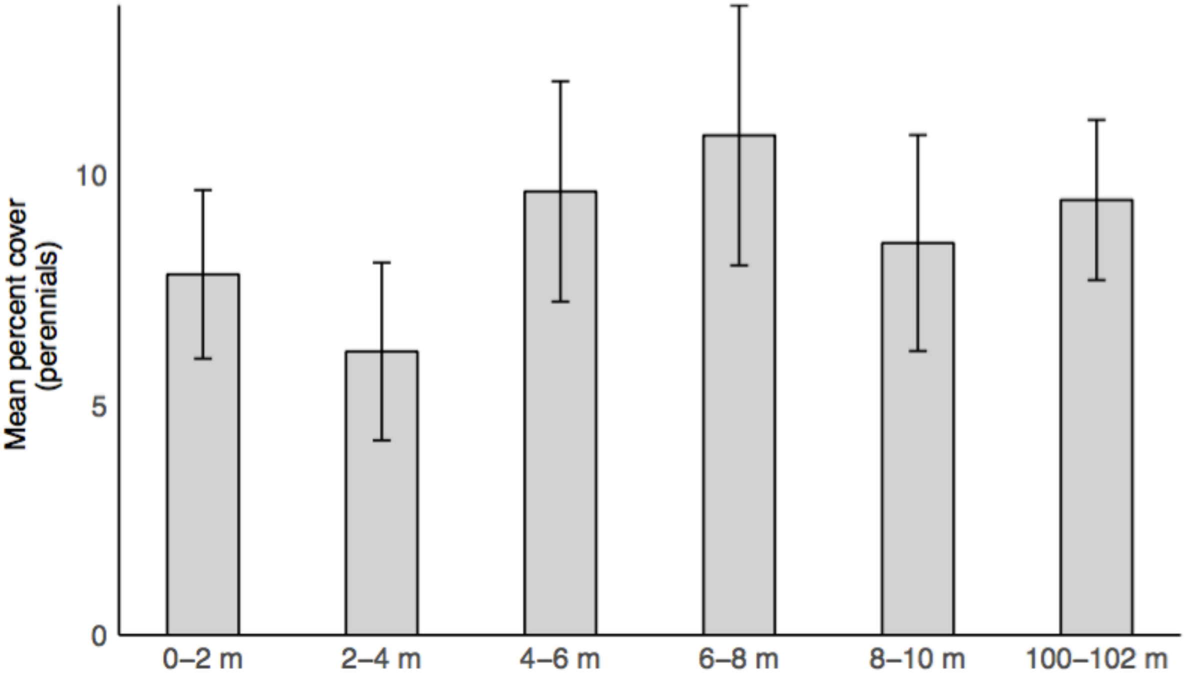

Figure A3-11. Pattern of mean percent cover with distance from tower for perennial species at 10 towers. Error bars represent the standard error of the mean.

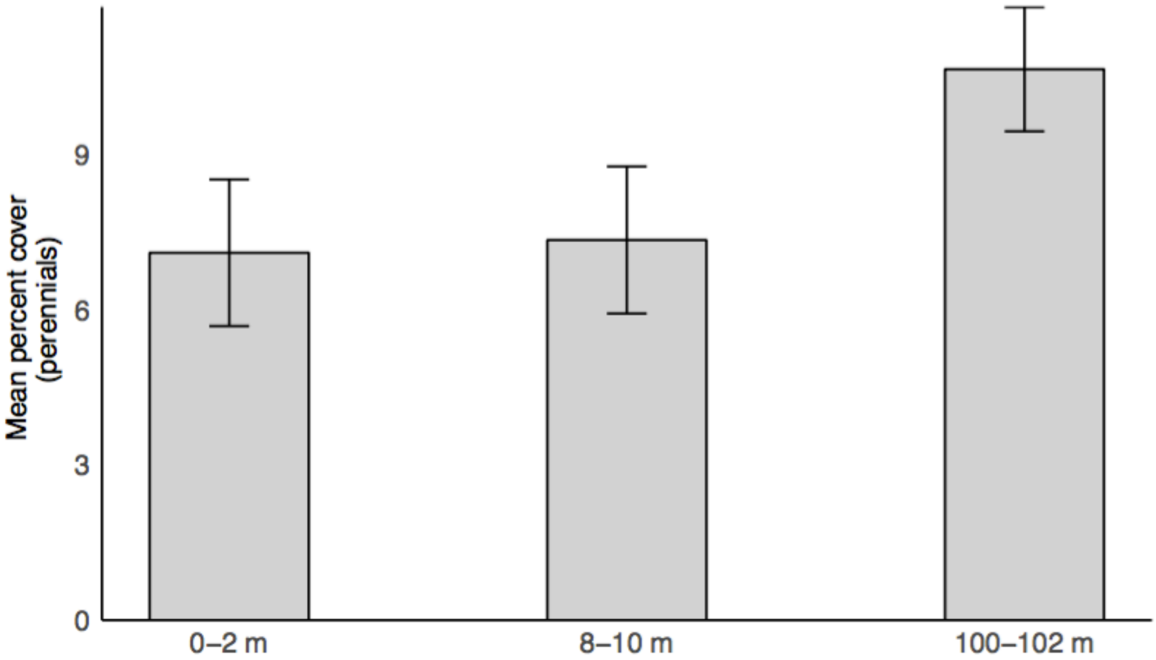

Figure A3-12. Pattern of mean percent cover with distance from tower for perennial species at 23 towers. Error bars represent the standard error of the mean.

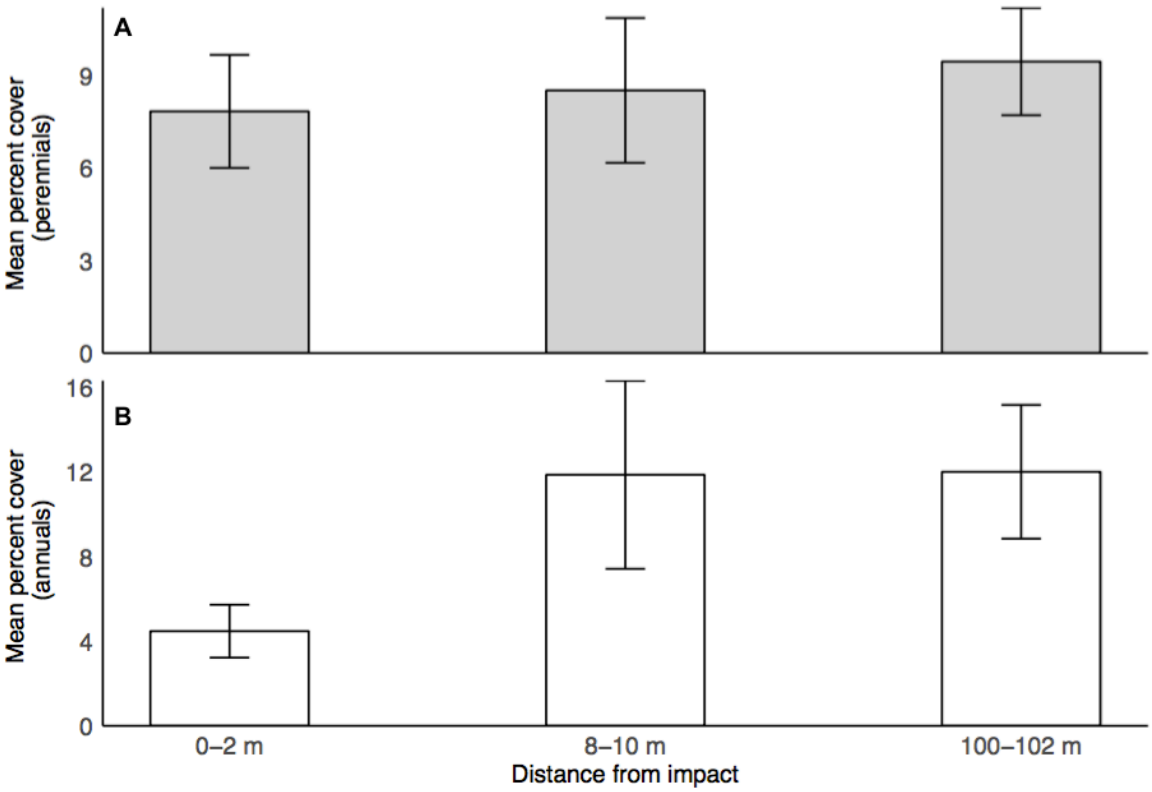

Figure A3-13. Pattern of mean percent cover with distance from tower for perennial species (A) and annual herbaceous species (B). Data are from 10 towers for both perennials and annuals. Error bars represent the standard error of the mean.

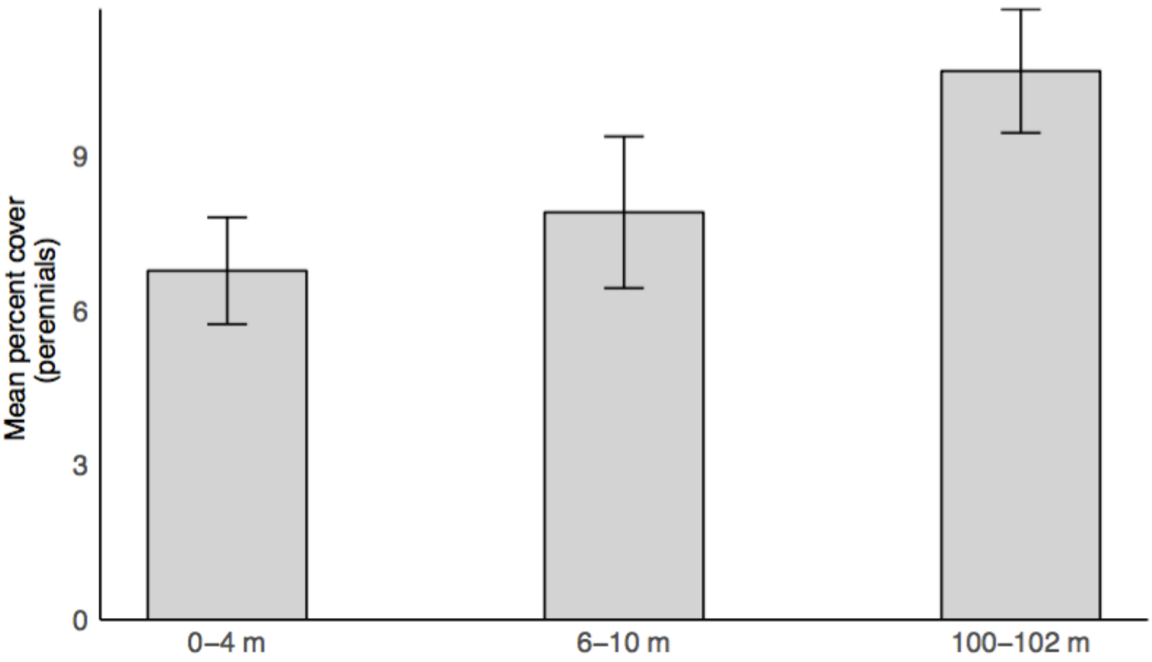

Figure A3-14. Pattern of mean percent cover with distance from tower for perennial species at 23 towers. Error bars represent the standard error of the mean. The first and second bars are averages of the data of the transects traversing 0–4 m and 6–10 m respectively.

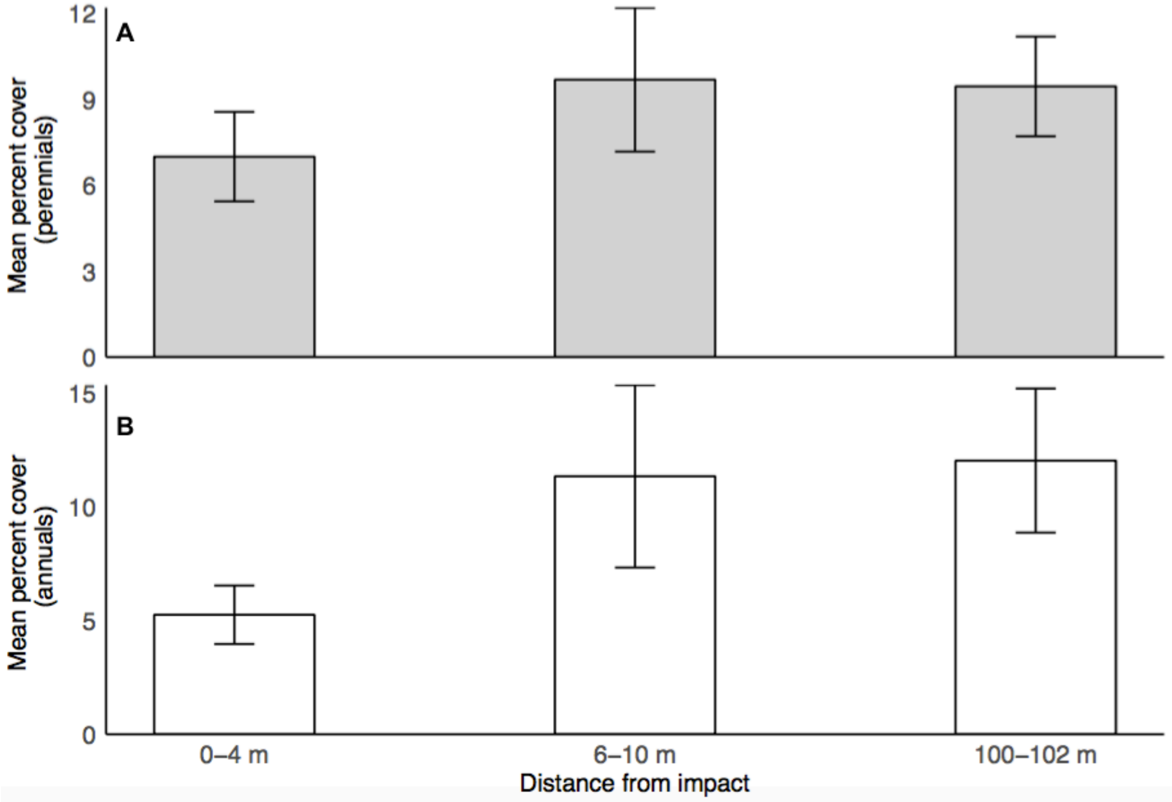

Figure A3-15. Pattern of mean percent cover with distance from tower for perennial species (A) and annual herbaceous species (B) at 10 towers. Error bars represent the standard error of the mean. The first and second bars are averages of the data of the transects traversing 0–4 m and 6–10 m respectively.

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CHAPTER 4

Soil Recovery on Lands Disturbed During Transmission Power Line Construction in the Colorado Desert of Southern California

4.1. Abstract

This study examined both the long-term (31 years since impact) and short-term (less than 1 year since impact) effects of transmission power line construction on soil characteristics. Bulk density, compaction, infiltration rate, soil organic matter, moisture content, soil carbon stocks, pH, salinity, and texture (sand content) were examined in an area dominated by creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*) in the lower Colorado Desert in southern California. The impact sites included areas impacted during transmission tower construction and conductor (wire) pulling and splicing. Soil characteristics measured at the tower and wire sites were found to be similar and both sites were treated as replicates for all further data analyses. Compaction at 3 cm from surface was significantly higher when compared to control at both the old ($p < 0.05$) and new ($p < 0.05$) impact sites. No significant differences were observed between the control and old impact sites for the rest of the soil characteristics analyzed. Both soil organic matter and carbon stocks to a depth of 8 cm were significantly higher at the new impact when compared to control ($p < 0.05$). Significant differences between control and new impact sites for rest of the soil characteristics were not observed, though bulk density, salinity, and pH appeared slightly different with $p < 0.1$. Lastly, the "fertile island" effect was examined by comparing measurements from under creosote bush canopies to the measurements from the bare ground located in between shrubs. There were statistically significant differences observed for all soil

characteristics except for moisture content, texture, and compaction (psi) at 3 cm. Results of the study suggest that surface compaction is likely a primary effect of construction activities with no significant impacts on other soil characteristics including compaction at 5 cm The results also support the fertile island effect characteristic of arid lands.

4.2. Introduction

Increases in population and urbanization have resulted in greater utility demand, and consequently, increases in associated environmental impacts (Abella, 2010). Growing demand and incentives for development of renewable sources of energy is leading to increases in the construction solar, wind, and electric power infrastructure in the deserts of southern California, resulting in disturbances to the desert landscape (Abella, 2010; California Energy Commission, 2017; Lathrop and Archbold, 1980a, 1980b; Lovich and Bainbridge, 1999; Reible et al., 1982; Tsoutsos et al., 2005; Vasek et al., 1975a, 1975b; Walsh and Hoffer, 1991). Land is cleared of vegetation during gas pipeline, aqueduct, and transmission power line construction for trenching, piling, refilling, grading, campsites, storage areas, tower sites, conductor pulling and splicing sites, and service roads (Brum et al., 1983; Lathrop and Archbold, 1980a, 1980b; Lovich and Bainbridge, 1999; Vasek et al., 1975a, 1975b). Removal of vegetation and loosening of the soil can also increase erosion and fugitive dust release (Grantz et al., 1998; Lovich and Bainbridge, 1999). Critical nutrients, such as nitrogen and phosphorus, are localized in the surface soil and erosion can disrupt this characteristic of soils (Bainbridge, 2012; Bolling and Walker, 2000; Lovich and Bainbridge, 1999; Schlesinger et al., 1996). Impacts to the soil affecting this vertical heterogeneity of soil nutrient distribution can then affect vegetation establishment and succession for several years after the disturbance (Bolling and Walker, 2000; Schlesinger et al., 1996). Heavy equipment used for construction, digging, and transport of materials can affect soil characteristics by increasing compaction (Bolling and Walker, 2000; Lovich and Bainbridge, 1999; Webb, 2002) and disrupting the soil surface stabilizers (Lovich and Bainbridge, 1999; Webb and Wilshire, 2012).

Islands of higher soil fertility under perennial shrubs relative to adjacent open areas is a characteristic feature of desert ecosystems (Bolling and Walker, 2002; Schlesinger et al., 1996; Thompson et al., 2005; Walker et al., 2001) This spatial heterogeneity in soil attributes in arid and semi-arid regions is well-documented (Herman et al., 1995; Morris et al., 2013; Titus et al., 2002; Walker et al., 2001; Wezel et al., 2000; Whitford et al., 1997; Wright and Honea, 1986). The physical presence of shrubs can influence soil properties (Charley and West, 1975; Dunkerley, 2000; Pressland, 1976; Rostagno et al., 1991; Titus et al., 2002). Animals burrowing under shrubs can increase soil aeration and water infiltration to the deeper soil layers (Garner and Steinberger, 1989; Walker et al., 2001). These “fertile islands” under shrubs are characterized by higher levels of organic matter from build-up of plant litter, animal waste and entrapment of wind-blown debris, soil nutrients and nutrient turnover, higher water content, and higher infiltration rates (Walker et al., 2001). Disturbances to the shrubs and the soil could possibly alter these spatial differences in soil resources and in turn affect habitat recovery (Hoover and Germino, 2012; Morris et al., 2013; Sankey et al., 2012).

Active rehabilitation of severely compacted soils can be expensive as it usually requires decompacting the soils with heavy equipment so most sites disturbed in the past have been abandoned without active soil restoration (Webb, 2002). Recovery of soil properties to pre-disturbance conditions can be a very slow process in arid environments (Kade and Warren, 2002). Repeated cycles of clay-mineral expansion during wetting, freezing and thawing, and biological activity are required for the loosening of highly compacted soils (Webb, 2002; Webb et al., 1983). These processes occur at a slower rate and intensity in arid regions, retarding the recovery of soil and vegetation (Belnap and Warren, 2002).

Soil is essential to the recovery of the desert habitat after an impact and the degree of soil compaction can be a major determinant of the rate of recovery and vegetation succession (Bolling and Walker, 2000; Knapp, 1991; Webb et al., 1987). Soil compaction is defined as the increase in soil density and strength resulting from the application of forces to a soil mass (Webb and Wilshire, 2012). Various land uses in the desert may lead to severely compacted soils, including military exercises, off-road vehicle use, livestock grazing, and construction of utility corridors (Bolling and Walker, 2000; Lovich and Bainbridge, 1999; Prose and Wilshire, 2000; Vasek et al., 1975a, 1975b; Webb, 2002; Webb and Wilshire, 2012). Most studies have focused on long-sustained impacts associated with abandoned towns and military training areas, presumably with minimal subsequent use, to help provide information on natural recovery rates of severely compacted soils (Knapp, 1992; Prose and Wilshire, 2000; Webb, 2002; Webb and Wilshire, 1980). Knapp (1991) found significant differences in vegetation structure between impact and reference sites 77 years following disturbances on abandoned roads in mining towns in Montana. Individual tank tracks from the military exercises during World War II and in 1964 were still visible in the Mojave Desert 50-60 years after the disturbance (Belnap and Warren, 2002; Prose and Wilshire, 2000). Webb and Wilshire (1980) discovered that soils were still highly compacted 51 years after a town was abadoned in southern Nevada. They also observed that creosote bush (*Larrea tridentata*) was conspicuously absent and suggested that it was incapable of establishing in compacted soil conditions. Webb (2002) studied natural recovery of soil on land in the Mojave Desert impacted by military training exercises and abandoned towns and estimated that recovery of the soil can take at least 100 years or longer.

Impacts associated with construction of transmission power lines can be classified as temporary and permanent impacts. Permanent impacts include the clearing of vegetation and impacts to the soil from construction of the service road along with the short spur roads connecting each tower to the service road. These roads are maintained throughout the life of the line and are used for repair and maintenance access. Temporary impacts include vegetation clearing/mowing associated with tower installation, campsites, staging areas, and heavy ground equipment usage to complete all activities associated with construction (Brum et al., 1983; Lathrop and Archbold, 1980b; Rorabaugh, 2013). Besides compaction of soils from traffic and heavy ground equipment, transmission power line construction may also affect other characteristics of soils including but not limited to the texture, infiltration rate, moisture content, and organic matter content (Bainbridge, 2012).

This study focuses on effects of temporary impacts associated with tower installation (tower sites) and pulling and splicing of the conductor wires (wire sites) on soil characteristics. Construction involves the clearing of vegetation and usage of heavy equipment. Soil compaction is likely a primary effect of construction. The main objective of this study is to evaluate the current status of soil characteristics in sites impacted during construction relative to adjacent undisturbed control sites. Data collected along two transmission power lines, one constructed 31 years ago and one constructed less than a year before sampling, are used to assess short-term and long-term effects of construction. The second objective is to determine if the presence of shrubs affects soil characteristics. The hypotheses are: 1. Soil characteristics measured at the old impact sites and undisturbed control sites will be indistinguishable (signaling recovery) but those measured at the new impact sites will be different from the control sites (indicating impact); and 2. Soil characteristics measured under shrub canopies will be significantly different from the respective soil characteristics measured in the bare ground between shrubs.

4.3. Methods

The study area was located along an approximately 60 km segment of transmission lines operated and maintained by the Southern California Edison Company (SCE) traversing through the Colorado Desert between 33°39’47” N, 115°58’23” W and 33°35’34” N, 114°50’45” W. The Colorado Desert is the western part of the Sonoran Desert and is located mostly in California’s Riverside and Imperial Counties. It is located at a lower elevation than the Mojave Desert to the north and much of the land lies below 1,000 feet in elevation. The climate is very arid, with as little as 127 mm (5 inches) of precipitation per year (California Public Utilities Commission, 2006). There is a biseasonal rainfall pattern with winter frontal systems and summer convectional storms (Burk, 1977; Lovich and Bainbridge, 1999). The sampling area is composed of broad alluvial valley floors dominated by creosote bush (*Larrea tridentata*) in association with white bursage (*Ambrosia dumosa*) on rocky mountain slopes, bajadas or intergraded slopes, and desert washes (personal observation and California Public Utilities Commission, 2006). This study focused on the impacts of transmission power line construction on the soil and its recovery over time. Sampling sites included areas temporarily disturbed during the construction of the two transmission lines. The first line was constructed in the early 1980s (1980–1982) and is called Devers-Colorado River No.1, or DCR1. The second transmission line, constructed recently (2011–2013), runs parallel to DCR1 and is called Devers-Colorado River No. 2 or DCR2. Both DCR1 and DCR2 are composed of numerous lattice steel transmission towers supporting cable (wires) conducting electricity over 250 km including the study area (Figure 4-1).

The sampling area is dominated by the Vaiva-Quilotosa-Hyder-Cipriano-Cherioni soil complex along both the DCR1 and DCR2 alignments (USDA-NRCS, 2017). This segment was selected to avoid areas with excessively sandy or rocky soil and because of the uniformity observed in terms of the dominant vegetation type, plant density, distance from slopes, and distance from anthropogenic disturbances such as camping grounds, designated off-roading paths, and the old Highway 10.

The specific sites sampled in this study were associated with the impacts caused during the construction of the transmission towers and conductor (wires) pulling and splicing. Tower construction involved clearing of vegetation for the foundation of the tower and soil compaction from vehicles and construction equipment (drill rigs, cranes, trucks, etc.). The area underneath the transmission tower enclosed by four concrete footings is about 6 m x 6 m. The total area that is typically impacted for tower construction is about 30 m x 30 m (California Public Utilities Commission, 2006). This can vary depending on the topography and the ability to use the service road as part of the impact area. Construction details of DCR1 were not available, but specific details of DCR2 were available and were used to make assumptions for DCR1. In this study, wire sites were defined as conductor pulling and/or splicing sites. The intensity of impact varies among these different sites because of the equipment used and the nature of the construction activity itself. Pulling sites are the most impactful because of the area of land necessary (30 m x 105 m on average), the leveling of the land by grading and clearing the site of vegetation, and the heavy equipment utilized. Typically, construction is designed such that pull and splice sites (30 m x 30 m on average) overlap to minimize costs and impacts to the land (Rorabaugh, 2013). The specific locations of every splice site or sites where both pulling and splicing were conducted was known and mapped for DCR2. Records or maps of specific locations for these sites were not available for DCR1. The only way to determine the locations of these sites was to look for splices (Figure 4-2) in the conductor along the length of DCR1. The wire sites for DCR1 and DCR2 were located almost parallel to each other along the route. Soil samples were obtained from both tower and wire sites along both DCR1 and DCR2 with the assumption that the soil characteristics analyzed at the two types of impact sites would be distinct owing to the differences in the construction equipment and activities. The survey area and all sampling sites were located on public land administered by the U.S. Department of the Interior, Bureau of Land Management (BLM).

A total of 10 sampling locations were identified based on soil complex, vegetation type, and impact type. At each location, soil samples were collected at tower sites and wire sites along both DCR1 and DCR2. At the time of sampling (November 1 and 2, 2013), construction at DCR2 had just been completed and the sampling locations were devoid of vegetation. Soil samples along DCR1 were collected both under the canopy of creosote bush and in the bare ground in the open spaces between the shrubs. Due to restrictions of having to collect soil samples within the SCE right-of-way, control sites were located within the boundary of the two lines, also known as the corridor. Sites were chosen mid-span between the tower site sampled and the tower east or west of it (Figure 4-3). The direction was chosen randomly. The location of the control sites was alternated along both lines, such that five sites were along DCR1 and the other five were along DCR2. The service road is located south of DCR2 and north of DCR1, so the control sites were located north of DCR2 and south of DCR1 within 10 m of the outermost conductor (wire). No splices were located in the wires at the control sites. Soil samples were collected under creosote canopies and in unvegetated areas at the control sites. Eighty (40 at DCR1, 20 at DCR2, and 20 control) samples were collected in total. Half of the DCR1 (20) and control (10) samples were collected under creosote canopies and the other half were collected in the unvegetated bare ground areas between shrubs. All samples along DCR2 (20) were collected in unvegetated areas.

At the tower and wire sites, of both DCR1 and DCR2, a point directly in the center of the tower and a point directly under the splice in the central conductor (wire) were established. A random number from 1–360 was selected as a compass direction (magnetic north as 360) and a second random number was determined for the number of paces taken in that compass direction. A new random number was chosen if the second number was greater than the disturbance area limit or if the locations landed on a shrub or in an erosional feature (e.g. wash). Specific locations of samples in the control sites were determined using a similar process, but direction (using a number between 0 and 180) was restricted to south and north of DCR1 and DCR2 respectively and sampling directly under the overhead wires was avoided. Soil core samples and on-site measurements were collected at the determined location. The top approximately 8 cm of soil was collected using a soil core sampler with a diameter of 5 cm. Approximately 155 cubic centimeters of soil was collected. The samples were collected over a period of 2 days and stored in coolers to minimize differences in soil properties. The soil samples were then transported offsite for the analysis of the soil characteristics.

The soil characteristics studied are listed below along with a definition and the method of analysis:

1. Infiltration rate – Infiltration is the process by which water on the ground surface enters the soil (Bainbridge, 2012). Infiltration rate (cm hr^{-1}) is a measure of the soil's potential to absorb water within a set time. Infiltration rate was measured in the field using a Turf Tec double ring infiltrometer (Turf-Tec International, 2013).

2. Bulk density – Bulk density is the weight of dry soil for a given volume (g/cm^3). Both soil particles and pore spaces are components of bulk

density. In general, the greater the bulk density the lesser the pore space for water movement, root growth and penetration, and seedling germination (Bainbridge, 2012). Bulk density was calculated in the laboratory by dividing the dry weight of the soil sample by the volume of the soil sample (approximately 155 cm^3). Soil dry weight was obtained by drying the soil sample in 2-minute cycles using a microwave. The sample was considered dry when its weight did not change after multiple consecutive drying cycles (USDA-NRCS, 2001).

3. Soil compaction – This is also called penetration resistance and is a measure of soil strength or the ease with which an object can be pushed into the soil. An increase in compaction is an indication of an increase in soil strength, affecting root penetration and plant survival, growth, and development (Bainbridge, 2012). The unit of measure is pound-force per square inch (psi). The psi was measured at both 3 cm and 5 cm from the surface in a single attempt. The depth (cm) to 300 psi was recorded in the same attempt as well (Taylor and Gardner, 1963). Compaction was measured using a dynamic cone penetrometer in the field (ASTM Standard D7380-08, 2008). The same individual obtained the compaction measurements at all sampling locations.

4. Soil moisture content (water content) – Soil moisture content is the amount of water contained in the soil sample. Soil moisture content can be affected by soil texture, precipitation, and organic matter (Bainbridge, 2012). At the time of sampling, it had not rained for at

least two months and it did not rain during sample collection. The initial weight of the soil sample was recorded in grams. The sample was then dried following the procedure outlined under bulk density and weighed again. The difference between the initial weight and dried weight of the sample was the weight of the water contained in the sample. Water content was calculated as a percent weight of water in grams by dividing the weight of water by the dry weight of the soil and multiplying by 100. This method is described in ASTM D4643-08 (1987).

5. Soil organic matter (SOM) – Soil organic matter is the organic component of the soil and consists of decomposing plant and animal residue (Bainbridge, 2012). The presence of SOM is important not only to soil quality and function but also as a source of nutrients to plants. SOM was measured by heating the dried soil sample at 440°C and measuring the ash content. Prior to heating, the weight of the dried soil sample was recorded. After the dried soil converted to ash by the heat, it was cooled down in a desiccator and the weight was recorded. The ash content was calculated as a percent by dividing the weight of the ash sample by the weight of the initial dried soil sample. SOM was also expressed as a percent in grams and was calculated by subtracting the ash content from 100. Method C in ASTM D2974-13 (1971) was followed.

6. Soil carbon stocks – By taking bulk density into consideration, carbon stocks indicate the soil carbon concentration at a given depth per area.

The derivation of carbon from organic matter can depend on the method used to determine amount of organic matter and the amount of organic carbon present in the soil (Pribyl, 2010), but a commonly used conversion factor (58% of organic matter is carbon) was used in this study to estimate soil carbon. Carbon stocks (gC/cm^2) were calculated by multiplying bulk density, fraction of carbon (58% of SOM), and the depth of the soil core sample (8 cm).

7. Soil pH – Soil pH is a measure of the acidity or alkalinity of the soil sample and ranges in values from 0 to 14 with 7 being neutral (Bainbridge, 2012). Values under 7 are considered acidic and values greater than 7 are considered alkaline or basic. Soil pH is an important characteristic as it can affect and control several chemical processes affecting both soil structure and plant function. A 1:1 soil to water ratio mixture was created by measuring 1/8-cup of subsample of soil and adding 1/8-cup to water to it (USDA-NRCS, 2001). The pH of this mixture was then measured using a YSI Pro Plus multiparameter (YSI Inc./Xylem Inc., 2013).

8. Salinity – Salinity is the salt content in the soil sample. High salinity can affect water availability to plants and affect soil structure and infiltration (Bainbridge, 2012). Soil salinity was measured as parts per thousand prior to measuring the pH using a YSI Pro Plus multiparameter (YSI Inc./Xylem Inc., 2013) on the same 1:1 soil to water ratio mixture described above.

9. Texture – Texture is the proportion of particle types (sand, silt, clay) within a soil sample (Bainbridge, 2012). Particle sizes of the dried soil samples were generally uniform and a single-set sieving method was used. The percentage (by weight) passing each sieve size was recorded. This method separated each soil sample into the three particle fractions and determined the proportion of each particle type by weight. Texture components (sand, silt, clay) were calculated as a percent, such that sand + silt + clay = 100 percent. Sand content as a percent was used in the analysis for this study. Method B as described in ASTM D6913-04 (2004) was followed.

The two main objectives of this study were to: 1. Determine if the soil characteristics vary between the old impact associated with construction of DCR1, new impact associated with the construction of DCR2, and control sites; and, 2. Evaluate if the presence of shrubs affected the soil characteristics. To resolve the first objective, two paired t-tests were conducted to compare the old impact (DCR1) sites to control sites and new impact (DCR2) sites to control sites respectively. For this analysis, only the data collected in the bare ground (for DCR1 and control) were used. To address the second objective, only data collected along DCR1 and control were used, since DCR2 did not have shrubs. A two-factor analysis of variance (ANOVA) with site type (impact or control) as one factor and shrub (creosote) presence as the second factor was conducted to determine if the data collected under shrubs were different from the data collected in the bare ground between shrubs. Analysis of similarity (ANOSIM) was conducted using the Bray-Curtis dissimilarity index to determine if all soil characteristics differed significantly between the DCR1 and DCR2 impact sites and the control sites. The Bray-Curtis dissimilarity index was also used in a non-metric multidimensional scaling analysis (NMDS) to visualize the similarities or grouping between sampling sites across both transmission lines and control sites. ANOSIM and NMDS were also conducted to assess if there were significant differences in soil attributes measured under shrubs and in the unvegetated spaces. The vegan package in R was used for these analyses (Jari Oksanen, F. et al., 2017)

All data and statistical analysis were conducted using R version 3.2.3 (R Core Team, 2015), and RStudio version 0.99.489 (R Studio Team, 2015).

4.4. Results

First, to determine if tower and wire sites were different from each other, two paired t-tests with data from DCR1 and DCR2 respectively were conducted. The results established that the two site types were not different from each other for any of the soil characteristics ($p > 0.05$) (Table 4-1). For all analyses that follow, tower and wire sites were treated as replicates.

Using only the data collected in the bare ground between shrubs, the soil characteristics of DCR1 (old impact), DCR2 (new impact), and control were compared. Bulk density was slightly lower at control, followed by DCR1 and DCR2 (Figure 4-4A). Bulk density is indicative of compaction, and a lower bulk density can imply lower compaction at control site relative to the two impact sites. Statistically, bulk density at DCR1 was not different from control ($p > 0.05$). Bulk density at DCR2, though not significant, differed slightly from the bulk density at control sites with $p < 0.1$ (Table 4-2).

Infiltration rate was lowest at control and no differences were observed between DCR1 and DCR2 (Figure 4-4B). Statistically both DCR1 and DCR2 were indistinguishable from control ($p > 0.05$).

Three soil compaction metrics were analyzed in this study. Depth to 300 psi has been used to evaluate planting conditions (rooting potential) for crop plants (Taylor and Gardner, 1963). The depth to hit 300 psi should be shorter in compacted soils and deeper (or longer) in less compacted soils because there is lesser resistance as the penetrometer probe is forced into the soil. The penetrometer probe traveled deepest at control sites. DCR1 and DCR2 hit 300 psi at identical depths (Figure 4-5A). Neither DCR1 nor DCR2 differed significantly ($p > 0.05$) from control in depth to 300 psi. Compaction (psi) at 3 cm and at 5 cm from surface were also measured. In both cases the control site had the lowest average compaction (psi) values. DCR1 and DCR2 had relatively identical psi values (Figure 4-5B and 5C respectively). DCR1 and DCR2 did not differ significantly from control in terms of compaction measured at 5 cm from surface ($p > 0.05$). The compaction at 3 cm measured at DCR1 and DCR2 differed significantly from control ($p < 0.05$) (Table 4-2) indicating that the surface is compacted.

A trend was observed in salinity values, with the control site having lower salt content than DCR1 and DCR2 (Figure 4-6A). Salinity at DCR1 and control were indistinguishable ($p > 0.05$) but DCR2 differed slightly from control with $p < 0.1$ (Table 4-2). Control site and DCR1 were indistinguishable and had lower pH values than DCR2 (Figure 4-6B). The pH measured at DCR2 differed slightly ($p < 0.1$) from control but pH at DCR1 and control were indistinguishable ($p > 0.05$).

Soil organic matter was lowest at control followed by DCR1 and DCR2 had the highest concentration (Figure 4-7A). Carbon stocks to a depth of 8 cm also followed the same pattern as soil organic matter (Figure 4-7B). DCR1 and control sites were indistinguishable ($p > 0.05$) in soil organic matter and carbon stocks. But both soil organic matter and carbon stocks at DCR2 sites were significantly different from control ($p < 0.05$).

Soil moisture content was relatively even between the three sites (Figure 4-8A) with no significant difference between both impact sites and control sites ($p > 0.05$). Sand content was lowest at DCR1 and highest at control (Figure 4-8B). DCR1 differed slightly from control with $p < 0.1$ but DCR2 was indistinguishable from control ($p > 0.05$). Overall these results, testing the first hypothesis, indicated that the control and both impact sites were not significantly ($p > 0.05$) different from each other for most soil characteristics (Table 4-2).

A two dimension NMDS analysis focusing on control, DCR1, and DCR2 was conducted to visualize potential clustering within or separation between all three site types when all soil characteristics were analyzed together (Figure 4-9). Though DCR1 data seemed to cluster with each other and the control and DCR2 data appeared more dispersed, a clear separation between the three site types was not apparent. ANOSIM confirmed this observation of no differences between control, DCR1, and DCR2 (R statistic = 0.06, $p = 0.09$). The R statistic is a relative measure of separation, with a value of zero indicating that there are no differences among site types and a value of 1 indicating that all samples within a site (DCR1 or DCR2 or control) are more similar to one another than they are to any sample in another site. Although $p < 0.1$ for this analysis, the very low R statistic indicated that the DCR and control sites were very similar to each other.

The next analysis utilized data collected under creosote shrubs and in the bare ground between the shrubs at control and DCR1 impact sites (no shrubs at DCR2 impact sites) to assess the spatial heterogeneity in soil characteristics. A two-factor ANOVA indicated that control and impact sites were not significantly different from each other for all the soil characteristics analyzed except for one compaction metric. Depth to 300 psi was significantly higher (deeper) in control relative to impact ($p = 0.01$). The interaction between site type (control, impact) and location (under shrub, bare ground) was not significant with $p > 0.05$ for all characteristics. Bulk density was significantly lower under shrubs compared to the bulk density in the bare ground at both control and impact sites ($p < 0.0001$) (Figure 4-10A). Infiltration rate was significantly higher under shrubs at both control and impact sites ($p < 0.0001$) (Figure 4-10B). Depth to 300 psi (Figure 4-11A) and compaction at 5 cm (Figure 4-11C) were significantly different ($p < 0.0001$ and $p < 0.05$ respectively) under shrubs at both control and impact sites relative to bare ground measurements. There were no significant differences in the compaction at 3 cm under creosote and in the bare ground at both control and impact sites ($p > 0.05$) (Figure 4-11B). Salinity (Figure 4-12A) and soil pH (Figure 4-12B) were significantly different under creosote shrubs relative to the bare ground measurements ($p < 0.05$ for both). Both soil organic matter (Figure 4-13A) and carbon stocks to a depth of 8 cm (Figure 4-13B) were significantly higher under shrubs relative to the bare ground measurements ($p < 0.0001$ and $p < 0.01$ respectively). There were no significant differences in the soil moisture content (Figure 4-14A) and sand content (Figure 4-14B) under creosote and in the bare ground at both control and impact sites ($p > 0.05$). Overall, the results confirmed the fertile island effect with significant differences in soil characteristics when measured under shrubs versus in the bare ground between the shrubs.

A two dimension NMDS analysis of data from under shrubs and the open spaces between shrubs (for both control and DCR1 impact) was conducted. Although there was some overlap, separation between the samples collected under creosote shrubs and in the bare ground was apparent in the NMDS plot (Figure 4-15). ANOSIM confirmed this separation (differences) between the samples from under shrubs and the samples from bare ground ($p=0.001$). However, the R statistic was low (0.16), indicating that the level of separation is small.

4.5. Discussion

The results suggest that impacts from transmission power line construction on soil may be negligible. Previous research focused on abandoned towns and roads, which are large-scale and localized sustained impacts. Comparatively, utilities (transmission line, aqueduct, and pipeline) have a single impact in time associated with construction, and the impact sites are relatively small and evenly distributed along a long linear corridor. Unlike abandoned towns and roads, the utilities do have an ongoing permanent impact; namely, the service road. The service road is usually maintained for the life of the utility infrastructure for maintenance and repair access and is used not only by the utility company but also by the public for recreation. The primary impact from overhead transmission line construction on soil is likely compaction from the heavy equipment required for the installation of towers and for splicing and pulling of wires. Although overhead transmission line construction is likely not as impactful as the underground pipeline or aqueduct construction, since trenching is not involved (Lovich and Bainbridge, 1999), I hypothesized that the soil characteristics at DCR2 (new) impact sites would be significantly different from control sites and DCR1 (old) would not be significantly different from control sites. Essentially, the objective was to examine short-term and long-term effects of construction on soil. The results showed that soil characteristics at DCR1 and control were similar, except with respect to soil compaction at 3 cm, indicating that the surface remains compacted. DCR2 and control were also similar except for compaction at 3 cm, soil organic matter, and carbon stocks to a depth of 8 cm. Although DCR2 and control were not significantly different ($p > 0.05$), there were slight differences observed for most characteristics with $p \leq 0.1$. It is likely that the equipment and methods used may not be significantly affecting soils as hypothesized, but the slight differences do imply an immediate effect. The results also indicate that soils remain compacted at 3 cm even thirty years after construction relative to control sites, implying that surface compaction is likely a primary effect of construction.

Although only compaction at 3 cm was significant, some trends were observed in the soil characteristics when comparing DCR1, DCR2, and control. All compaction metrics (including compaction at 3 cm), for example, indicated that the impact sites (DCR2 and DCR1) were more compacted than control. Soil compaction can result in lower infiltration rates (Webb, 2002), but the control sites in this study had the lowest infiltration rate relative to both DCR sites, indicating that other factors may be influencing the infiltration rate. Soil organic matter and carbon stocks were lowest at control and highest at DCR2 ($p < 0.05$). Walker et al. (2001) measured organic matter and moisture content under shrubs, followed by shrub removal and measurement of same characteristics seven months after removal. The authors established that even seven months after the removal of the shrubs (*Larrea tridentata, Ambrosia dumosa, Coleogyne ramosissima*), the soil organic matter content was higher when compared to the bare ground open spaces between shrubs. Studies examining the presence of the resource islands in soils after sagebrush (*Artemesia* spp.) removal showed that "ghost" islands were still discernible up to 9 years (Halvorson et al., 1997) post-fire and 6–14 years after cutting (Bechtold and Inouye, 2007; Burke et al., 1989). It is unlikely that samples were collected along DCR2 from areas that were all previously (prior to land clearing for DCR2 construction) under shrub canopies, but further research is required examining longevity of these fertile islands after different types of disturbances. Another reason for higher organic and carbon content at DCR2 sites could be from the recent construction activities, such as grading, which can result in organic matter getting spread more evenly across the disturbed surface.

The results replicated the fertile island occurrence characteristic of arid ecosystems (Rostagno et al., 1991; Schlesinger et al., 1996; Titus et al., 2002; Walker et al., 2001; Whitford et al., 1997). This is a well-studied and recorded phenomenon and numerous authors have documented a distinct spatial pattern of soil nutrient distribution, with higher concentrations of nutrients (e.g., nitrogen, phosphorus, and carbon) under shrub canopies compared to the open spaces between shrubs in arid shrub land systems (Beatley, 1979; Crawford and Gosz, 1982; Garcia-Moya and McKell, 1970; Romney et al., 1980; Rostagno et al., 1991; Schlesinger et al., 1990; Titus et al., 2002).

Most of the vegetation clearing associated with transmission line construction is removal or crushing of the above-ground portion of a plant, although depending on the technique used (grading), some root systems can also be impacted. Research focusing on the formation of these islands and if they remain in place even in the absence of the shrub canopy after an impact like transmission line construction is necessary in the desert habitat.

Studies have indicated that the rate of vegetation recovery after an impact can be affected by the impacts to the soil (Bolling and Walker, 2000; Qi et al., 2015; Webb, 2002; Webb and Wilshire, 1980). Although there is a slight (but not significant) suggestion of an impact at the new impact (DCR2) sites, the overall results of this study indicate that the newly impacted site (DCR2) has soil characteristics similar to adjacent, presumably undisturbed habitat and older impact site (DCR1). Desert soils are typically nutrient-poor, salty, and sandy (Abella, 2010; Abella and Newton, 2009; Bainbridge, 2012; Lovich and Bainbridge, 1999) and the fact the three categories of sites (old impact, new impact, control) exhibit similar or close to similar soil characteristics is encouraging for restoration of lands impacted by transmission power line construction. With projected increases in the establishment of alternative energy sources and construction of solar and wind energy plants in the desert (California Energy Commission, 2017), it will be beneficial to refine policies and processes that focus on the restoration of temporary impact sites. Based on the results of this study and the significance of the heterogeneity of soil properties, research focusing on impacts to this heterogeneity by taking into consideration the different types and intensities of disturbances (e.g. different shrub removal techniques, construction techniques, etc.)

may help guide post-construction restoration requirements. Soil recovery is a key step in habitat rehabilitation since it facilitates the recruitment of plants, in turn attracting animals, and eventually leading to a functioning restored habitat.

4.6. Tables

Table 4-1. Results of the paired t-tests comparing the wire and tower sites of both DCR1 and DCR2 transmission power lines.

Soil Characteristics	**DCR1 (Tower vs Wire) P-Value**	**DCR2 (Tower vs Wire) P-Value**
Bulk Density (g/cm^3)	0.27	0.25
Infiltration Rate (cm/hr)	0.17	0.89
Soil Compaction at 3cm (psi)	0.97	0.89
Soil Compaction at 5cm (psi)	0.11	0.57
Depth to 300 PSI (cm)	0.10	0.40
Salinity (parts per thousand)	0.73	0.25
pH	0.80	0.78
Organic Matter (%g g^{-1})	0.33	0.63
Moisture Content (% g g^{-1})	0.64	0.99
Texture (Sand content) (%)	0.42	0.95
Carbon stocks to depth 8 cm (gC/cm^2)	0.23	0.28

Table 4-2. Results of the paired t-tests comparing the control to both DCR1 and DCR2 transmission power lines.

Soil Characteristics	Control vs. DCR1		Control vs DCR2	
	T-Value	**P-Value**	**T-Value**	**P-Value**
Bulk Density (g/cm^3)	-0.88	0.40	-1.95	0.08
Infiltration Rate (cm/hr)	-0.79	0.45	-0.64	0.54
Soil Compaction at 3cm (psi)	-3.41	0.01	-2.99	0.02
Soil Compaction at 5cm (psi)	-1.50	0.17	-1.43	0.19
Depth to 300 PSI (cm)	1.61	0.14	1.46	0.18
Salinity (parts per thousand)	-0.99	0.35	-2.17	0.06
pH	-0.04	0.97	-1.98	0.08
Organic Matter (%g g^{-1})	-1.06	0.32	-2.90	0.02
Moisture Content (% g g^{-1})	0.33	0.75	-0.68	0.51
Texture (Sand content) (%)	2.16	0.06	0.81	0.44
Carbon stock to depth 8 cm (gC/cm^2)	-1.46	0.18	-3.32	0.01

4.7. Figures

Figure 4-1. Lattice steel transmission towers in the lower Colorado Desert. Devers-Colorado River No. 2 (DCR2) is on the left in the image and Devers-Colorado No. 1 (DCR1) is on the right.

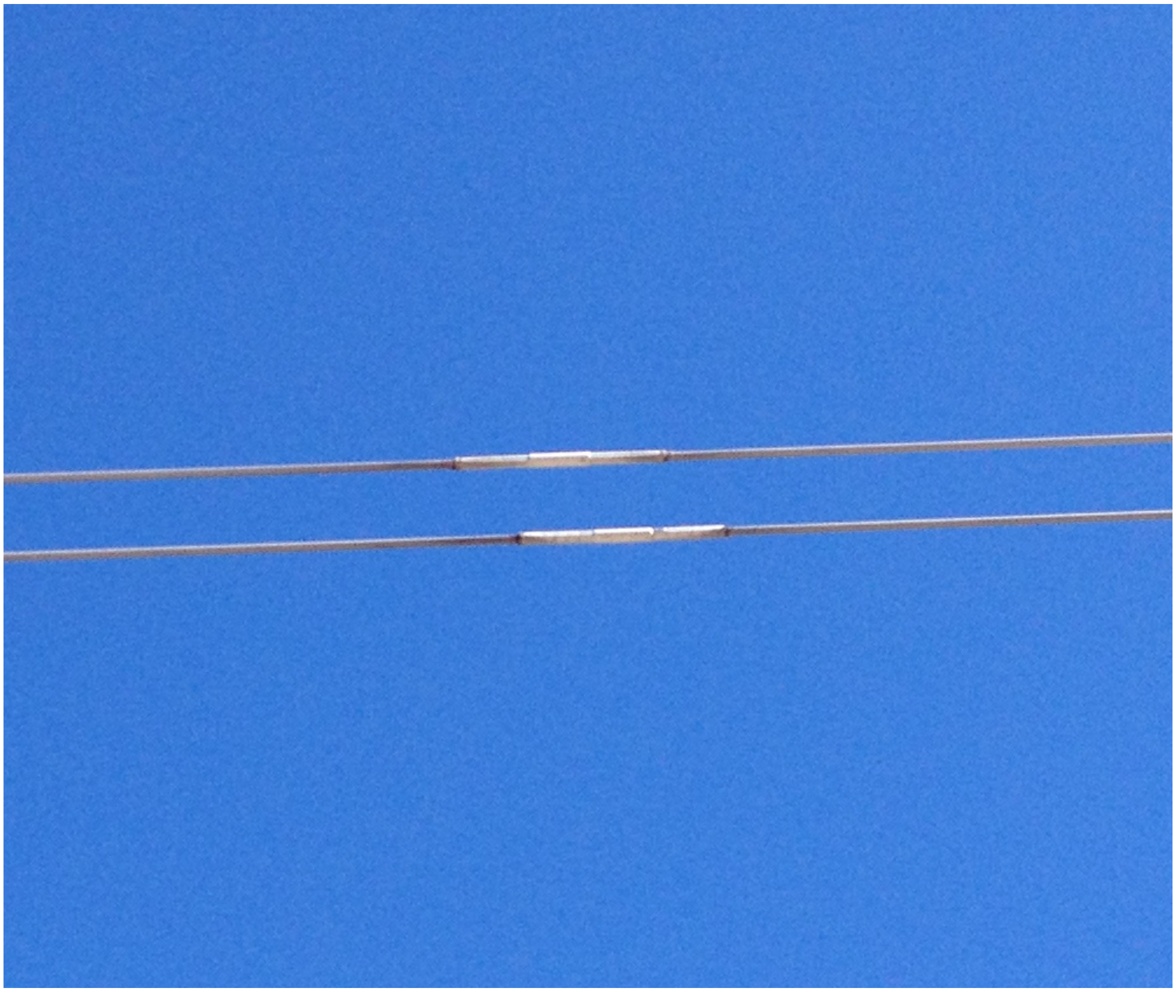

Figure 4-2. Splices in the conductor or wires of a transmission power line.

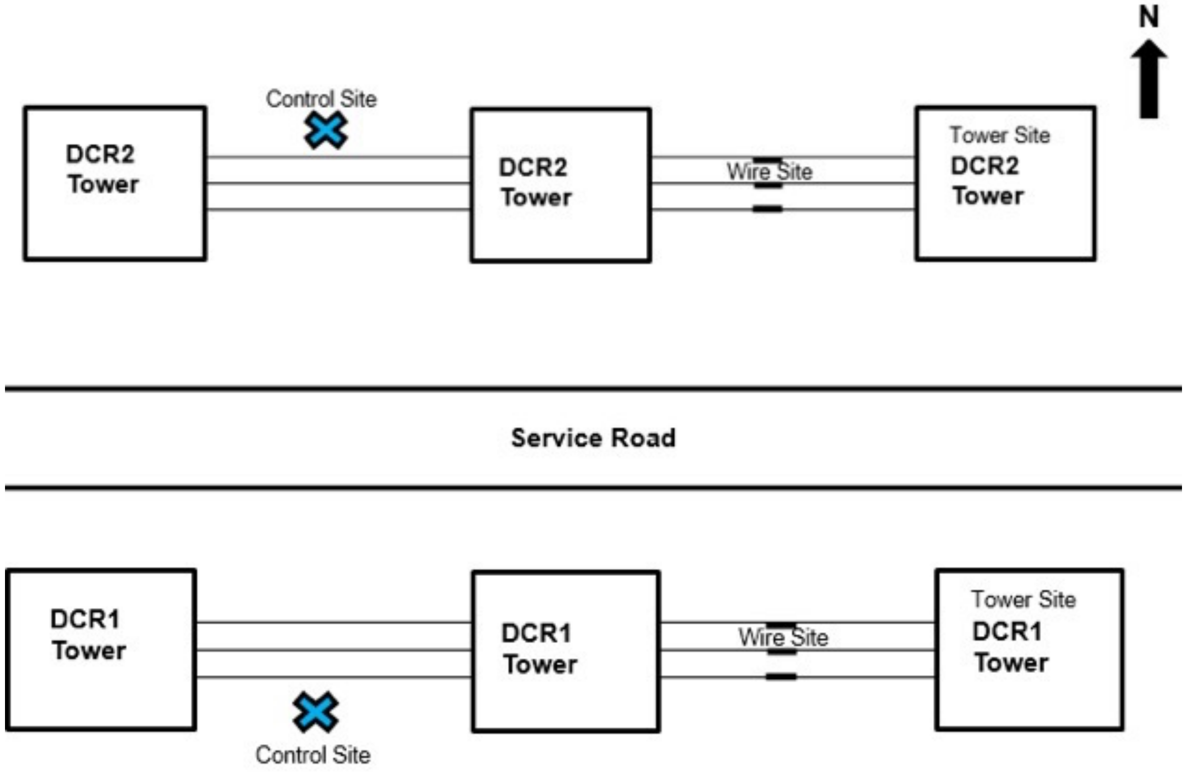

Figure 4-3. Location of control site relative to tower and wire sites along both Devers-Colorado No. 1 (DCR1) and Devers-Colorado No. 2 (DCR2). Ten locations were sampled and each location had one tower site along DCR1, one tower site along DCR2, one wire site along DCR1, one wire site along DCR2, and one common control site. The location of the control site was either along DCR1 or DCR2 and east or west of the tower and wire sites.

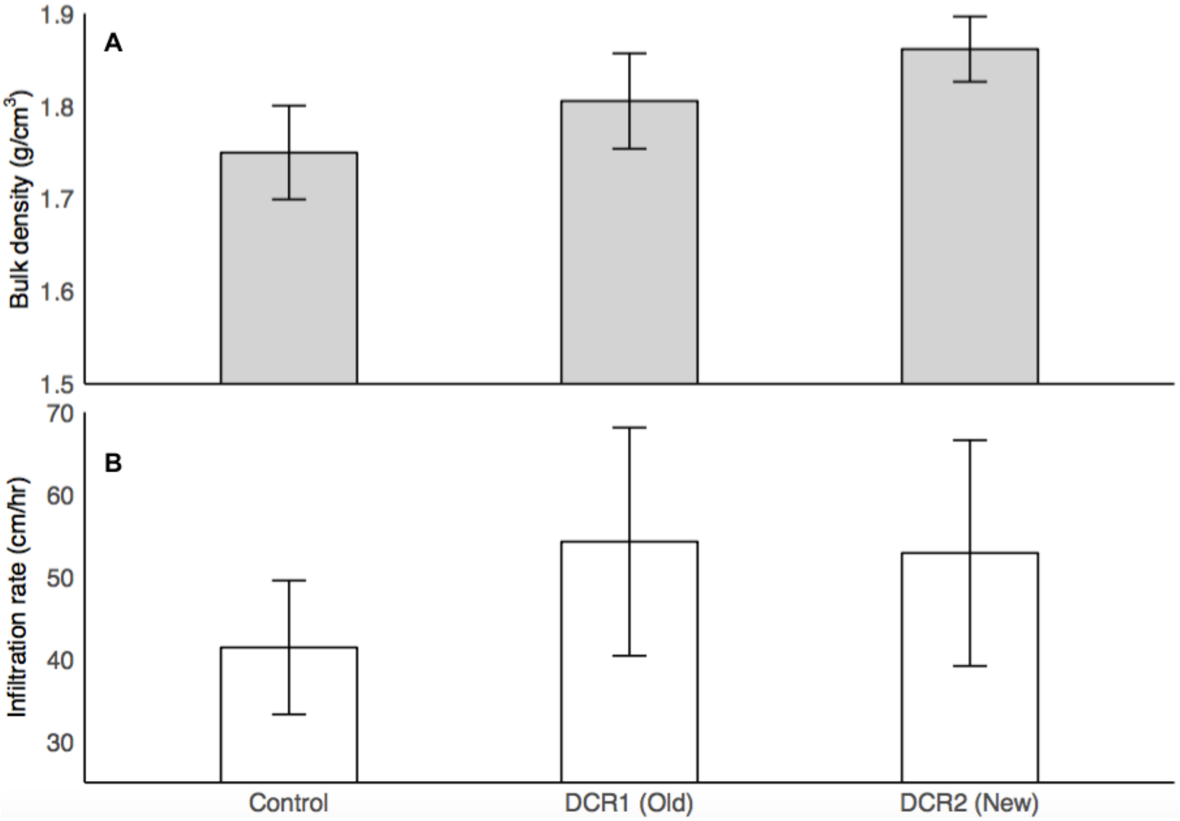

Figure 4-4. Bulk density (A) and infiltration rate (B) measured at control, DCR1 (old impact), and DCR2 (new impact). Error bars represent the standard error of the mean.

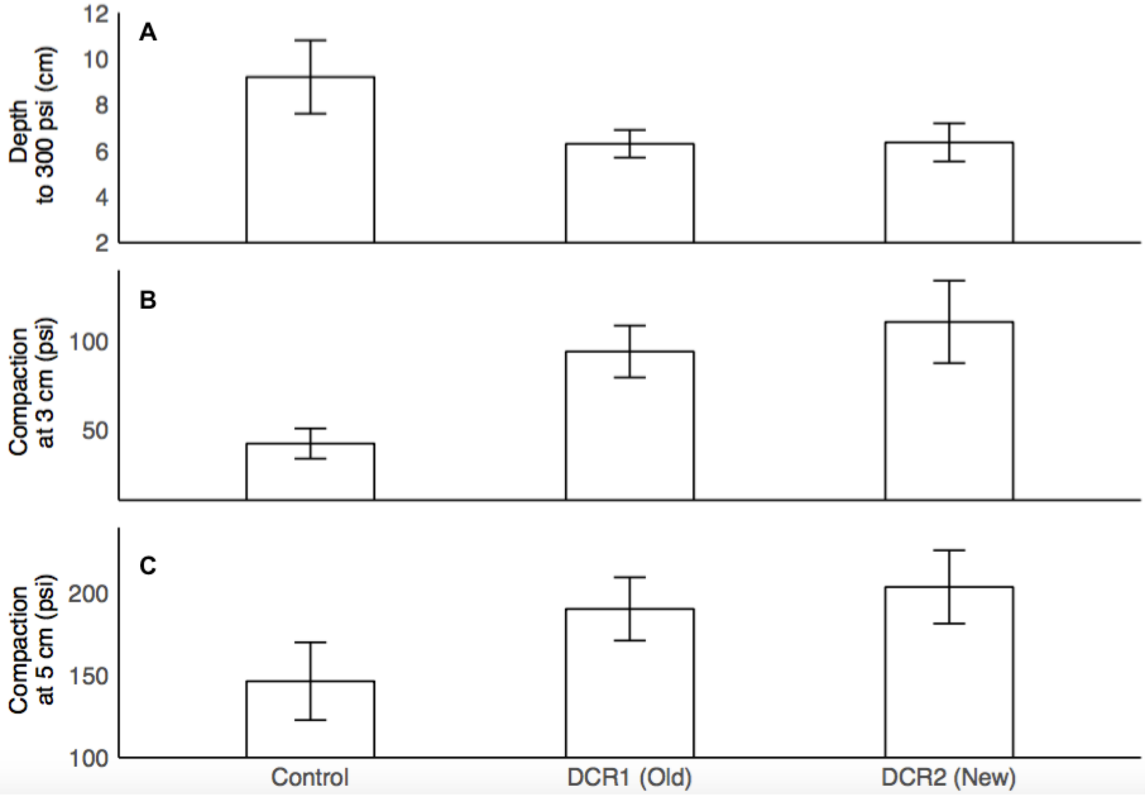

Figure 4-5. Three metrics of soil compaction: Depth to 300 psi (A), compaction at 3 cm (B), and compaction at 5 cm (C) at control, DCR1 (old impact), and DCR2 (new impact). Error bars represent the standard error of the mean.

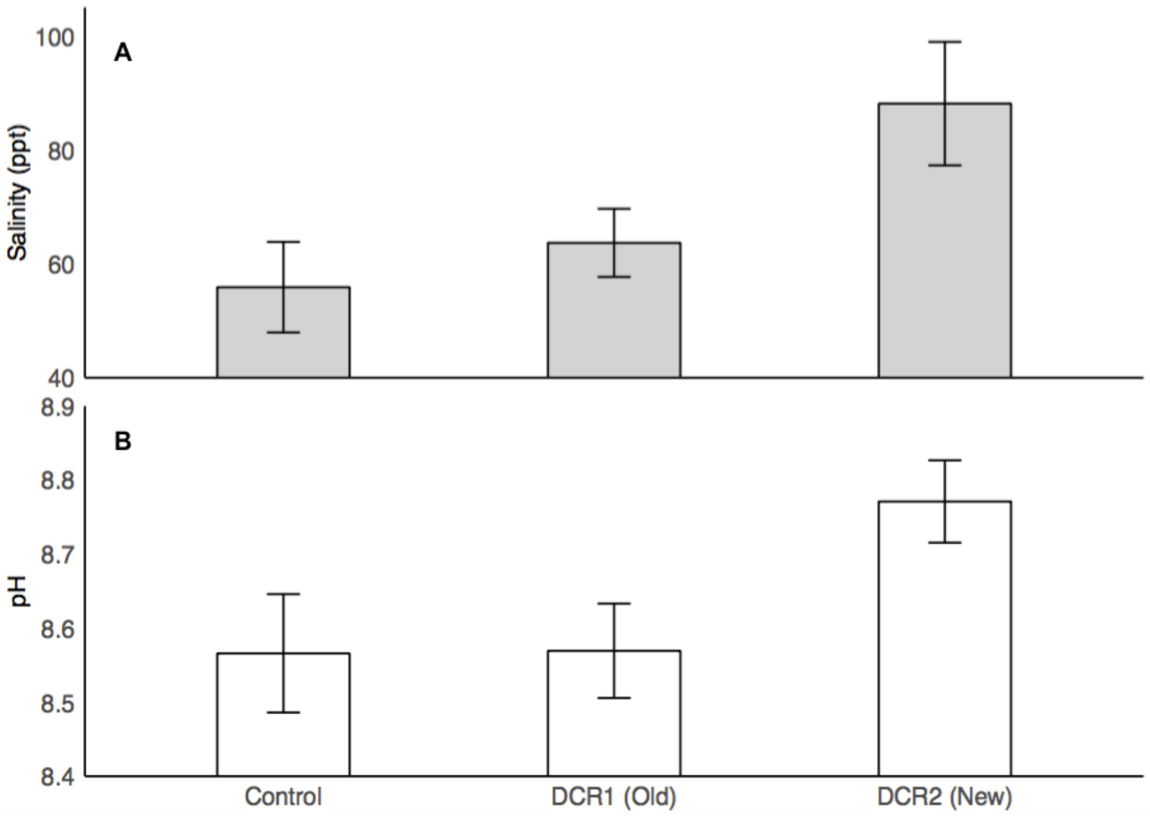

Figure 4-6. Soil salinity (A) and pH (B) at control, DCR1 (old impact), and DCR2 (new impact). Error bars represent the standard error of the mean.

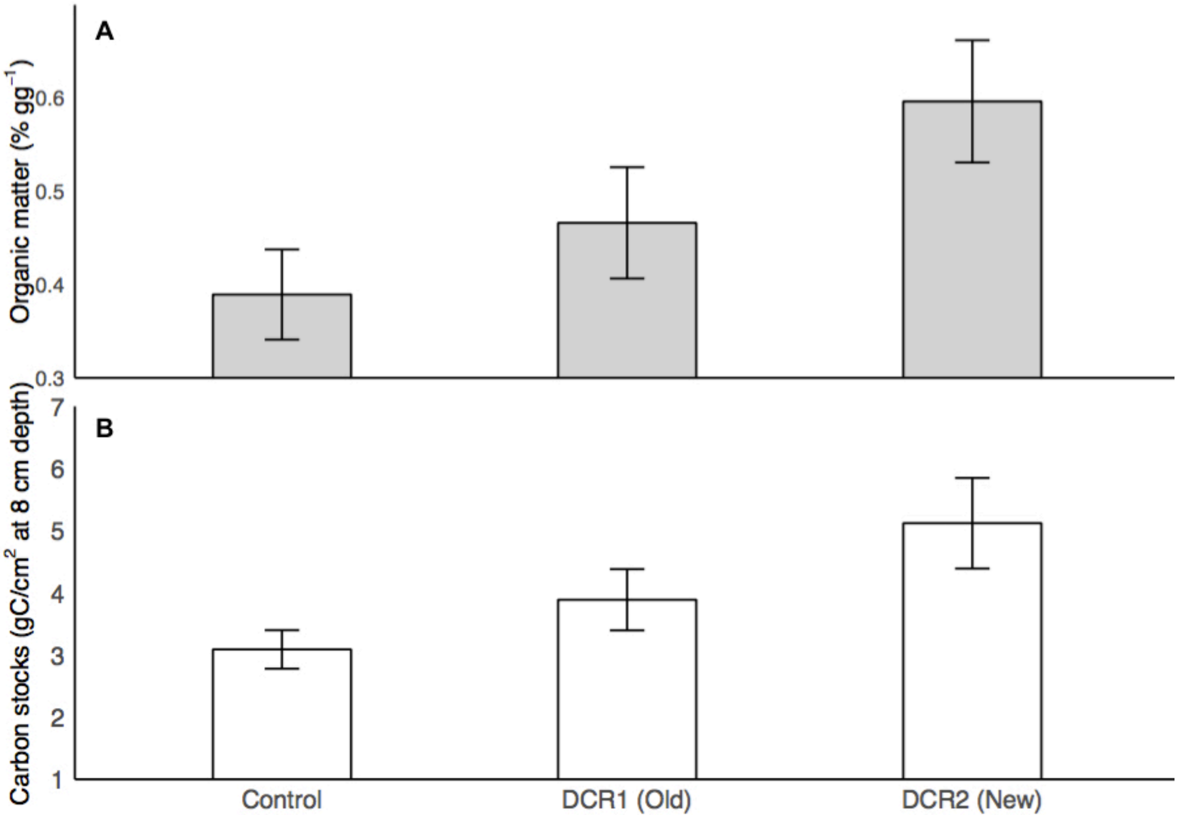

Figure 4-7. Soil organic matter (A) and carbon stocks to a depth of 8 cm (B) at control, DCR1 (old impact), and DCR2 (new impact). Error bars represent the standard error of the mean.

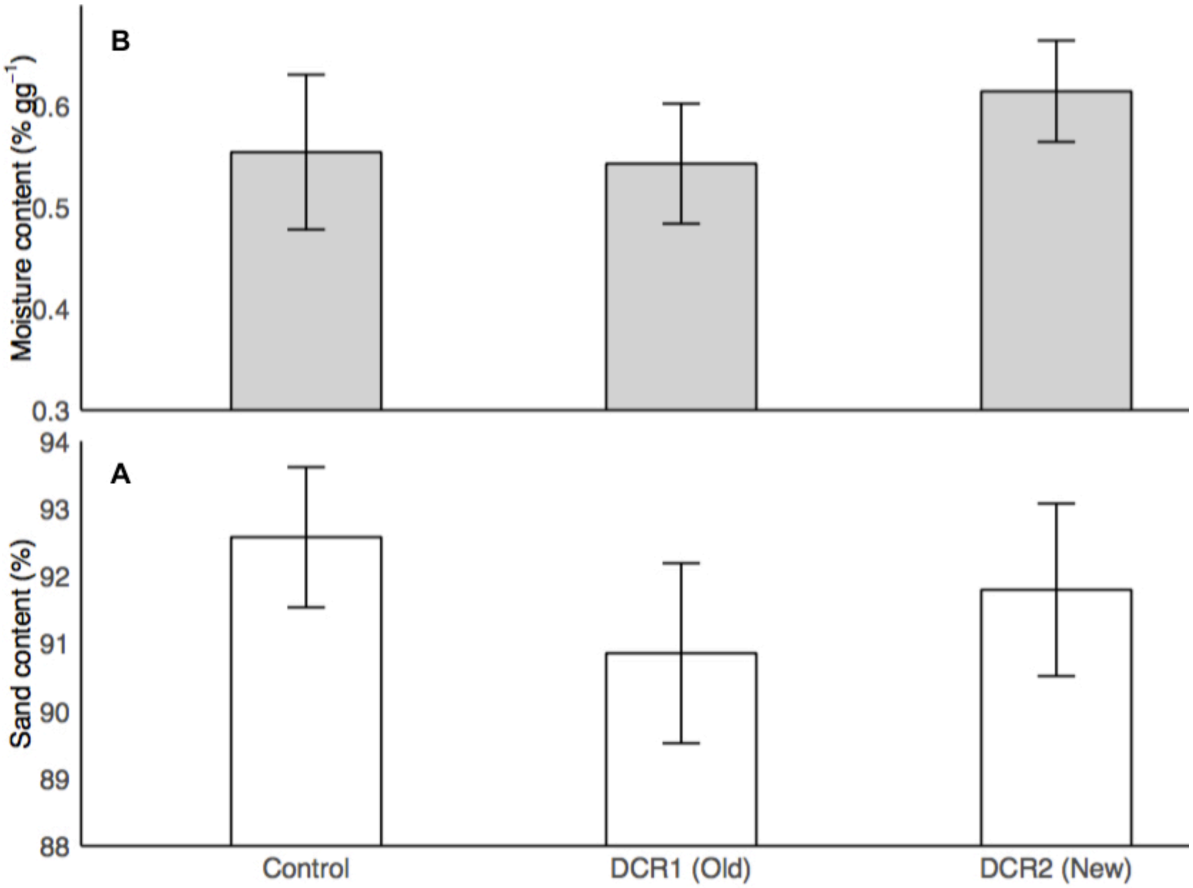

Figure 4-8. Soil moisture content (A) and sand content (B) at control, DCR1 (old impact), and DCR2 (new impact). Error bars represent the standard error of the mean.

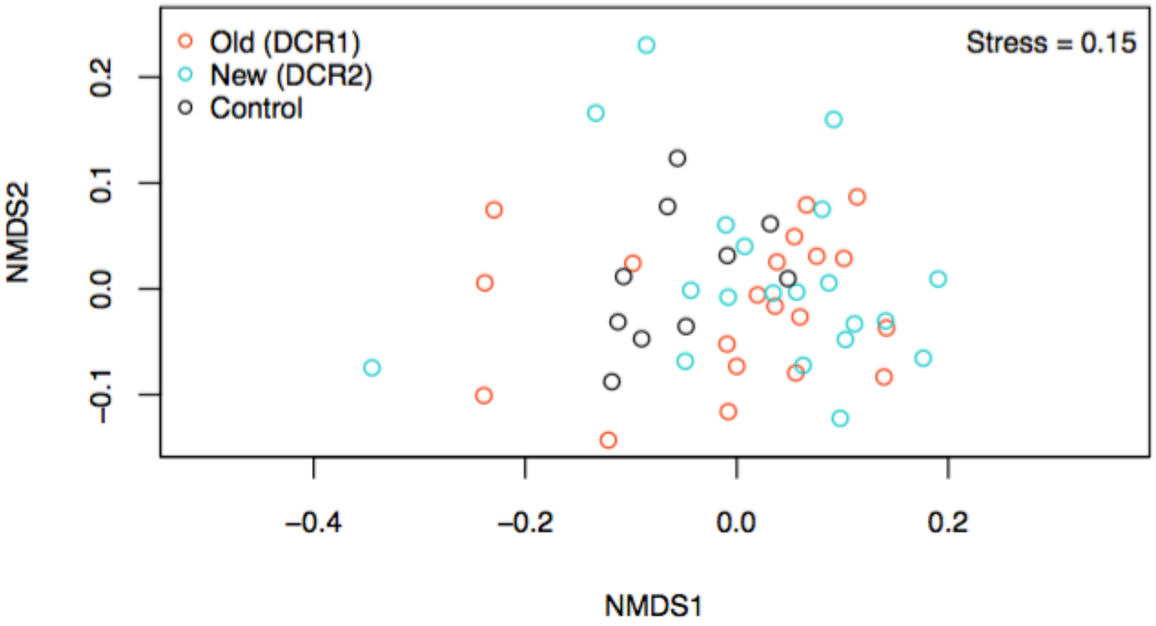

Figure 4-9. Non-metric multi-dimensional scaling ordination of the soil characteristics of DCR1 (old), DCR2 (new), and control sites.

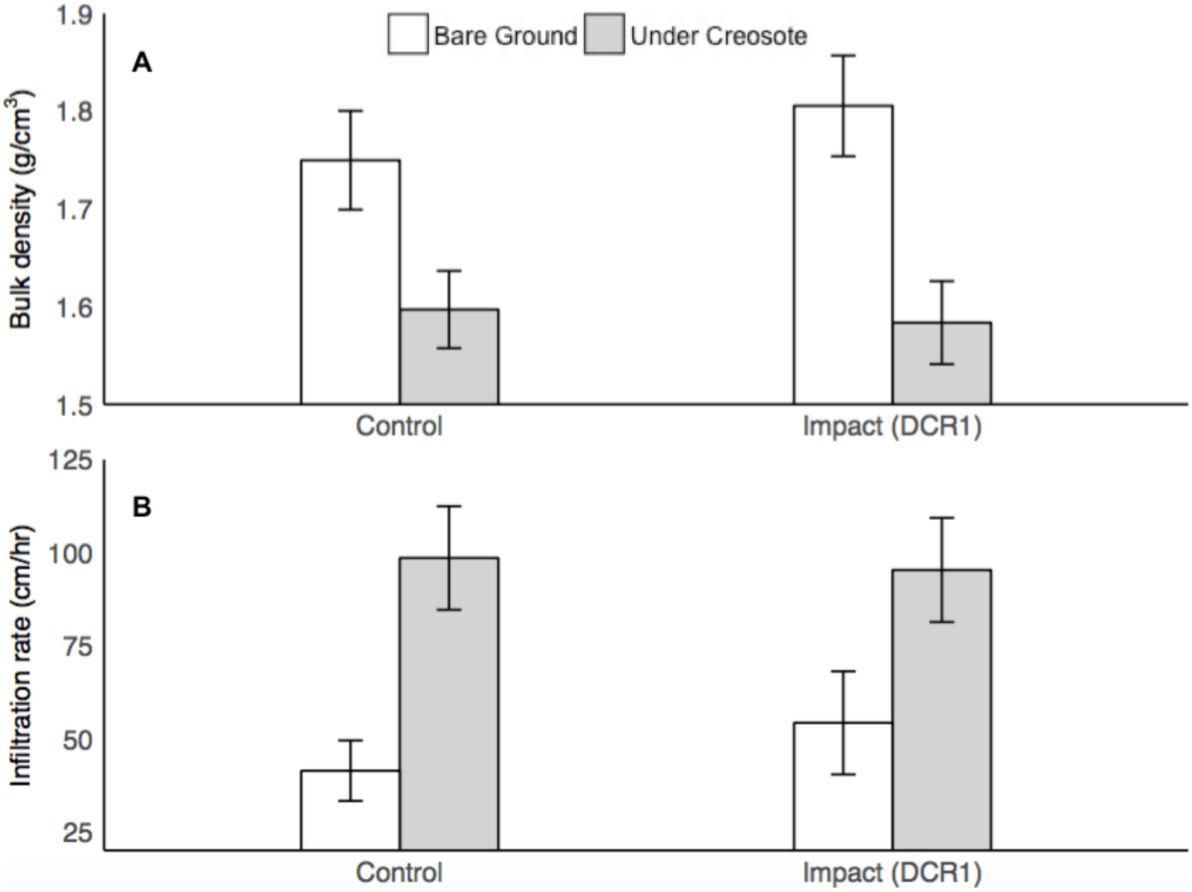

Figure 4-10. Bulk density (A) and infiltration rate (B) at control and impact (DCR1) sites under creosote bush and in the bare ground in between shrubs. Error bars represent the standard error of the mean.

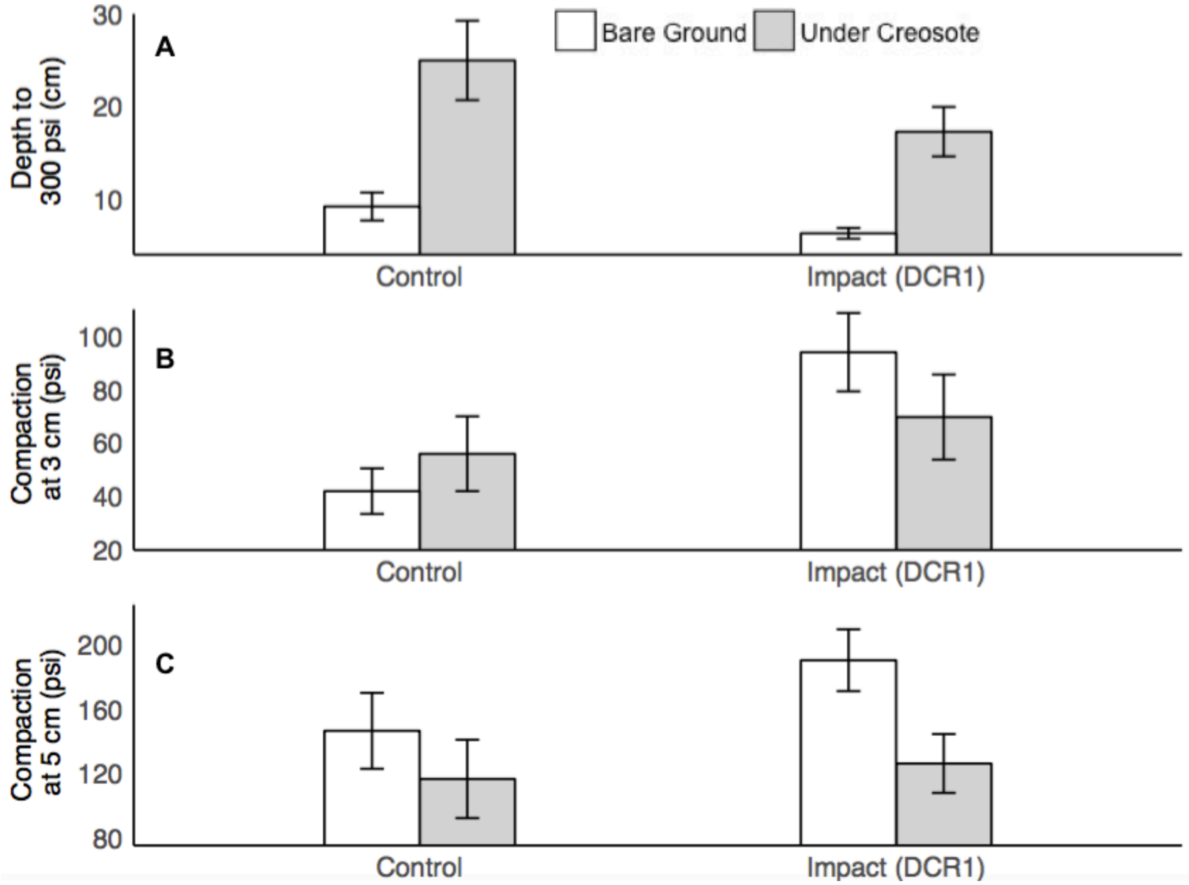

Figure 4-11. Three metrics of soil compaction: Depth to 300 psi (A), compaction at 3 cm (B), and compaction at 5 cm (C) at control and impact (DCR1) sites under creosote bush and in the bare ground in between shrubs. Error bars represent the standard error of the mean.

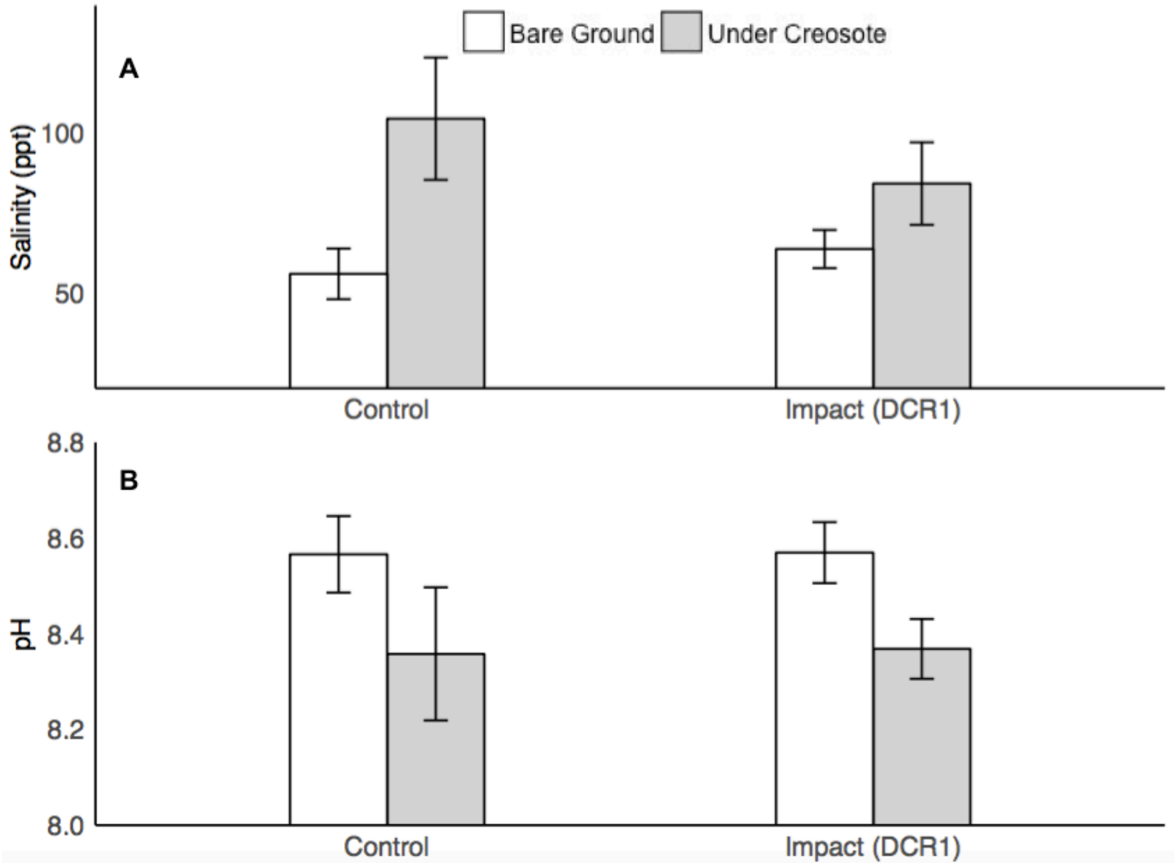

Figure 4-12. Soil salinity (A) and pH (B) at control and impact (DCR1) sites under creosote bush and in the bare ground in between shrubs. Error bars represent the standard error of the mean.

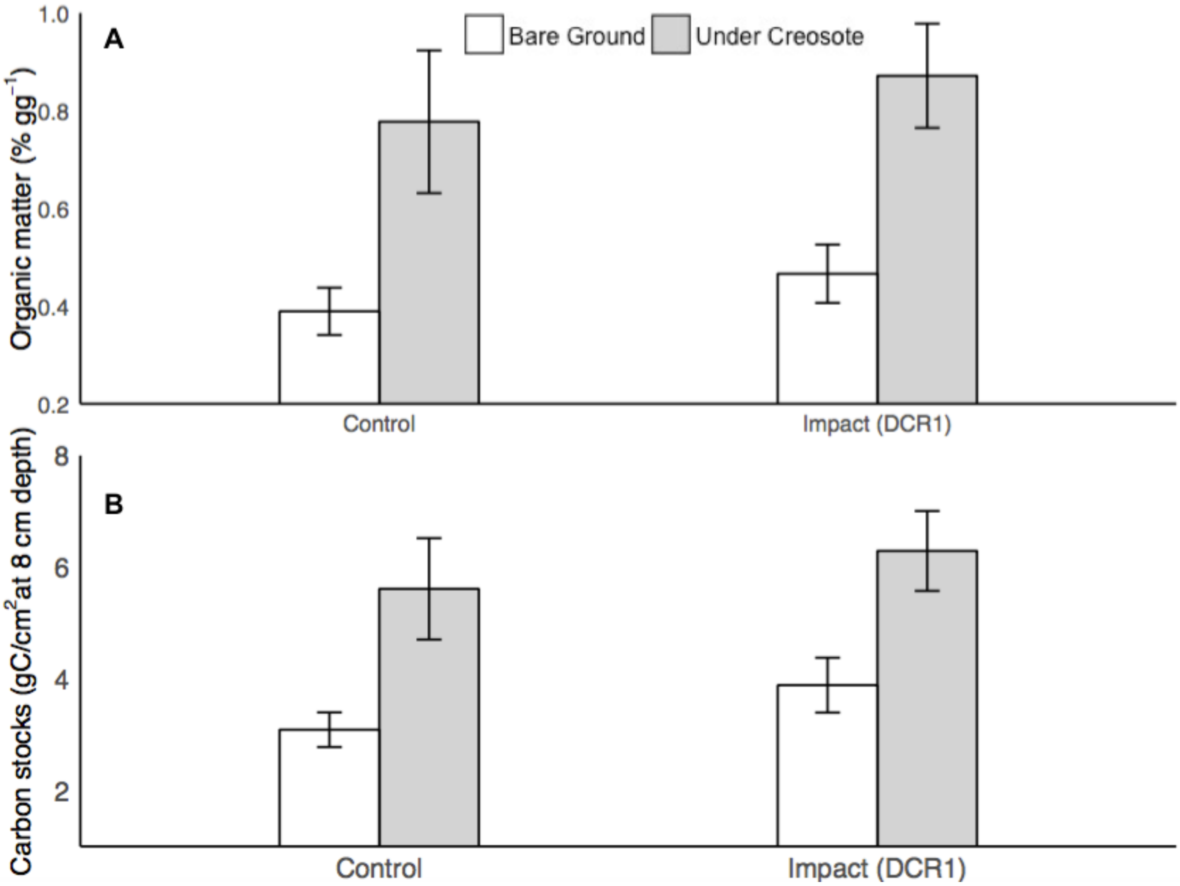

Figure 4-13. Soil organic matter (A) and carbon stocks to a depth of 8 cm (B) at control and impact (DCR1) sites under creosote bush and in the bare ground in between shrubs. Error bars represent the standard error of the mean.

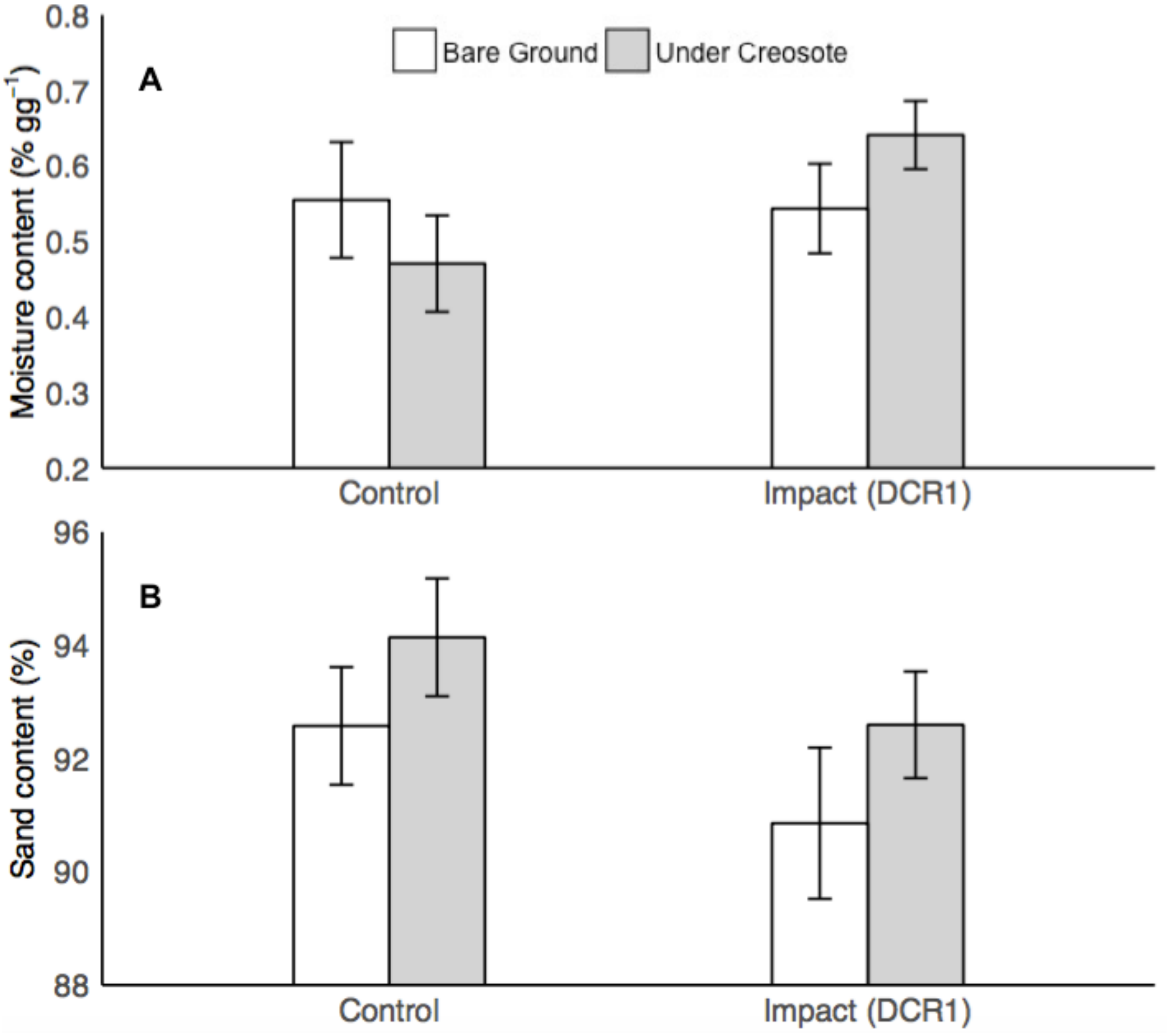

Figure 4-14. Soil moisture content (A) and sand content (B) at control and impact (DCR1) sites under creosote bush and in the bare ground in between shrubs. Error bars represent the standard error of the mean.

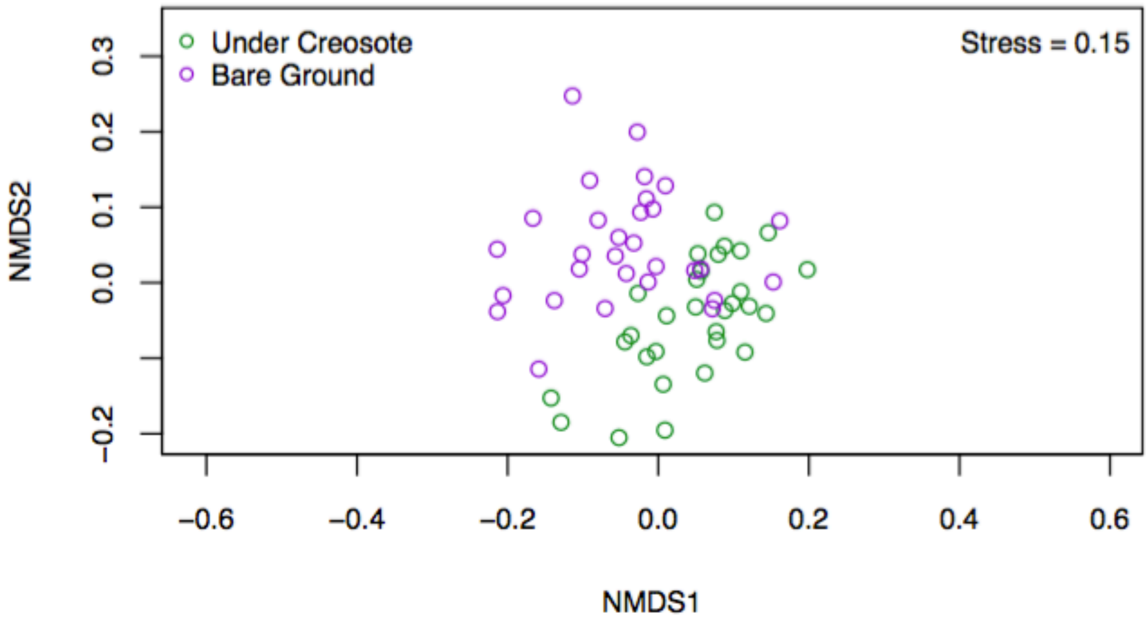

Figure 4-15. Non-metric multi-dimensional scaling ordination of the samples collected under shrub canopies and in the bare ground between shrubs for both impact (DCR1) and control sites.

4.8. Appendix

Paired t-test results comparing control sites to DCR1 and DCR2 impact sites respectively are shown as box and whisker plots of the mean differences (natural log) with standard error and the minimum and maximum differences as the whiskers (Figures A4-1–4-11).

4.8.1. Figures

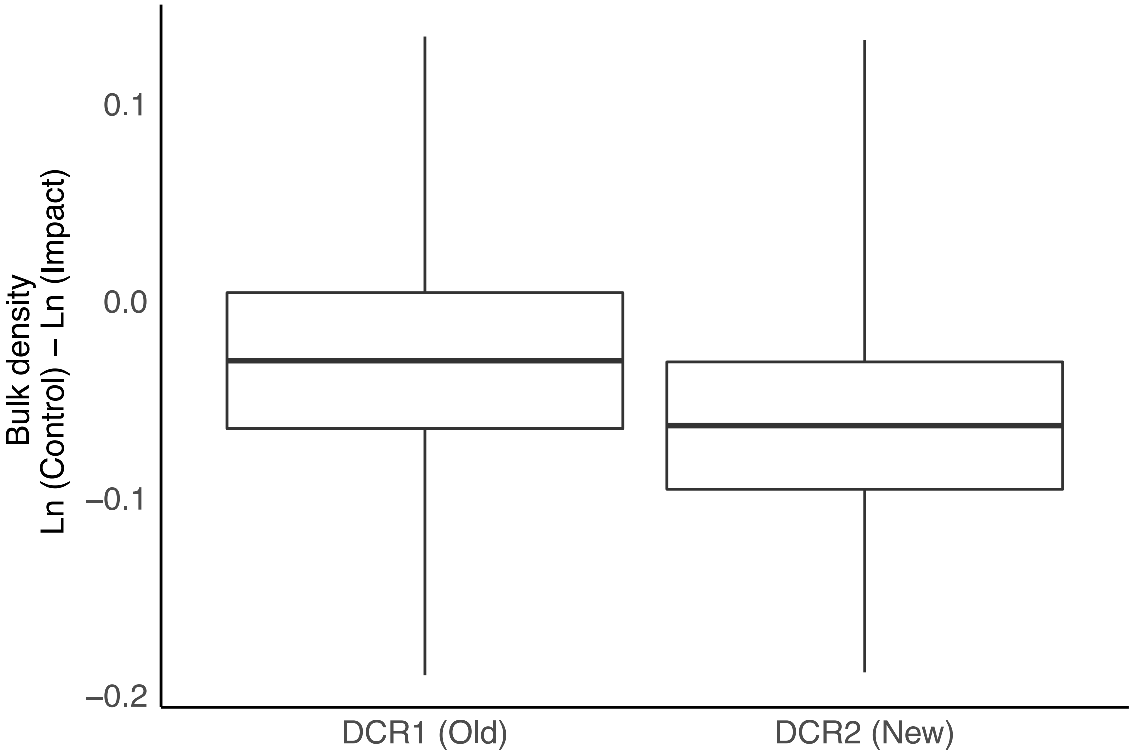

Figure A4-1. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in bulk density (g/cm^3).

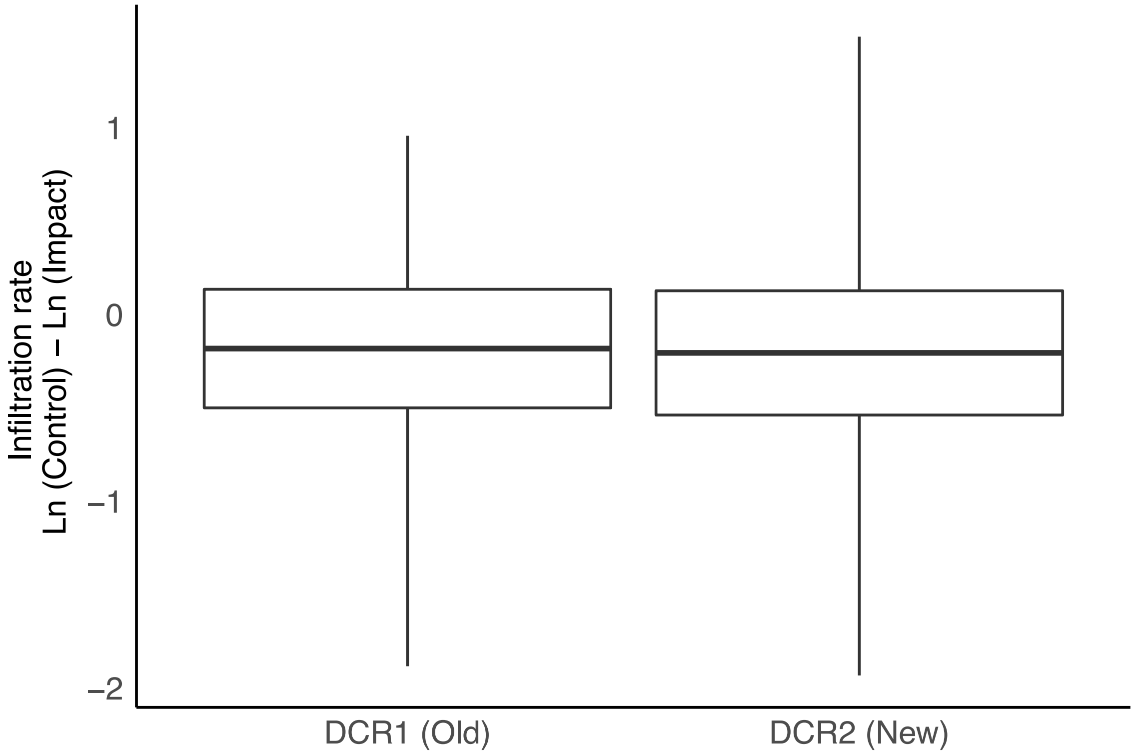

Figure A4-2. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in infiltration rate (cm/hr).

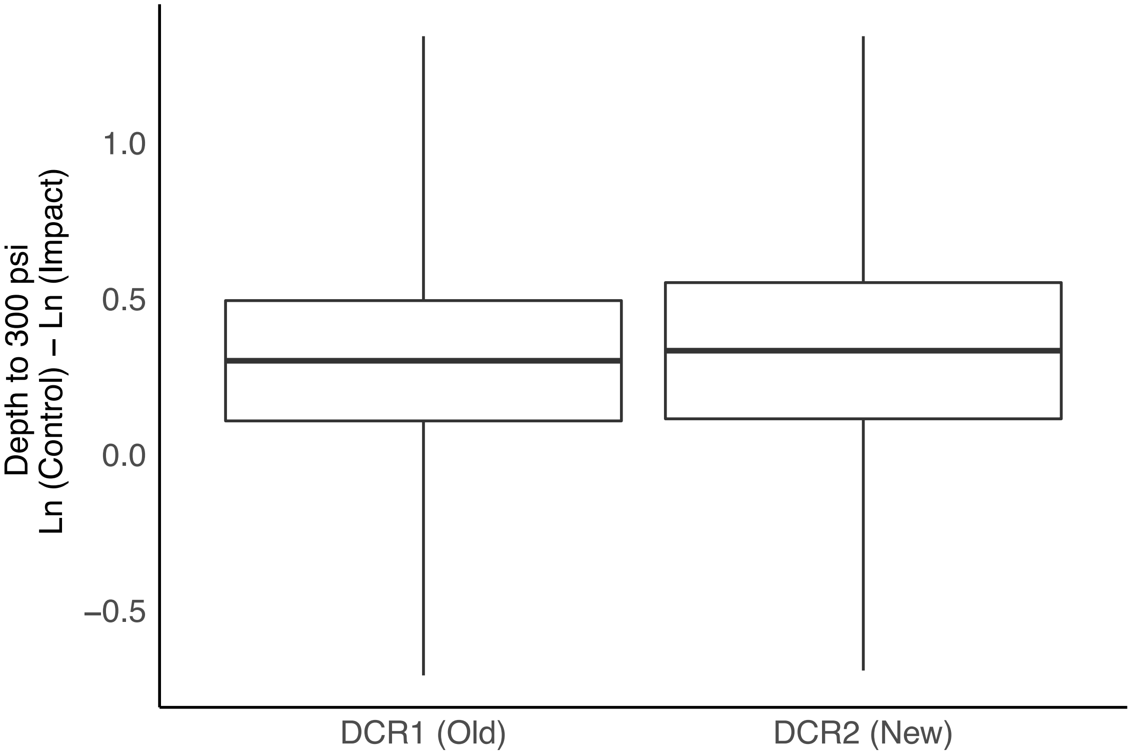

Figure A4-3. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in the depth to 300 psi (cm).

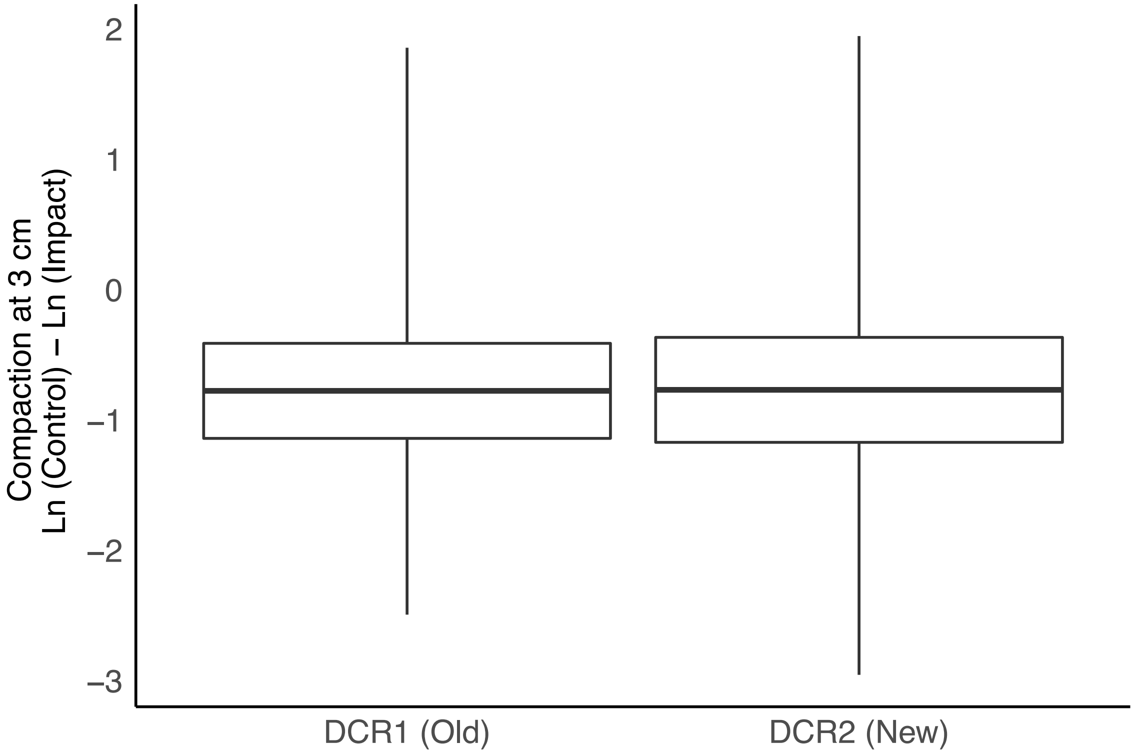

Figure A4-4. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in compaction at 3 cm (psi).

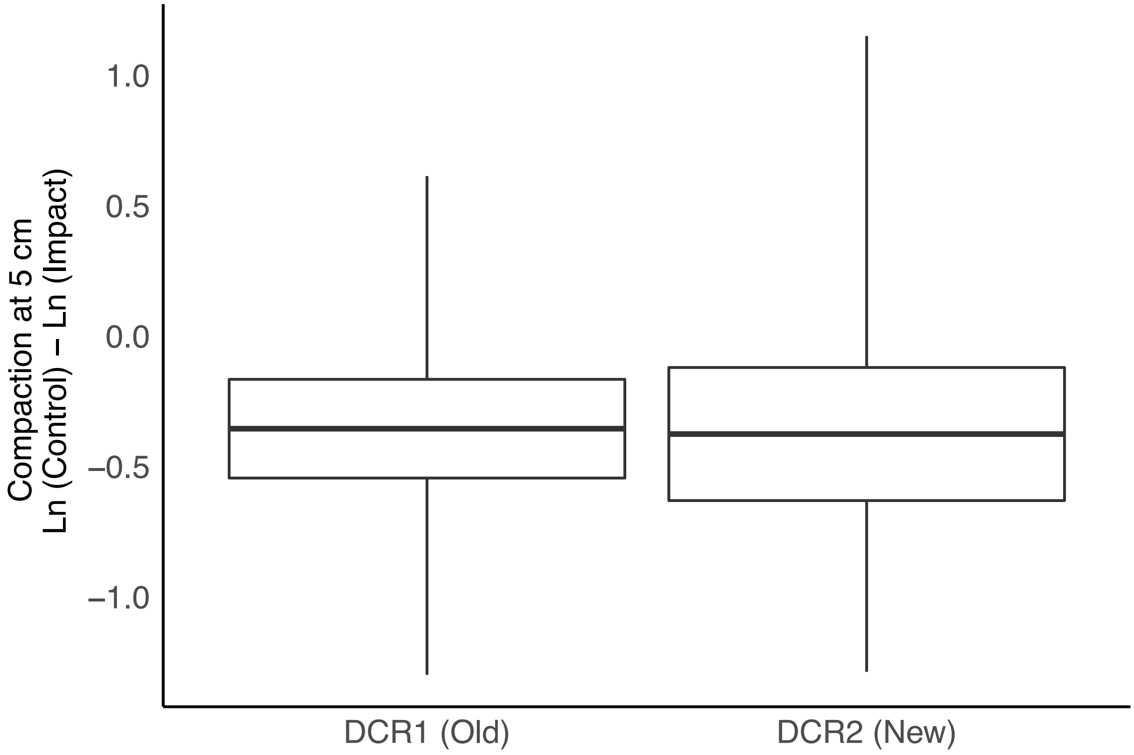

Figure A4-5. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in compaction at 5 cm (psi).

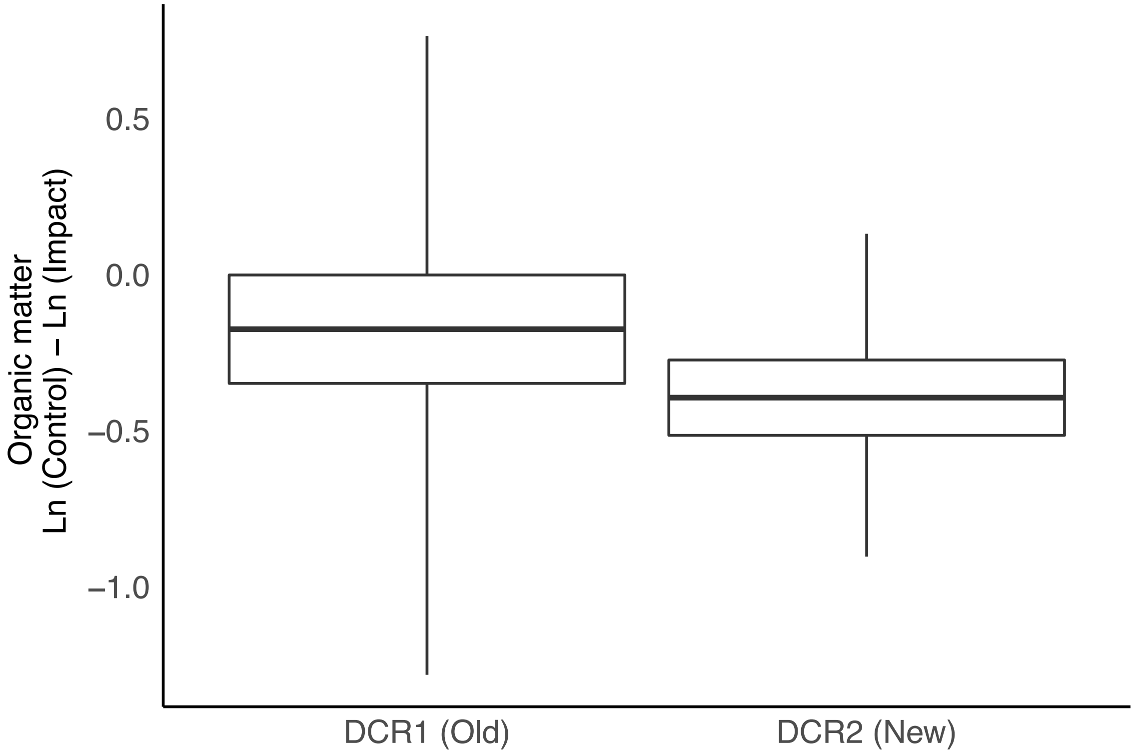

Figure A4-6. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in soil organic matter (%gg^{-1}).

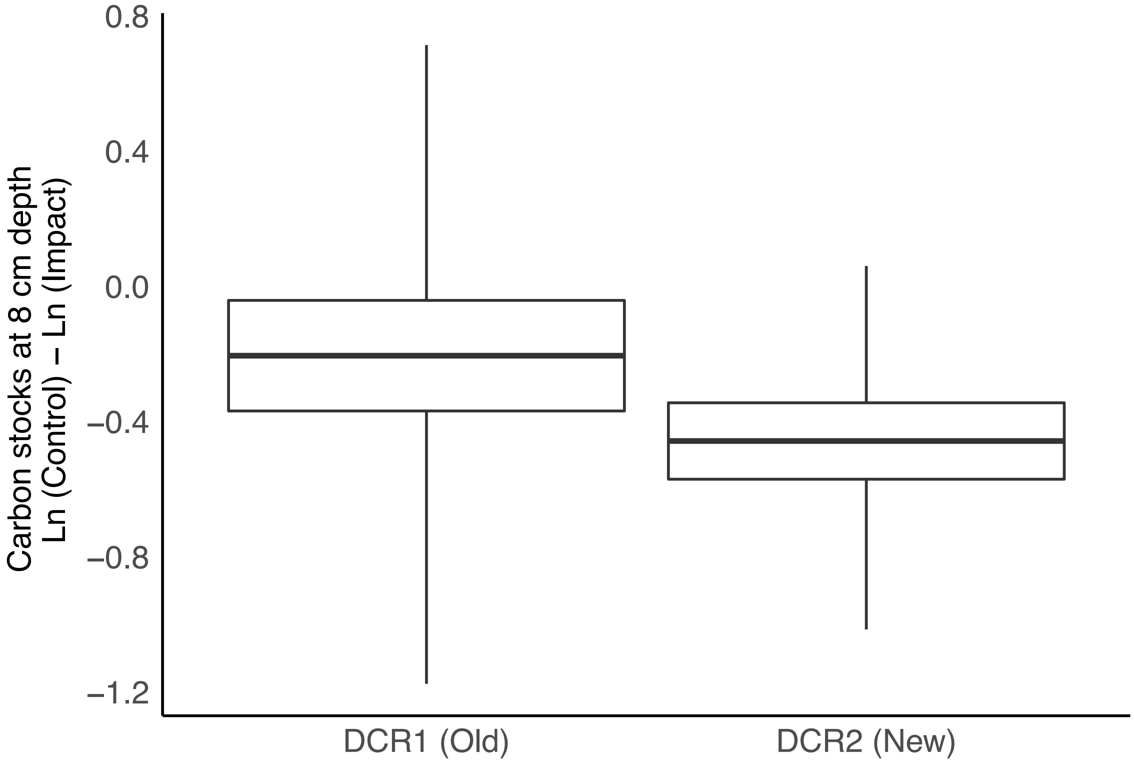

Figure A4-7. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in carbon stocks to 8 cm depth (gC/cm^2).

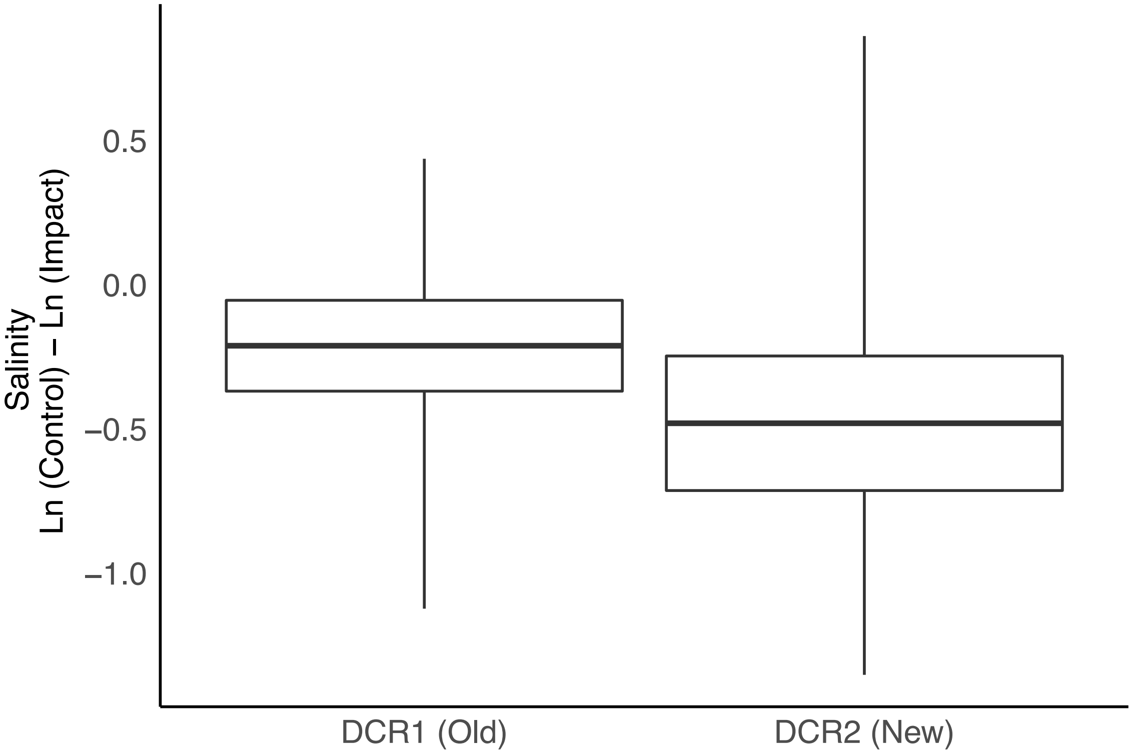

Figure A4-8. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in salinity (parts per thousand).

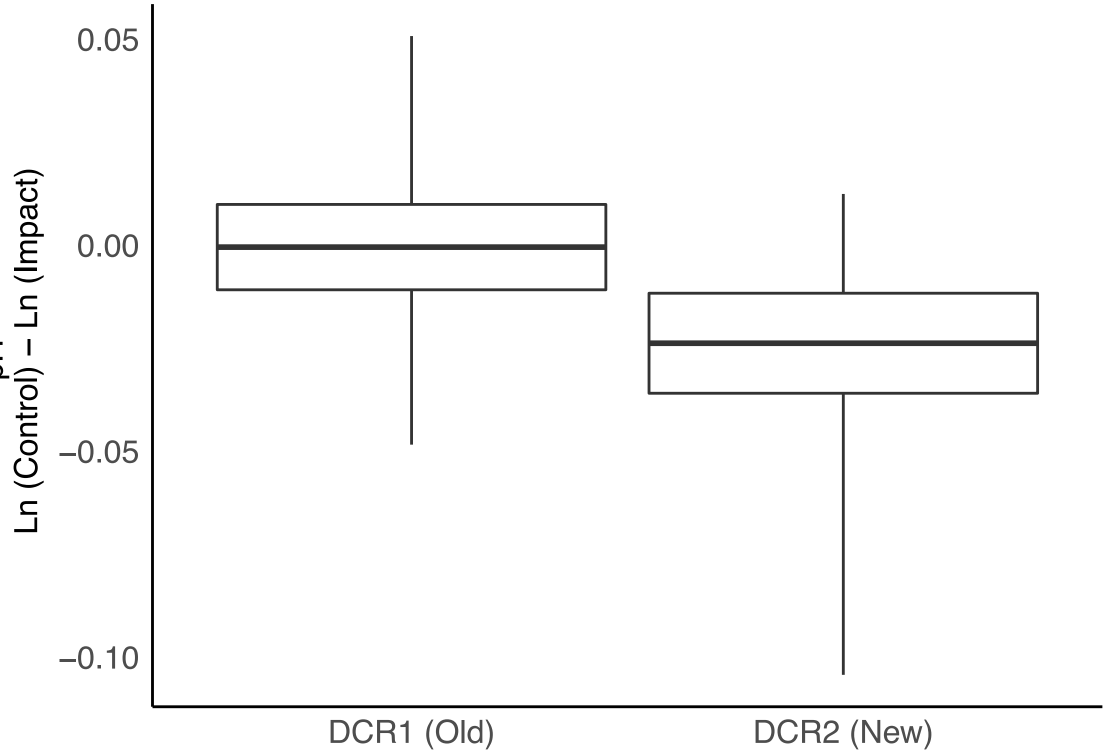

Figure A4-9. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in soil pH.

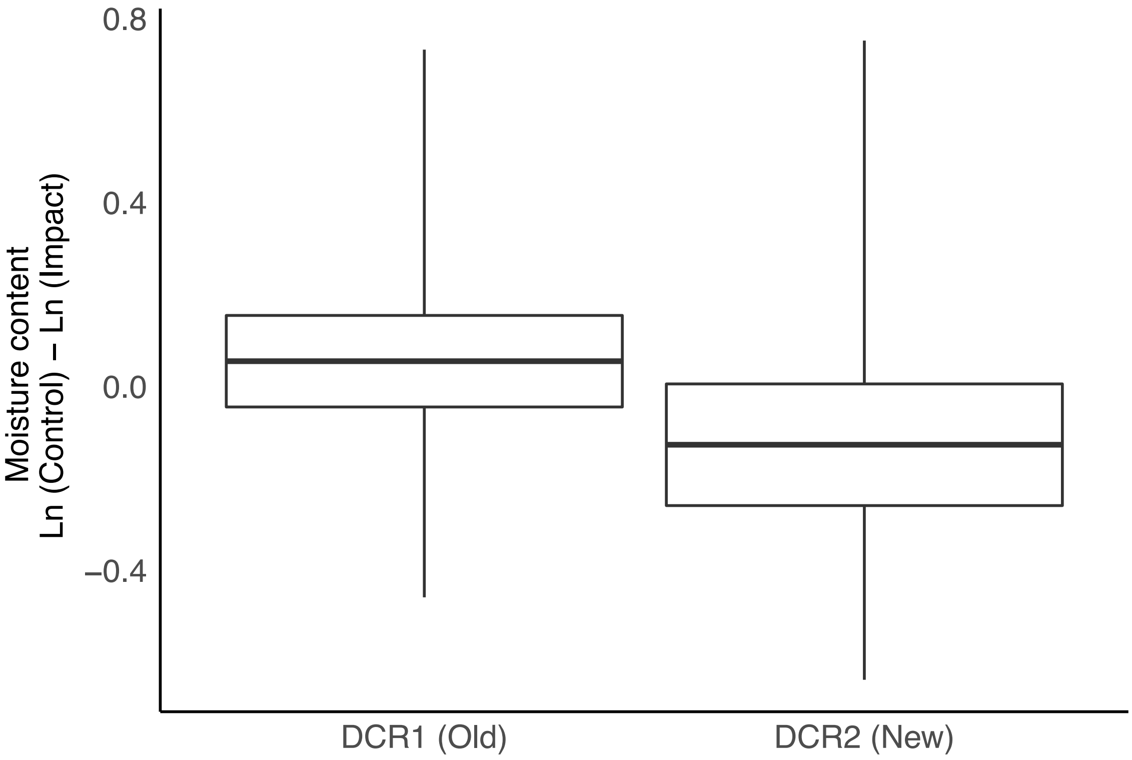

Figure A4-10. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in soil moisture content (%gg^{-1}).

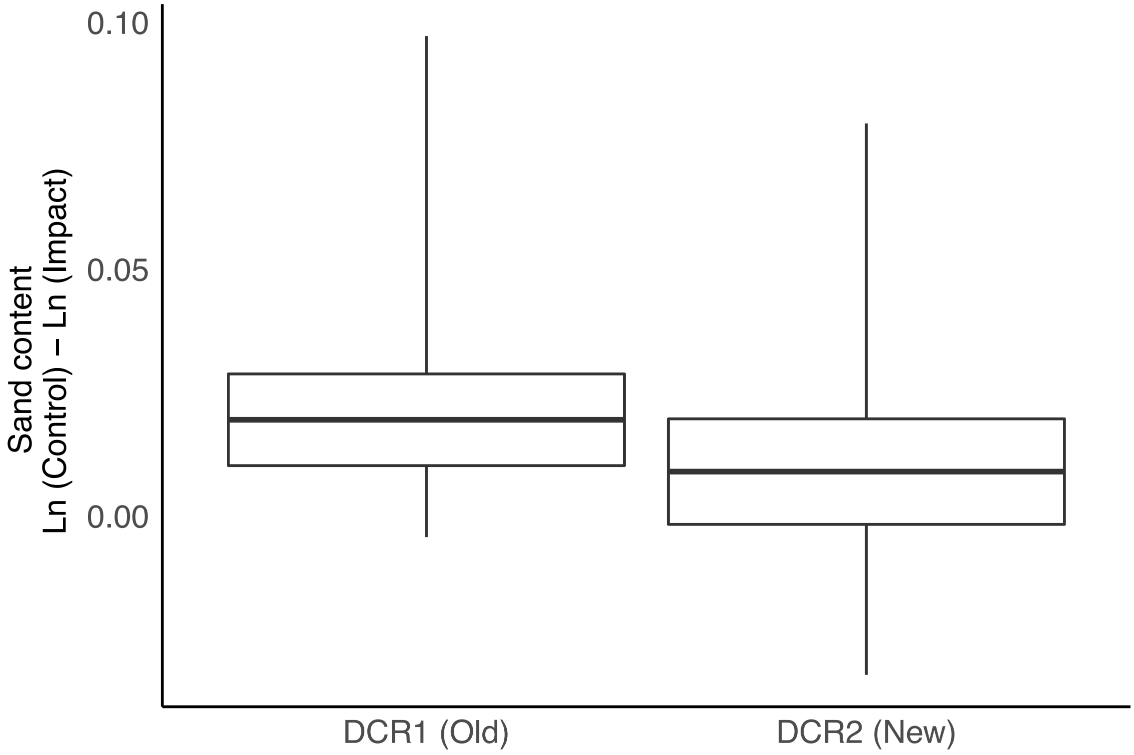

Figure A4-11. Box plots showing the mean difference between control and impact, standard error of the mean, and the minimum and maximum difference in sand content (%).

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CHAPTER 5

Conclusion

I will begin this chapter by summarizing the main ideas and results of each chapter in the dissertation. I will then discuss some future research opportunities and land management implications.

5.1. Summary of findings

Chapter 1 provided a summary of research on the recovery of desert habitats from anthropogenic impacts. Previous research established that typically desert habitats have been left to recover naturally with no active intervention. Most of the previous research predicting recovery time have focused on intense and long-sustained disturbances such as recovery from abandoned towns, roads, and military training areas. Not including the service road and spur roads connecting the towers to the service road, transmission power lines comprise of long linear corridors with impacts occurring during construction at only one point in time. In addition, impacts associated with overhead transmission power line construction may not be as intense as the impacts associated with pipeline and aqueduct construction which typically involve trenching (Lovich and Bainbridge, 1999).

The main objective of this research was to ascertain if vegetation and soil characteristics impacted by transmission power line construction had recovered. To answer this, first, I wanted to determine the effects of construction activities. In chapter 2, I attempted to determine the immediate impact on vegetation from transmission tower construction. NDVI immediately after construction was compared to the pre-construction baseline and the results of three independent analyses indicated there were no differences. Comparisons in NDVI between impact and control sites within the same year during and immediately after construction also yielded no differences indicating that the impact from construction was not detectable. The results also indicated an increase in greenness of both impact and control sites over time. This study, however, did not provide any information on the quality of vegetation present.

Chapter 3 examined the species richness, plant density, and percent cover of vegetation (perennial and annual species) in the field at impact sites relative to control sites thirty-three years after construction. Control sites were in adjacent undisturbed areas. The results, like in chapter 2, indicated no differences between control and impact sites. Both chapters 2 and 3 focused on vegetation.

Impacts to soil can affect vegetation recovery (Bolling and Walker, 2000; Webb and Thomas, 2003) and chapter 4 examined short-term and long-term impacts of construction on soil characteristics. Soil data were collected thirty-one years after construction and within one year of construction completion of transmission power lines. The results indicated that soils remain compacted at 3 cm from surface even thirty years after construction. Though not significant with $p > 0.05$, most of the soil characteristics measured at the new impact sites were slightly different from the control sites ($p < 0.1$), indicating there may be an immediate effect of construction on the soil. However, the lack of significant differences between impact and control sites for most of the soil characteristics implies that transmission construction may not be as impactful on soil as other anthropogenic disturbances that have been studied previously. The results also confirmed the fertile island effect (Rostagno et al., 1991; Schlesinger et al., 1996; Titus et al., 2002; Walker et al., 2001; Whitford et al., 1997) of arid ecosystems with soil characteristics measured under shrub canopies significantly differing from the corresponding soil characteristics measured between shrubs in the bare ground.

The segment of transmission power line (DCR1) studied in the three chapters was the same, but the impact and control sites were defined differently. In chapter 2, I used transmission tower locations as the impact sites and established a corresponding control site 50 m south of each impact site. In chapter 3, I established 2 m x 30 m belt transects starting at the edge of the transmission tower and up to 10 m away. The exact area of impact associated with the towers is not precisely known and the distance gradient served to assess if there was a distance from impact effect on vegetation. The control transect was located 100 m away. In chapter 4, besides sites impacted during tower construction, sites impacted by conductor pulling and splicing (wire sites) were also assessed. In addition, data were collected along both DCR1 and DCR2 to assess long-term and short-term effects of construction respectively. Regardless of the different methods of assessment, the results indicated no significant differences between the impact and control sites for vegetation characteristics. Complete soil recovery, on the other hand, was not achieved since soils remained compacted at the surface even thirty years after construction.

The results of this research indicate that complete soil recovery (compaction) might be lagging vegetation recovery on sites impacted during transmission power line construction. Even though the soil is compacted at the surface relative to adjacent undisturbed control sites, it has not affected vegetation reestablishment and recovery, indicating that the level of impact from transmission power line construction to soils may not be substantial.

5.2. Implications to Land Management

California is assertively pursuing energy from renewable sources to meet its renewable portfolio standard (California Public Utilities Commission, 2017). The renewable portfolio standard (RPS) requires 33% and 50% of all electric energy be sourced from renewables by 2020 and 2030 respectively (California Public Utilities Commission, 2017). To meet California's RPS and growing customer demand, the deserts of California are expected to support new construction of renewable sources, such as solar and wind, and the related infrastructure, including transmission power lines and substations (California Energy Commission, 2017). Desert regions are occupied by sensitive and protected plant communities and wildlife species and at the same time, are expected to support the shift to solar and wind energy sources. The growing demand for renewable energy sources emphasizes the ever increasing need to strike a balance between human progress and habitat management and conservation (Hernandez et al., 2014; Lovich et al., 2011; Tsoutsos et al., 2005; Turney and Fthenakis, 2011). To streamline permitting of renewable energy projects, under both state and federal law, the Desert Renewable Energy Conservation Plan (DRECP) has been proposed under the collaborative effort of multiple local, state, and federal agencies including the Bureau of Land Management (BLM), California Public Utilities Commission (CPUC), California Energy Commission (CEC), United States Fish and Wildlife Service (USFWS), etc. Specifically, the DRECP is focused on facilitating the timely permitting of solar, wind, and other sources of renewable energy and the associated transmission power lines in the Mojave and Colorado Desert regions (California Energy Commission, 2017) of southern California. A consequence of this is the multitude of direct and indirect impacts on desert habitats.

This dissertation introduced and evaluated some of the primary effects of transmission power line construction on vegetation and soil. But there are several other negative effects such as mortality of animals along roadways, habitat fragmentation and affects to gene flow and movement, increased access to otherwise remote areas for illegal activities such as hunting and vandalism of cultural sites, and increased erosion (Andrews, 1990; Lovich and Bainbridge, 1999). In addition, the transmission towers provide perches and nesting sites for ravens (*Corvus corax*) that prey on the state and federally threatened desert tortoise (*Gopherus agassizzi*) and other wildlife (Lovich and Bainbridge, 1999). The other indirect impact is from increased access through recreational activities such as camping, tours, and off-road vehicle usage along the service roads that can bring in trash and invasive plant species (Brooks, 1999; Brooks and Lair, 2005). Invasive species can increase the likelihood of fire and affect the plant community structure (Abella, 2009; Brooks and Pyke, 2001; Lovich and Bainbridge, 1999).

With the projected increase in development in the desert with respect to renewable energy sources, there are going to be large areas of temporary and permanent impacts that will require restoration. Application of active restoration techniques can alleviate the effects of disturbances and speed recovery, but unpredictable results and environmental conditions can impede success and make it more challenging (Abella and Newton, 2009; Lovich and Bainbridge, 1999). Research on active restoration has indicated that it is affected by the same factors that affect natural recovery and it is just as unpredictable in terms of success (Abella and Newton, 2009; Bainbridge, 2012; Weigand and Rodgers, 2009). Besides ecological goals, active restoration is also characterized by monetary, time-based, and regulatory goals (Miller and Hobbs, 2007). Considering the added costs of active restoration, it is valuable to explore the natural recovery of habitats impacted by disturbances of varying intensities since this can be significant factor in successful recovery (Bolling and Walker, 2000). Additionally, understanding the process of natural recovery may help determine the level of effort necessary during active restoration.

Restoration techniques can include seeding, irrigation, transplanting seedlings, weed control, mulch application, recontouring, reapplication of topsoil, and application of erosion control measures (Abella and Newton, 2009; Bainbridge, 2012). Research focused on active restoration methodologies applied to various types and intensities of disturbances is necessary to efficiently restore impacted areas in the desert. With the implementation of the DRECP, there is a research opportunity to study the effects of passive restoration (natural recovery) and active restoration on the same impact type in the same location. The results of this research will help resource agencies and restoration ecologists improve the overall efficiency of active restoration.

Research on natural recovery can also help ascertain if walking away from an impact is a viable option. With the projected increase in the rate of development in desert habitats, walking away from an impact may no longer be an option in the future. Undeniably, with the changing climate, unpredictable precipitation events, increases in carbon dioxide and nitrogen deposition, increasing access, and introduction of resilient invasive species, restoration is going to be even more challenging. It will be critical for agency leaders and restoration ecologists to constantly communicate and share their practical knowledge and experiences to ensure cost-efficient and ecologically-efficient restoration of the impacted land in the deserts. In this dissertation, I have been alluding to habitat restoration focusing on vegetation. But restoration research could benefit from taking a holistic approach by investigating several direct and indirect effects of the impacts and developing restoration objectives that involve ecosystem function rather than just focusing on vegetation communities. It is reassuring that even when restoration is not actively implemented, the desert habitat perseveres and is capable of eventual recovery.

5.3. References

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