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Effect of Depostition From Static Rocket Test Fires on Corn and Alfalfa

Scout Mendenhall
Utah State University

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EFFECT OF DEPOSITION FROM STATIC ROCKET TEST FIRES ON CORN AND ALFALFA

by

Scout Mendenhall

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

Dr. Laurie McNeill Environmental Engineering Major Professor	Dr. William Doucette Environmental Chemistry Committee Member
Dr. Bruce Bugbee Crop Physiology Committee Member	Dr. Mark McLellan Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

Effect of Deposition from Static Test Fires on Corn and Alfalfa

by

Scout Mendenhall, Master of Science

Utah State University, 2012

Major Professor: Dr. Laurie McNeill
Department: Civil and Environmental Engineering

A greenhouse study was conducted to determine the effects of deposition from static rocket test fires on corn and alfalfa. Seeds were germinated in a wide concentration range of depositional material, called test fire soil (TFS). Additionally, the impact of chloride and aluminum, two major components of test fire soil, on germination was also evaluated. Furthermore, plants were grown in packed columns and exposed to test fire soil, either in the root zone or on foliage. Tissue was weighed and analyzed to compare biomass production and plant composition.

Corn and alfalfa exposed to test fire soil in the root zone produced less biomass than controls, but foliar treatment had no effect on biomass production. No kernels were produced by corn exposed to test fire soil in the root zone. Leaves of plants exposed to test fire soil in the root zone accumulated more metals and nutrients than controls, whereas plant tissue treated with test fire soil on the leaves contained only elevated levels of aluminum, although levels were still within reasonable concentrations for plants.

Germination of seeds was not affected below 1% test fire soil in soil; however higher concentrations of test fire soil decreased percent germination. Addition of chloride to soil also inhibits germination, but addition of aluminum has no effect on germination percentage. Corn germination was restored in test fire soil leached with 200 mm artificial rainwater.

The results of this research contribute information regarding the potential impact of test fire soil from static test fires on crop production. Test fire soil inhibits germination and growth if deposited in the root zone, and even foliar application alters tissue composition. However, plant composition is not altered significantly in terms of feed criteria, and germination can be restored by irrigating the TFS.

The effects of test fire soil are attributed to high levels of chloride that induce salt stress. Crop damage may be avoided by conducting static test fires after crops are harvested or providing extra irrigation to soil impacted with the TFS.

(91 pages)

PUBLIC ABSTRACT

Effect of Deposition from Static Test Fires on Corn and Alfalfa

Scout Mendenhall

Alliant Techsystems, Inc (ATK) manufactures solid rocket motors for the National Aeronautics and Space Administration (NASA) at the Promontory, UT facility. Periodically ATK conducts static test fires, where the rocket is restrained horizontally and fired into a hillside. The plume entrains native soil and is carried by the wind until it cools and settles. Although the area around ATK is sparsely populated, residents of nearby Penrose and Thatcher, UT are concerned with the deposition of the test fire soil (TFS) from the static rocket tests. In 2010, several crop fields nearing harvest were dusted with TFS, prompting the investigation of its effects on corn and alfalfa.

The objective of this research is to determine the impacts of TFS on the germination, biomass production, and plant composition of corn and alfalfa exposed to TFS deposition. One significant component of TFS is chloride, an inorganic anion that induces salt stress in plants. If large amounts are deposited, TFS contains enough chloride to prevent germination and reduce growth. This study was designed to determine the effect of a worst-case scenario, 1 inch of TFS deposition, which is the maximum amount that has been observed historically.

Germination studies were performed with various concentrations of TFS in soil. The highest concentration evaluated was 10% TFS in soil. This concentration was calculated from the worst-case deposition scenario, one inch of TFS tilled into the top 10 inches of soil. At concentrations of 1 - 10% TFS, germination was reduced, but below 1% TFS, no effect was noticed. A germination study was performed after washing the

TFS with artificial rainwater. After 7 days there was no significant difference between corn germination in the leached TFS and controls, indicating that the adverse effects of the TFS can be mitigated by washing the chloride out of the root zone.

Biomass production was measured by weighing the tissues collected from plants exposed to TFS in a greenhouse. Exposure to TFS occurred in either the soil (root zone) or on the leaves of the plant. Plants treated with TFS in the root zone had severely reduced biomass production. Corn did not produce any appreciable yield, and alfalfa production decreased drastically after exposure to TFS.

Plant tissue was analyzed for metals and anions. Corn and alfalfa exposed to TFS in the root zone accumulated higher levels of metals and nutrients than controls and foliar-treated plants. Plants whose leaves had been treated with TFS accumulated more aluminum than controls. Although treatment caused significant differences in plant composition, the metal or nutrient levels were not high enough to be considered detrimental to plant health.

This study shows that high amounts of deposition from static test fires at ATK could result in damage to field crops especially during more sensitive growth stages. Adopting test-fire guidelines that will reduce TFS deposition on seeds and young plants may reduce the impacts of static test fires and prevent crop damage. Conducting test fires after harvest would further prevent the change in plant tissue composition. Providing extra irrigation to soil impacted with the TFS may also help to mitigate potential impacts.

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Scout Mendenhall

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CHAPTER 1

INTRODUCTION

1.1 Background

Alliant Techsystems (ATK) is a worldwide company specializing in aerospace and defense systems. They are the world's leading producer of ammunition and solid rocket propulsion systems, with facilities located throughout the USA (Alliant Techsystems Inc. [ATK] 2011). ATK supplies US armed forces with munitions and missiles. Under contract with the National Aeronautics and Space Administration (NASA), ATK also provided the solid rocket motors (SRMs) that propelled the space shuttles into orbit.

ATK manufactures SRMs for NASA's space program at their Promontory facility, located in northern Utah. SRMs contain propellant consisting of powdered aluminum, ammonium perchlorate, polybutadiene acrylic acid acrylonite, iron oxide, and an epoxy curing agent (NASA 2006). Combustion of an SRM provides 11.6 million newtons (2.6 million pounds) of thrust during liftoff to propel the space shuttle into orbit (ATK 2007).

In order to promote safety and success of NASA's missions, ATK is contracted to periodically evaluate the capability and reliability of the SRMs before sending payload into orbit. Solid rocket motors are evaluated by performing static test fires. The first static test conducted at the ATK Promontory Facility was in 1977 (ATK 2010). Since then, 54 tests have been conducted for NASA's space program (Jason Wells, ATK, personal communication, 20 May 2011).

In a static test fire, the SRM is fixed in a horizontal position, blazing the exhaust into a hillside. After ignition, the propellant burns for approximately two minutes at a temperature of 3315 K (6000 F) (Williams and Malone 1999) and forms an exhaust cloud composed mainly of soil, aluminum oxide, hydrochloric acid, and water. Nearly 1.5 million kg of native soil, rocks and debris are entrained in the searing plume as the motor is fired into the hillside (Jason Wells, personal communication, 31 August 2010). The plume of rocket exhaust and native soil, called Test Fire Soil (TFS), rises in the air, carried by wind currents until it cools and settles back to the ground.

Because wind direction and velocity vary, deposition does not fall in the same location every time a motor is fired. The TFS has fallen on several nearby communities, fields, wetlands, and salt flats that surround ATK property. To the north, Thatcher, Bothwell, and Tremonton have been sprinkled with TFS. East of the test site, the town of Penrose and the Salt Creek Wetland Management Area are often dusted with deposition. TFS has also been deposited on rangeland and salt flats south and west of the test site. ATK dispatches cleanup crews to remove the TFS from roofs and vehicles when deposition affects nearby communities.

As much as 2.5 cm (1 inch) of TFS accumulated on a house in Penrose, UT during one test fire event, although that much deposition is unusual (Reggie Petersen, personal communication, 6 July 2011). Deposition rates of TFS from the February 2010 static test were observed to be highest directly downwind from the test site, ranging from 6.7×10^{-4}-0.09 g $m^{-2}s^{-1}$ (0.04-5.4 g $min^{-1}m^{-2}$), with higher rates observed closest to the test site (Doucette and McNeill 2011).

Local residents raised concerns that TFS deposition increased corrosion of cars, mailboxes, and barbed wire fences. This prompted ATK to ask Utah State University to perform a corrosion study investigating the impact of TFS on metal surfaces in 2009.

Prior to the February 2010 static test fire, mild steel coupons were placed at three locations where meteorologists at ATK expected the plume to deposit TFS. A fourth location was identified upwind to act as a control site. Mild steel coupons were attached to a piece of plexiglass and placed on tripods, subject to the deposition of TFS following the test fire. After the TFS had stopped falling, another set of mild steel coupons that had not been exposed to TFS was placed next to the exposed coupons. The coupons exposed to TFS initially corroded at a faster rate, but after several months the corrosion rates of the exposed and non-exposed coupons were similar (Doucette and McNeill 2011).

ATK contracted USU to investigate the effects of TFS on other surfaces in addition to mild steel. USU prepared to perform another corrosion study in August 2010, comparing corrosion rates of mild steel, painted metal, autobody finish, and vinyl siding. Plume predictions indicated that test racks should be positioned east of the SRM test site. Instead the wind carried the plume northeast, missing the coupons. TFS was deposited on the town of Thatcher, UT and surrounding farmland, and crops nearing harvest were dusted with TFS.

Deposition from the static tests has fallen on the small farming communities of Thatcher and Penrose numerous times, but rarely so close to harvest. Local residents depend heavily on crop production. Farmers wondered if the TFS had a negative impact on their crops, perhaps reducing yield or polluting the corn and alfalfa. Residents posed their concerns to ATK, who agreed to work with USU to explore the effects of TFS deposition on corn and alfalfa. This thesis presents a study to determine the effects of TFS on the germination, growth, and contaminant concentration of corn and alfalfa. Plants grown in a greenhouse were exposed to TFS. Plant tissue was analyzed and biomass production was measured to quantify the impact of TFS on crop growth and development.

1.2 Literature Review

1.2.1 Test Fire Soil

Large quantities of TFS are deposited after each test fire event. NASA estimates the test fire of one 504,000 kg solid rocket motor releases 107,000 kg of HCl and 152,000 kg of Al_2O_3 (NASA 1977). ATK estimates 1.5 million kg of native soil are entrained in the exhaust cloud (Jason Wells, personal communication, 31 August 2010). TFS was collected from three test fire events, including the February 2010 firing of Flight Support Motor (FSM)-17, the August 2010 firing of Development Motor (DM)-2 and the September 2011 firing of DM-3. TFS from the September 2009 firing of DM-1 was provided by ATK.

TFS was collected from DM-1, FSM-17, and DM-3 on polyethylene tarps spread on the ground prior to the static test. The TFS was then transferred to HDPE buckets and air-dried at USU. DM-2 TFS was collected off roofs, vehicles, and driveways. The TFS was analyzed for metals and common inorganic anions at USU. Aluminum was the only metal that was significantly higher in all four types of TFS than in native soil collected at the test fire site. It exists in concentrations 2 to 4 times higher than the native soil.

Chloride was also significantly higher in TFS than in native soil, but at concentrations two to three orders of magnitude higher in TFS than in soil.

Aluminum and chloride may contribute to problems in agriculture. A summary of the aluminum and chloride concentrations for the four test fire events is shown below, in Table 1.

Although similarities are noted between types of TFS (high aluminum, chloride levels), TFS is not identical in composition or texture from test to test. The ratio of rocket exhaust to entrained soil also varies with environmental conditions. Temperature, humidity, and grooming of the hillside around the test site are other factors influencing the heterogeneous nature of TFS.

Elemental components vary in different types of TFS. For example, the ratio of aluminum to chloride varies between 1-1.6 for the TFS shown in Table 1. The ratio of aluminum to chloride in soil is orders of magnitude higher. Other differences are noted between types of TFS. Levels of beryllium, selenium, and cadmium are statistically similar for DM-1 and DM-2 TFS, but less than DM-3 TFS. On the other hand, DM-3 TFS levels are lower than DM-1 and DM-2 for aluminum, vanadium, manganese, iron, copper, barium and lead. There are no statistical differences in concentrations of chromium, cobalt, nickel, zinc, arsenic, antimony, and thallium (data not shown here).

Table 1 Concentrations of aluminum and chloride in four Test Fire Soils and one native soil

Sample	Aluminum (mg/kg)	Chloride (mg/kg)
DM-1 TFS (Sept 2009)	65100	56100
FSM-17 TFS (Feb 2010)	59000	35900
DM-2 (Aug 2010)	70400	69100
DM-3 (Sept 2011)	31500	25200
Native Soil	17300	50-120

Moisture content of TFS also varies from test to test. The TFS fell from the sky like muddy rain in February 2010, and pH < 2 was noted in some cases (Doucette and McNeill 2011). A local resident described the deposition of TFS from earlier test fires to be like dirty snow that collected on roofs, cars, mailboxes, and crops (Reggie Petersen, personal communication, 6 July 2011).

1.2.2 Impacts from Shuttle Launches and Vertical Static Tests

Actual Space Shuttle launches at Kennedy Space Center (KSC) and vertical static tests produce exhaust clouds that have been studied by NASA (1978, 1979), Hinkle and Knott (1985), Anderson and Keller (1983), Dreschel and Hall (1990), and others. The launch pad at KSC is flooded with water before a launch or test fire to protect the launch vehicle from sound waves (NASA 1987). The water vaporizes and mixes with the exhaust products, forming an exhaust cloud largely consisting of aerosols and gases, but little soil. In contrast, at ATK the plume does contain large quantities of soil. Although the character of deposition is different, similarities exist between the exhaust clouds of launches or vertical static tests and horizontal static tests.

Hinkle and Knott (1985) gave an overview of damage caused by the exhaust cloud from space shuttle launches at the KSC, including damage to vegetation, changes in water chemistry, decreased buffering of surface soil, and elevated levels of several heavy metals after deposition of the exhaust cloud, which will be discussed separately below. Residents have complained of similar effects after test fires, although no documentation is available regarding TFS impacts.

1.2.3 Impact on Vegetation

Vegetation can be affected by the deposition of the acidic exhaust cloud. According to Schmalzer et al. (1985), vegetative cover surrounding the launch pad at the KSC generally decreased in response to the exhaust cloud, with the loss of several shrub species. Grasses seemed to be more resistant, except in places of high impact or frequent exposure. Zammit and Zedler (1988) investigated the effect of low pH on seeds and seedlings in a laboratory setting that mimicked deposition from shuttle launches in Florida. They found that germination of seeds was inhibited below pH 1.0. Seedlings and seeds that did germinate below pH 2.0 generally did not live beyond 30 days.

Acid rain events were also reported to cause damage to the surrounding environment (NASA 1978, 1977). Acid rain is produced when droplets of rain scavenge gaseous hydrochloric acid in the exhaust cloud, lowering the pH of the rainwater and forming aerosols which cause extensive damage to plant tissue (Foster et al. 1988; Heck 1980; Schmalzer et al. 1985). After a test fire in Homestead, Florida in 1967, citrus crops were marred by acid rain, and in 1975, rainfall with pH values 1-2 was observed after the launch of a Titan Centaur Launch Vehicle at the KSC (NASA 1978, 1977).

Humidity impacts the extent of damage to vegetation. Effects of hydrochloric acid are more pronounced at high humidity, when water in the air scavenges the hydrochloric acid (Heck 1980; Schmalzer et al. 1985). Heck (1980) explains that plant damage is enhanced if dew is present on leaves, suggesting that early-morning launches may have a greater impact to vegetation.

1.2.4 Impact on Water Chemistry

Water chemistry is altered by the hydrochloric acid in the exhaust cloud, causing a decrease in pH of stagnant or shallow water that may be accompanied by fish kills (Dreschel and Hall 1990; Hawkins et al. 1984; Hinkle and Knott 1985; Schmalzer et al. 1985). Aware of these occurrences, Milligan and Hubbard (1983) performed a field study where fish were exposed to the exhaust cloud of the Space Transportation System-5 launch and collected to determine the cause of death. Fish in an open container died from exposure, whereas fish in a covered container did not. The water in the open container had a pH of 2.4, contrasted against a pH of 7.2 in the closed container. In the shallow water at the edge of the lagoon, a fish kill occurred 1.5 hours after the launch where a pH of 6.2 was noted. Although concentrations of heavy metals were elevated in the exposed container, they did not exceed the threshold of toxicity, and were not assumed to contribute to acute fish kills (Milligan and Hubbard 1983). Hawkins et al. (1984) furthered the study by examining the bodies of fish who met their demise in a launch-related fish kill, finding evidence of damage to the gills from the acid exposure.

1.2.5 Impact on Soil Chemistry

Exposure to the acidic plume induces a rapid drop in soil pH that generally recovers with time, as acid is neutralized by soil. Hinkle and Knott (1985) observed increasing drops in pH and longer recovery times in soils near the Kennedy Space Center, where the soils are repeatedly subject to the exhaust cloud. Diminishing acid neutralizing capacity correlates with increased concentrations of dissolved metals in the soil (Dreschel and Hall 1990).

1.2.6 Aluminum

Aluminum (Al) toxicity is common in acidic soils, where Al is in a mobile and readily-exchangeable form (Langer et al. 2009; Mora et al. 1999). Aluminum inhibits development of plant roots, prevents water and nutrient uptake, and reduces overall plant growth (Delhaize and Ryan 1995).

Agricultural production can be affected by high levels of aluminum when the soil is acidic. Aluminum toxicity has been reported to stunt growth in several crops, including wheat (Miyasaka et al. 1989), barley (Ali et al. 2011), soybean (Abo et al. 2010), cucumber (Pereira et al. 2010), and corn (Bennet et al. 1987). To mitigate aluminum toxicity in cocoa seedlings, lime or organic matter may be applied to prevent toxicity (Shamshuddin et al. 2004).

Some cultivars of plant species may exhibit tolerance to Al toxicity by producing exudates in the root zone as a defense mechanism (Langer et al. 2009; Pereira et al. 2010; You et al. 2005). These exudates, produced by the roots, form chelated Al compounds (Delhaize and Ryan 1995), or precipitate Al in the cell wall (Gaume et al. 2001). Other plants may not exhibit tolerance to aluminum, and even within species, some cultivars are more susceptible than others (Delhaize and Ryan 1995; Langer et al. 2009; Miyasaka et al. 1993).

The soils in the area around ATK are neutral or alkaline with pH 7 or higher. The availability of aluminum is expected to be very low because aluminum is predominantly in precipitated form in alkaline soil. The effects of aluminum toxicity are not expected to be evident in crops affected by TFS.

1.2.7 Chloride

Deposition of the exhaust cloud introduces large quantities of chloride, which remain after neutralization of the hydrochloric acid by the carbonates in the soil. Chloride is a mobile inorganic anion which does not sorb appreciably to soil particles, but is transported by water (White and Broadley 2001; Xu et al. 2000). Chloride is necessary for plant growth in small amounts, but at high levels causes salt stress and ion toxicity (White and Broadley 2001).

Chloride ions contribute to osmotic potential, which affects the flux of water. Salt stress occurs when elevated concentrations of ions induce high osmotic potential in the soil (Munns 2002; Taiz and Zeiger 2006). Plants must expend greater energy to generate water potentials exceeding the osmotic potential to maintain uptake of water.

Ion toxicity occurs when excess ions interfere with uptake of nutrients, disrupting synthesis of proteins and enzymes (Taiz and Zeiger 2006). Plants may accumulate chloride in plant tissue as a result of transpiration (Munns 2002). As chloride concentrations increase, the cells become dehydrated and die if accumulation exceeds toxic levels.

To some degree, effects of high chloride can be offset if sufficient nutrients are available (Kinraide 1999; Munns 2002). For example, the growth of olive trees subject to salt stress was not affected as drastically when sufficient calcium was available (Melgar et al. 2007). Tattini and Traversi (2008) studied the response of Mediterranean evergreens to salt stress at low and high levels of calcium, finding that calcium mitigated salt stress in some species.

Soils are considered saline when the electrical conductivity (EC) of a saturated soil paste exceeds 4 dSm^{-1} (Munns and Tester 2008; Waskom et al. 2007). The EC of a saturated TFS paste (1g TFS:0.25 mL de-ionized water) exceeded the maximum detection limit of available equipment, so de-ionized water was added until a reading could be obtained. The diluted mixture (1 g TFS:50 mL water) had an EC of 2.85 dSm^{-1}. Although the measurement was not obtained using a saturated paste, the results suggest that the EC of TFS is definitely greater than 4 dSm^{-1}. Multiplying the dilution factor by the EC of the mixture, the EC of the paste is estimated to be approximately 570 dSm^{-1}. This corresponds to an extremely high osmotic potential of -20.5 MPa. The osmotic potential of seawater ranges from -2.6 to -2.9 MPa (Taiz and Zeiger 2006). The high osmotic potential induced by TFS is expected to have a detrimental effect on crop growth, especially if TFS is deposited in large quantities.

The threshold of sensitivity to salinity depends on crop type. Field corn may be affected when EC exceeds 2.7 dSm^{-1}. Yield losses of 50% are expected when the soil has an EC of 7.0 dSm^{-1}. Alfalfa yield is affected at 2.0 dSm^{-1}, with a 50% reduction in yield expected when the EC is 8.8 dSm^{-1} (Kotuby-Amacher et al. 2000). The EC of TFS is much higher than the tolerance of corn or alfalfa, and dramatic yield reductions are likely if plants are heavily impacted by TFS.

1.2.8 Foliar Deposition

Another much greater short-term concern of TFS deposition is the exposure of plant foliage. Although foliar uptake is usually low compared to uptake via root systems, it can play an essential role in plant health. When nutrients are not readily available in soil or when plants are nutrient deficient, foliar sprays can be used to improve plant nutrition (Fernandez and Eichert 2009; Marschner 1995, 2012). For example, symptoms of chlorosis in peach trees were relieved after leaves were dipped in solutions containing iron (Fernandez et al. 2008). Foliar application of ferrous sulfate to strawberry leaves seemed to reverse chlorotic effects but was less effective than addition of iron fertilizers in the root zone (Pestana et al. 2012). Foliar sprays containing phosphorous may improve phosphorus-deficient wheat (Mosali et al. 2006; Noack et al. 2011) and persimmons (Hossain and Ryu 2009).

Foliar exposure to certain substances can also damage plants. For example, herbicides are sprayed on foliage to maintain weed control. Irrigation water may even damage plant tissue. Pepper foliage was injured from exposure to saline water from a sprinkling irrigation system (Maas 1993), as were corn (Isla and Aragüés 2010) and alfalfa (Isla and Aragüés 2009). High levels of sodium and chloride accumulated in plant tissue watered with saline irrigation water, resulting in low potassium concentrations and ion toxicity. Exposure of foliage to depositional TFS may result in uptake of metals or chloride that could harm the plant.

Leaves are protected by a waxy cuticle which prevents loss of water and leaching of minerals from plant tissue (Marschner 2012). However, the cuticle is not completely impervious, and substances on leaves may permeate into plant cytoplasm (Noack et al. 2011). Environmental factors such as relative humidity, temperature, and age of the leaf affect the thickness and permeability of the cuticle (Devine et al. 1993). As relative humidity decreases, the driving gradient increases, and more wax is necessary to prevent water loss. In a greenhouse where humidity is high, plants produce less wax than in the field where the moisture content of the air is lower. As a result, greenhouse plants may be more susceptible to foliar exposure of TFS. Impacts may be seen in greenhouse studies where no effects would be observed in the field.

1.2.9 Ground Deposition

The deposition of TFS on top of the soil may create a crusty layer that prevents the diffusion of oxygen into the soil. Many plants do not grow well in oxygen deficient soil conditions (Taiz and Zeiger 2006). Wetland plants whose roots are often submerged in water form aerenchyma, air space between cells that provides transport of oxygen from shoots to the roots (Justin and Armstrong 1987). Some plants, like corn, develop aerenchyma if soil conditions become flooded or otherwise oxygen deficient (Fukao and Bailey-Serres 2004). On the other hand, alfalfa does not develop aerenchyma, and is more sensitive to flooding (Torabi et al. 2011). TFS deposition could impact plant growth simply by its presence on top of the soil if it reduces oxygen transfer into the soil.

1.3 Objectives

Although environmental impacts associated with rocket launches have been observed at the Kennedy Space Center in Florida, the impact of the static tests conducted by ATK are likely to be different since the rockets are horizontally restrained and are directed into a hillside. However, the environmental effects of ATK's static test fires have not been studied in detail and little data has been collected at the ATK Promontory Facility. Deposition on fields and communities near this area sparked local concern in recent years, prompting ATK to evaluate the environmental impact of the deposition from static test fires.

The main objective of this thesis is to determine the impacts of TFS on the growth and nutrient composition of corn and alfalfa exposed to deposition from the static rocket tests at the ATK Promontory facility. These effects were observed primarily by exposing corn and alfalfa to TFS under a variety of conditions. Plant mass and tissue concentrations of metals and anions were compared to establish effects on yield and plant composition. The impact of TFS in the soil and root zone was investigated using column leaching studies to evaluate the mobility of two major components of TFS: aluminum (low mobility expected) and chloride (high mobility expected). The findings of this study will be used to determine if ATK needs to take steps to prevent crop damage. The objective was met by performing several specific tasks:

1. Studies were performed to determine the impact of TFS and its major components (chloride and aluminum) on germination.
2. Plants were exposed to TFS under a variety of conditions in a controlled greenhouse environment. Plant tissue was collected periodically and weighed to compare mass production in the exposed and non-exposed treatments. Plant tissue was also analyzed for total metals and anions to compare plant composition. Variables considered in this study include plant maturity at exposure, point of exposure, and length of exposure. Four exposure conditions were tested:
    a. Corn and alfalfa were grown in soil that contained TFS at a concentration of 10%.
    b. Corn and alfalfa were grown in soil. TFS was added to the top of the soil after 54 days, approximately halfway to plant maturity.

   c. Plants were grown in soil and TFS or soil was applied to foliage after 54 days, approximately halfway to plant maturity.
   d. Plants were grown in soil and TFS or soil was applied to foliage after 54 days. TFS was rinsed off after one week.

3. Column leaching studies were performed to determine the mobility of chloride and aluminum in soil. Soil columns contained TFS either on the surface or mixed homogenously in the soil column to match the plant exposure studies.

CHAPTER 2

MATERIALS AND METHODS

2.1 Germination Studies

Studies were performed to observe the impact of TFS on corn and alfalfa seed germination. These studies followed the 120-hour Standard Toxicity Test for lettuce seed germination described by the Environmental Protection Agency (United States Environmental Protection Agency [USEPA] 1987).

2.1.1 Initial Evaluation

The initial test was performed using TFS from September 2009 firing of DM-1. Treatments included 50%, 10%, 2%, and 0.4% TFS by weight in soil and a control plot without the addition of TFS. A sandy loam with a pH of 6.98, electrical conductivity of 0.90 dS/m, consisting of 1.7% organic matter (Alec Hay, personal communication, 14 May 2012) was used as the base soil. Triplicate petri dishes (150 mm x 15 mm) each received 100 g of the prepared soil treatment and 20 corn kernels or 40 alfalfa seeds. Seeds were pressed gently into the soil using the bottom of a 600-mL glass beaker. The seeds and soil were moistened with 30 mL de-ionized water gently poured in the center of the dish, spreading outward. The wetted soil was covered with 90 g of sand. The petri dish was placed in a gallon Ziploc bag and zipped shut, leaving as much air as possible in the bag. The bagged petri dishes were placed in a darkened growth chamber at 24±2°C. The growth chamber remained dark for 48 hours, followed by 16 hours of light and 8 hours of darkness for the remainder of the test. The seedlings were then counted and percent germination was determined.

2.1.2 Follow-Up Germination Study

Additional studies were performed to observe the effects of aluminum and chloride on germination, following the same 5-day procedure. This second study used five media: soil with TFS, soil with aluminum, soil with chloride, soil with the combination of aluminum and chloride, and soil without any additives. Aluminum was added to soil in the form of aluminum oxide, and chloride was added in the form of hydrochloric acid. Soil treatments tested a chloride target range of 65-6500 $mgkg^{-1}$ and an aluminum target range of 65-6500 $mgkg^{-1}$.

2.2 Plant Study

A greenhouse study was performed to determine the impact of TFS on the biomass production and composition (chloride, aluminum and other metals) of corn and alfalfa. Plants were grown in columns packed with soil as described in Section 2.2.1. Two routes of TFS exposure were explored: through the root zone (2.2.2) or foliage (2.2.3). Plant tissue was collected, weighed, and analyzed periodically for total metals and anions (2.2.4).

2.2.1 Soil Columns

Corn and alfalfa were grown in packed columns made from 12.7 cm (5 inch) diameter PVC pipe cut in 1.22 m (4 ft) lengths. The columns were capped at one end, and tapped with fittings to aid in leachate collection. Holes were drilled on the side of the columns 7.6 cm (3 inches) below the top of the endcap. The holes were threaded, and 0.318 cm (1/8 inch) NPT fittings with 0.635 cm (0.25 inch) tube connectors were inserted (Fig. 1).

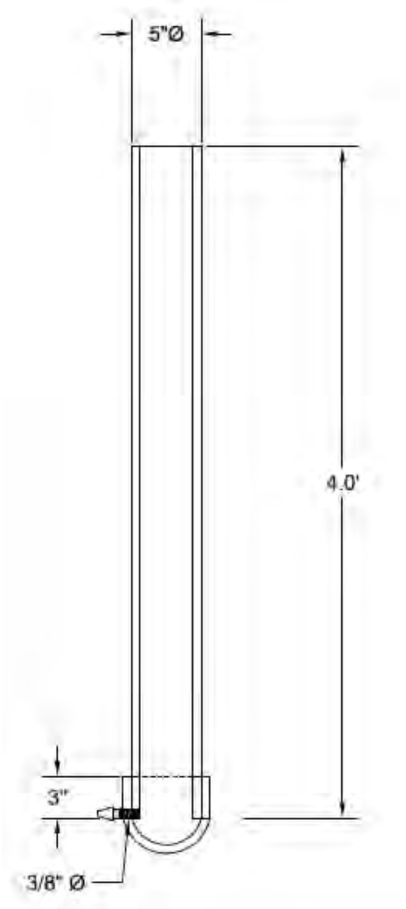

Fig. 1 Construction of column

Columns were packed with a sandy loam soil (pH=7.0, EC=0.90 dS m^{-1}, 1.7% organic matter) and fertilizer (Osmocote 15-9-12 NPK, 3-4 month release) prior to planting. Although soil conditions were different in various treatments (as described in sections 2.2.2 and 2.2.3), they were all packed with moistened soil as recommended by Lebron and Robinson (2003). Logan, UT tap water (pH 7.3, electrical conductivity 300 uS/cm, hardness 200 mg/L $CaCO_3$) was added and the soil was turned several times to promote a homogenous mixture. Soil was scooped into the columns, which were periodically lifted up and dropped 2.5-5 cm (1-2 inches) off the floor to minimize void volumes. As the column was being filled with soil, approximately 20 g fertilizer was added in 5 g increments one quarter, halfway, and three quarters of the way up from the bottom of the column, and 15.2 cm (6 inches) from the top. One of every three triplicate columns was equipped with an ECH_2O Soil Moisture Sensor EC-5 (Decagon Devices, Pullman, WA) placed halfway down the column and 15.2 cm (6 inches) from the top of the soil (Fig. 2).

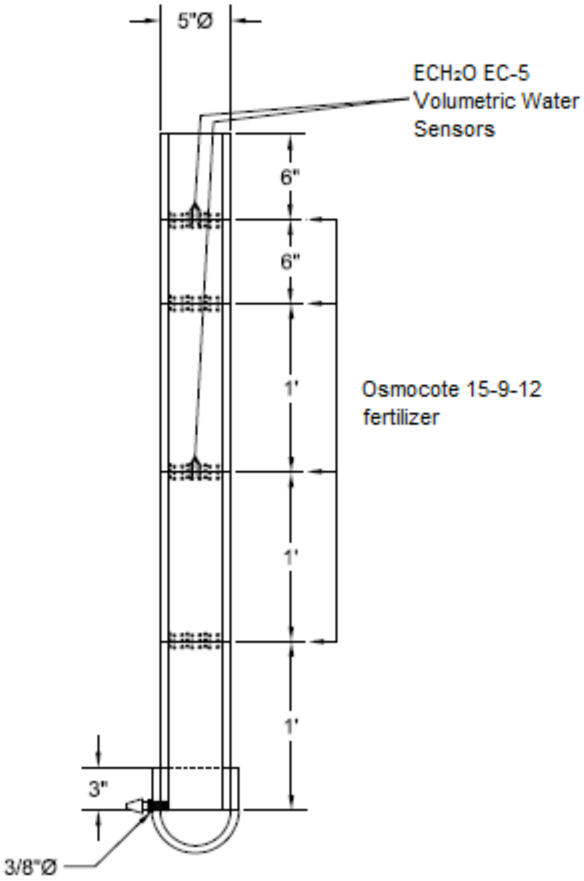

Fig. 2 Packed column, including Osmocote 15-9-12 NPK fertilizer (3-4 mo release) and ECH_2O EC-5 soil moisture sensors. Approximately 20 g fertilizer was added at four depths. Water sensors were placed halfway down and 15.2 cm (6 in) from the top of the column.

Seeds were planted following column packing. Three corn kernels (*Zea mays*, cv. ‘Dekalb 5259’) were planted per column, spaced equally apart and approximately 3.8 cm (1.5 inches) deep. Three alfalfa seeds (*Medicago sativa*, cv. ‘Rugged’) were planted in each column 1.9-2.5 cm (0.75-1 inches) deep. The seeds were lightly covered and misted with tap water from a spray bottle and covered tightly with aluminum foil to prevent the columns from drying out. The foil was left in place except to lightly mist until germination of at least one seed, whereupon the foil was discarded. Corn plants were thinned to one per column, 27 days after sowing.

The columns were watered using tap water dispensed from an automated irrigation system. Pressure compensating drippers were attached to 0.635 cm (0.25-inch) tubes that supplied water from a 2.5 cm (1-inch) waterline that was pressurized at 0.414 MPa (60 psi). Irrigation was automated using a CR1000 datalogger and multiplexer (Campbell Scientific, Logan, UT), and solenoids. The fraction of water in the soil, also called the volumetric water content (VWC), was measured by the EC-5 probes, recorded by the datalogger, and used to automate irrigation. Watering occurred when the VWC of the soil near the lower sensor dropped below a threshold value of 0.1-0.15. Each triplicate set of columns depended on the water sensor readings from a single column within the set of triplicates. The drippers released water for four minutes at a flow rate of 33 mL/minute to allow water to penetrate the column and encourage development of a deep root system. A 3 cm x 4 cm piece of a Scotch-Brite™ pad was placed under the drippers to spread the water over the soil. The scotch pad and drippers were held in place on top of the soil by wire poked 7.6-10.2 cm (3-4 inches) into the soil.

The irrigation scheme was designed to prevent leachate, although some was generated on occasions when the schedule was adjusted. In these cases, all the columns produced similar volumes of leachate, regardless of treatment, suggesting that the automated irrigation was consistent between treatments. The sensors were affected by addition of TFS in or on the soil, producing unreliable measurements, so plants treated with TFS on the soil were watered on the same schedule as control plants.

2.2.2 TFS Exposure in Root Zone

The effect of TFS on growth of plants was investigated by treating the soil with TFS. Three soil conditions were evaluated: soil with 2.5 cm (1 inch) of DM-1 TFS on the soil surface (application to plants 54 days after sowing), 10% DM-1 TFS mixed throughout the soil column (exposure to seeds), and soil without the addition of any TFS. The sandy loam soil used in Section 2.1 as a base soil for germination studies was used in columns where alfalfa was to be planted. The soil used in the columns containing corn was a Collett silty clay loam taken from a corn field located in Thatcher, UT (41°41’48.94”N, 112°17’15.81”W) belonging to Lynn Summers. TFS was provided by ATK from the September 2009 firing of DM-1.

Eighteen columns were prepared for this experiment: nine for corn, and nine for alfalfa (Fig. 3). Six columns were packed with soil and half were planted with corn and the other half with alfalfa, receiving the application of 2.5 cm (1 inch) of TFS to the top of the soil 54 days after planting. This treatment, called “TFS on soil surface,” represented the deposition of TFS on the ground surface where plants were already established (approximately halfway to maturity of corn or after the first cutting of alfalfa). Six more columns were packed with a mixture consisting of 1 part TFS and 9

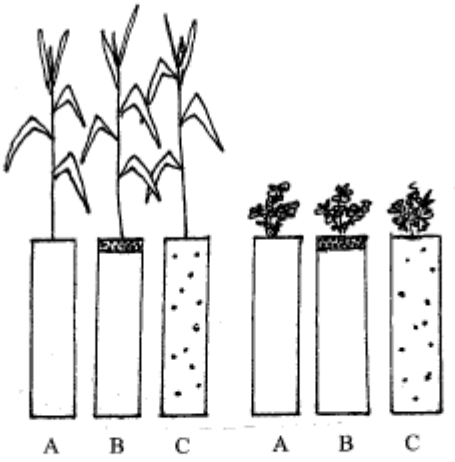

Fig. 3 TFS exposure in root zone treatments included a) soil, b) TFS on the soil surface, and c) 10% TFS, for both corn and alfalfa. Triplicate corn and alfalfa plants were grown for each treatment.

parts soil. This treatment, called "10% TFS," represented the deposition of 2.5 cm (1 inch) of TFS on the soil, plowed into the soil prior to planting. Corn or alfalfa seeds were sown directly into the 10% TFS mixture. Finally, six columns were packed with soil and remained free of TFS exposure to act as controls. Comparisons were made to field corn grown in Thatcher, UT from the farm of Lynn Summers (as described above).

2.2.3 TFS Exposure to Foliage

The effect of deposition on plant foliage was explored using four configurations: DM-1 TFS applied to the foliage (TFS deposition), DM-1 TFS applied to the foliage and rinsed off at a later date (TFS wash), soil applied to the foliage (soil deposition), and soil applied to the foliage and rinsed off at a later date (soil wash). Twelve columns were packed with soil according to the procedure described in Section 2.2.1 and planted with corn or alfalfa. Corn was grown in soil from Thatcher, UT and alfalfa was grown in greenhouse soil. No TFS was added to the soil in the columns.

The exposure of plant foliage to DM-1 TFS occurred after the plants were well established. Treatment of corn occurred after 54 days of summer sunlight, whereas treatment of alfalfa occurred after 130 days of growth in winter sunlight. The plants were lightly misted with de-ionized water before application of soil (50 g) or TFS (40 g—an equivalent volume) directly to foliage. Paper bags were cut and folded into cones around the plants to catch falling soil and TFS, minimizing contamination of the root zone. Soil and TFS were sprinkled over the plant tissue by hand. One week after foliage treatment, three of the plants exposed to soil and three exposed to TFS were rinsed with tap water, using a light shower setting on a watering wand. Plant foliage was rinsed under a flow of 3.55 L/min for 2 minutes. The soil in the columns was covered with plastic to prevent TFS or soil from washing into the root zone of the plants.

2.2.4 Collection and Analysis of Plant Samples

Samples were collected and analyzed periodically throughout the study. The first corn sampling occurred approximately 60 days from sowing, one week after treatment to soil surface or foliage. Leaves (V-stage 7 and 8) were collected from all treatments except 10% TFS, which was not sampled at all because there was insufficient mass. The second sampling of corn leaves occurred about 90 days from sowing. Leaves (V-stage 12 and 13) were collected from control plants and those whose foliage had been treated with soil or TFS, whereas V-stage 9 and 10 leaves were collected from plants treated with TFS on top of the soil because no other leaves had been produced. No tissue was collected from plants grown in 10% TFS because there was insufficient mass. The remaining corn leaf tissue was collected approximately 130 days after planting. Mature ears of corn were also harvested at this time. The first alfalfa sampling occurred before addition of TFS on the soil surface, at 52 days. Two more cuttings were collected 87 and 119 days from planting.

A razor blade was used to cut corn leaves from the plant above the collar of the leaf to prevent damage to the stalk. At the end of the experiment, ears of corn were collected and shelled to compare treatment effects on yield (production of kernels). Corn dried on the plant for 2 weeks before transfer to an oven at 60°C for 5 days. The kernels were shelled off the cob and weighed to 0.1 g. Alfalfa was cut to a height of 10.2 cm (4 inches).

Plant tissue was rinsed with de-ionized water and placed into a paper bag that had been labeled and weighed. The bag and rinsed plant material was placed in a 1390FM Forced-Air Oven (VWR Scientific, Radnor, PA) to dry at 80°C for 48 hours. The bag and dried plant tissue were weighed to determine the dry weight of the plant tissue. Plant material was ground using a Thomas Wiley® Mini Mill (Arthur H Thomas Co., Philadelphia, USA) prior to performing analyses. Analyses were performed to determine elemental and anion concentrations in plant tissue.

An aliquot of each sample was taken to the Utah State University Analytical Laboratories (Logan, UT), where Plant Fertility Package tests were performed for Total N, P, K, Ca, Mg, Fe, Zn, Mn, Cu, Na, S, and other elements. Plant tissue was digested with nitric acid and hydrogen peroxide on a heated block following EPA Method 3050b (USEPA 1996) and analyzed for metals using an Iris Intrepid II Inductively-Coupled Plasma Atomic Emission Spectrometer (ICP-AES) (Thermo Electron, Madison, WI). Total Nitrogen was analyzed by combustion using LECO TruSpec C/N Analyzer (LECO Corporation, St. Joseph, MI). Detection limits for the ICP-AES are shown in Table 2.

Table 2 Detection limits for Thermo IRIS Intrepid II ICP-AES

Element	Detection Limit	Unit
Al	6	mg/kg
As	0.5	mg/kg
B	1	mg/kg
Ba	0.05	mg/kg
Ca	0.0004	%
Cd	0.05	mg/kg
Co	0.25	mg/kg
Cr	0.3	mg/kg
Cu	0.4	mg/kg
Fe	0.15	mg/kg
K	0.0023	%
Mg	0.000035	%
Mn	0.05	mg/kg
Mo	7.5	mg/kg
Na	4	mg/kg
Ni	0.15	mg/kg
P	0.0004	%
Pb	1.5	mg/kg
S	0.00035	%
Se	2	mg/kg
Si	4.5	mg/kg
Sr	1.5	mg/kg
Zn	0.25	mg/kg

Another aliquot of each sample was extracted and analyzed at the Utah Water Research Laboratory (UWRL, Logan, UT) for common inorganic anions. Extraction included addition of 10 mL de-ionized water to 1 g of ground plant tissue (or equivalent weight/volume ratio) in a 50 mL Fisherbrand centrifuge tube and shaking it for 30 minutes on an automated shaker (Eberbach Corporation, Michigan, USA), followed by 20 minutes of centrifuging at 4000 rpm (Beckman Model J2-21), and filtering through a 0.2-um nylon syringe filter (Environmental Express, South Carolina, USA). Analysis of the extract was performed by ion chromatography, modified from EPA Method 300.1-

Determination of Inorganic Anions in Drinking Water (USEPA 1997), using a Dionex ICS-3000 Ion Chromatography system (Sunnyvale, CA).

The analysis of soils for metals was conducted at the UWRL. A microwave digestion procedure was used to prepare soil for analysis. The digestion procedure followed EPA Method 3050b (USEPA 1996). Approximately 0.5 g soil was placed in an APCU-40 75 mL TFM vessel (Milestone, Italy). Sides of the vessel were rinsed with 5 mL de-ionized water, to which 9 mL concentrated nitric acid (trace metal grade, Fisher Scientific) and 2 mL hydrogen peroxide 30% by weight were added. These were capped in an APCU-TR40 Safety Shield (Milestone, Italy), and placed in an Ethos EZ Microwave Digestion System (Milestone, Italy). The samples experienced a 15 minute ramp time to reach 200°C, after which they were held at constant temperature for 30 minutes, and then allowed a cool-down period of 20 minutes. Samples were diluted to 100 mL in a volumetric flask and filtered using Whatman No. 42 filters before analysis for total metals by inductively coupled plasma-mass spectrometry (ICP-MS) following EPA Method 6020 (USEPA 2007).

2.3 Leachate Study

Leachate studies were performed to evaluate the mobility of chloride and aluminum through soil columns. The methods closely followed the Leaching Studies procedure described by the Fate, Transport and Transformation Test Guidelines (USEPA 2008). Columns were created by cutting clear plastic pipe (6-cm diameter) into lengths of 30 cm. These were prepared for packing by securing a Whatman 42 filter tightly on the bottom of the column using #64 (8.9 cm x 0.635 cm) and #84 (8.9 cm x 1.3 cm) rubber bands. The three soil treatments described in Section 2.2.2 were added in 10-20 g increments and compacted using a Fisher Vortex Genie 2 (Scientific Industries, Bohemia NY) to remove voids. Each soil treatment was analyzed using four replicate columns that held 28 cm of consolidated soil treatment. A Whatman 42 paper filter 6 cm in diameter was placed on top of the soil to spread water over the surface area of the top of the column. Artificial rainwater (0.01 M $CaCl_2$) was applied at a rate of 0.2 mL/min using a Cole Parmer Masterflex L/S peristaltic pump (Barnant Co, Barrington, IL) for 48 hours, simulating a 200 mm rain event over 2 days. Leachate was collected in 60-mL plastic snap cap vials placed below columns 40, 44, and 48 h after the experiment began. Leachate was analyzed for total metals by ICP-MS and anions were analyzed by ion chromatography, as described in Section 2.2.4.

The top 3 cm of leached soil was collected after conclusion of the leachate study and used in a germination study following procedures similar to those described in Section 2.1. Twenty corn kernels or 40 alfalfa seeds were planted in triplicate petri dishes with leached soil, leached TFS, or leached 10% TFS in soil, covered with 30 mL de-ionized water and 90 g white sand, bagged and placed in a constant temperature growth chamber. After 48 hours of darkness, a 16 h photoperiod followed by 8 hours of darkness commenced for 10 days. Germinated seedlings were counted at 5, 7, and 10 days.

2.4 Statistical Analysis

Statistical analyses were performed using R statistical software. Significant differences were determined by ANOVA ($p<0.05$) and Tukey Honest Significant Difference tests.

CHAPTER 3

RESULTS

3.1 Germination

3.1.1 Initial Evaluation

The results of a 5-day test for corn and alfalfa are summarized in Table 3, with TFS concentrations ranging from 0-50% TFS. Corn germination was not affected by 0.4% or 2.0% TFS treatments. No germination was observed in 10% or 50% TFS within the 5 day period of the test; however corn was observed to germinate in the 10% TFS after 8 days (about 15% germination; data not shown). No germination occurred in 50% TFS. Alfalfa was impacted by 0.4% TFS, with germination reduction of 30%, statistically lower than controls. Alfalfa did not germinate in TFS concentrations higher than 0.4% TFS.

Although corn germination percentage was not statistically different from 0-2% TFS, the corn in 2% TFS was smaller than in 0 or 0.4% TFS (Fig. 4).

Table 3 Germination study results for corn and alfalfa in concentrations ranging from 0-50% TFS.

	Average Percent Germination	
Percent TFS in soil	Corn	Alfalfa
0	95 ± 1.0	92 ± 1.0
0.4	100 ± 0	62 ± 2.9
2	97 ± 0.6	0 ± 0.0
10	0 ± 0.0	0 ± 0.0
50	0 ± 0.0	0 ± 0.0

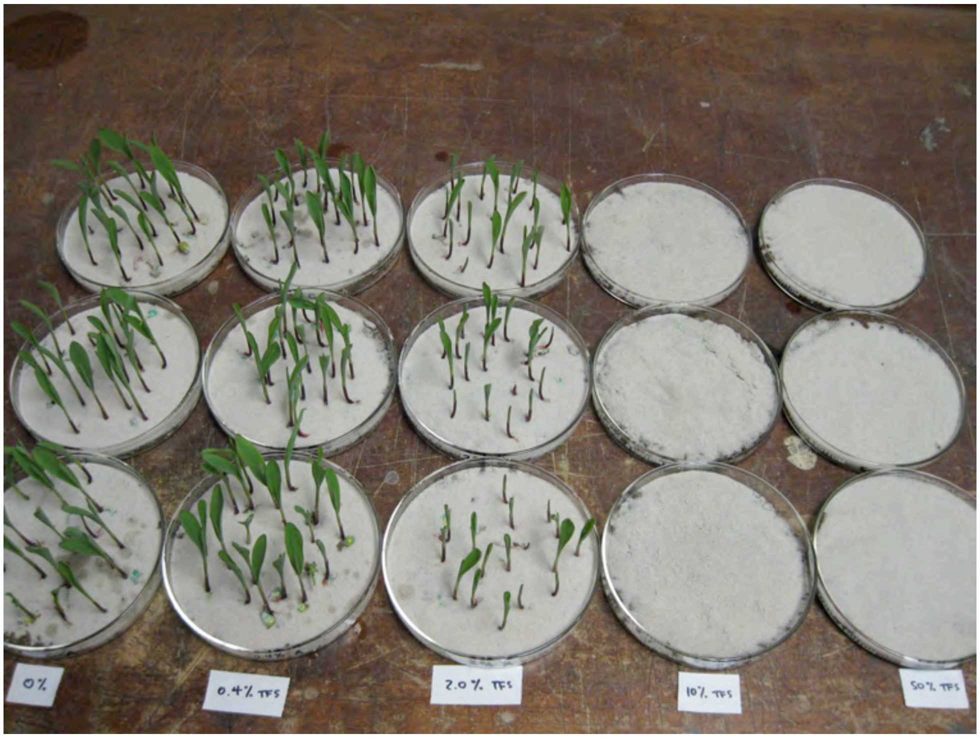

Fig. 4 Photo of initial germination study. From right to left, control (soil), 0.4% TFS, 2% TFS, 10% TFS, and 50% TFS. Germination in 0-2% TFS not statistically different, but 2% corn appears smaller than controls or those germinated in 0.4% TFS

Germination percentage reduction in 10% and 50% could be explained by the high salt content of the TFS. This assumption was tried in a follow-up germination study that examined germination in various concentrations of TFS or soil treatments where aluminum or chloride was added to soil.

3.1.2 Follow-Up Germination Study

The follow-up germination study observed the effect of chloride and aluminum on germination percentage. Results are tabulated in Tables A1 and A2.

While aluminum had no significant effect, chloride at concentrations of 2000-3000 mgkg^{-1} soil reduced alfalfa germination to approximately 40-50% and completely prevented germination above 6000 mgkg^{-1} (approximately 10% DM-1 TFS) (Fig. 5). In contrast, corn germination decreases at chloride concentrations above 2500 mgkg^{-1}, and drops to 3-13% germination at concentrations above 2800 mgkg-1 (approximately 5% DM-1 TFS) (Fig. 6).

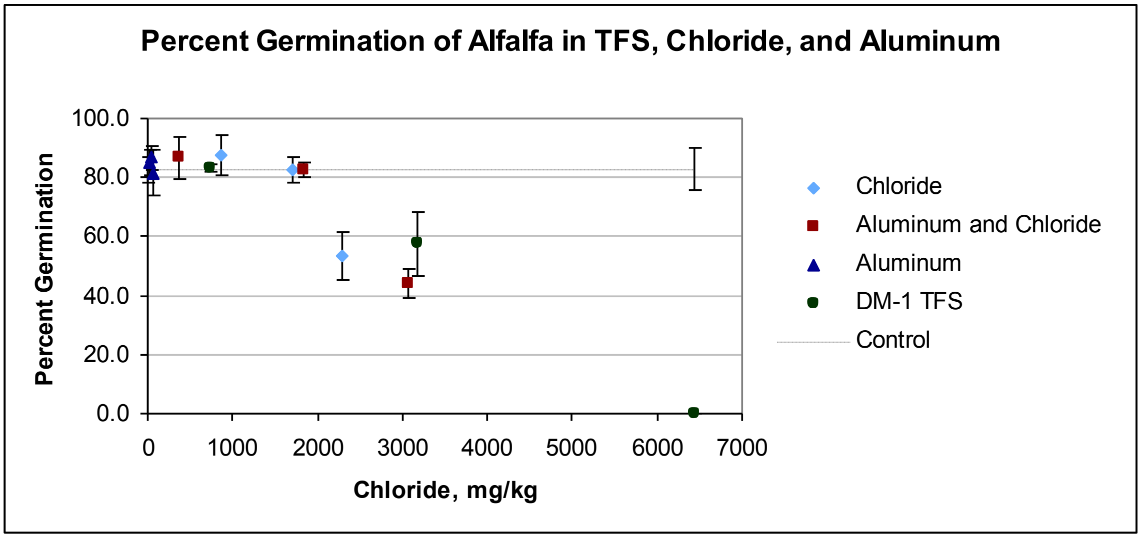

Fig. 5 Effect of chloride on germination of alfalfa. Error bars represent one standard deviation.

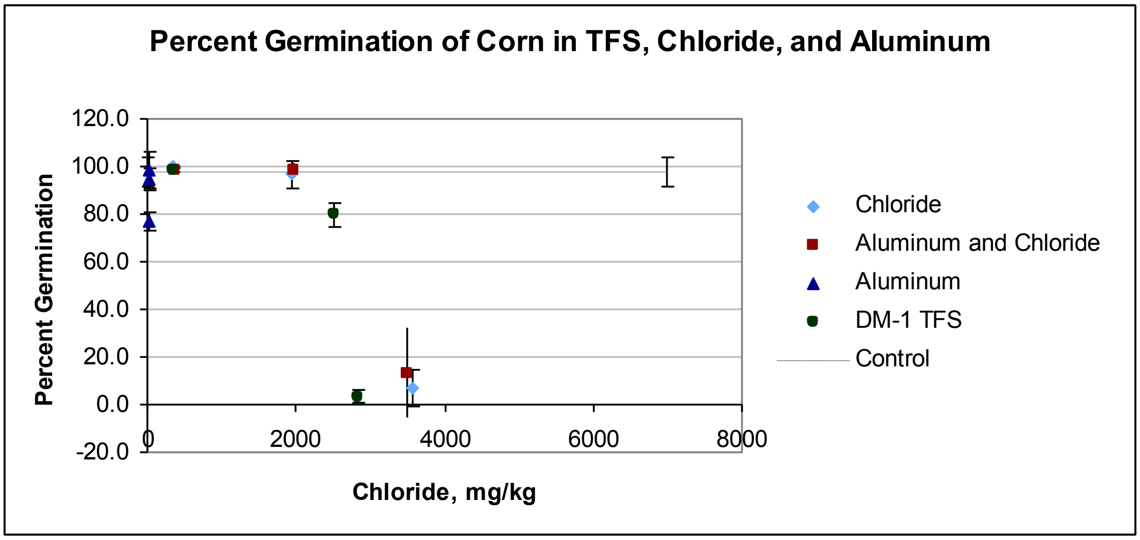

Fig. 6 Effect of chloride on germination of corn. Error bars represent one standard deviation.

Addition of TFS, chloride, or the combination of chloride and aluminum to soil affected the germination percentage of corn or alfalfa, but these treatments were not significantly different from each other at the same chloride concentration. On the other hand, soil treated only with aluminum had the same germination percentage as the controls, suggesting the ill effects of TFS appear to be caused by chloride. Elevated chloride levels decrease germination, regardless of chloride source (TFS or HCl).

No effect on germination was noted at chloride concentrations below 700 mgkg^{-1}, likely because the chloride concentration is below reported inhibitory levels. Li et al. (2010) found that germination percentage of alfalfa was not affected by 30 mmolL^{-1} salt, but germination was reduced to approximately 75% by 60 mmolL^{-1}. In another study performed by Torabi et al. (2011), germination percentage was impacted above 150 mmolL^{-1} NaCl. No effect was noted in treatments with less than 2000 mgkg^{-1} chloride. In 10 mL de-ionized water, such soil creates an extract containing 200 mgL^{-1} or 5.6 mmolL^{-1} chloride. The chloride is below the reported ranges of impact, explaining the absence of treatment effect at concentrations below 2000 mgkg^{-1} chloride.

3.2 Corn Plant Study

3.2.1 Biomass Production

Control corn plants grown in soil produced 13-14 mature leaves, whereas corn treated with TFS on the soil surface only produced 9-10 mature leaves. New leaves started to form, but they were discolored and only one fully mature leaf was produced after application of TFS to the soil surface. Plants grown in 10% TFS reached a final height of 46-53 cm (18-21 inches), produced tassels, silks, and undeveloped ears 3.8 cm

(1.5 inches) long, with growth patterns that were delayed 25-30 days. The effects of treatments TFS on soil and 10% TFS was visually apparent (Fig. 7).

The biomass produced by plants treated with soil on the leaves (washed or unwashed) was not affected. However, the TFS appeared to "burn" the leaves at the point of contact (Fig. 8), and did have some effect on metal content of corn leaves. Leaves damaged by TFS did not recover (washed and unwashed), but new leaves developed normally.

Soil oxygen levels were not measured to determine if any of the TFS treatments in the root zone decreased oxygen transfer to roots. However, the ability of corn to produce aerenchyma suggests that it would be able to adapt and survive even in oxygen deficient soil conditions.

The total dry mass produced by the controls was the same as corn treated with soil or TFS foliar deposition (washed or unwashed), as well as the field corn. The total mass production of corn treated with TFS on the soil surface was significantly lower than the controls grown in soil and plants whose foliage was treated. Corn grown in 10% TFS produced the least amount of biomass compared with all other conditions. The end-of-summer harvest for corn plant tissue is summarized in Table 4 (see Table B1 for more results). This final mass includes leaves and stalks, but not ears of corn.

Mature ears of corn were produced by control plants and plants whose foliage was treated with soil or TFS. Each of these plants produced one ear of corn whose masses were not significantly different, with average yield (kernel production) ranging from 115.5 to 130.2 g, shown in Table 5. Ears of field corn were collected and found to have similar mass to the controls.

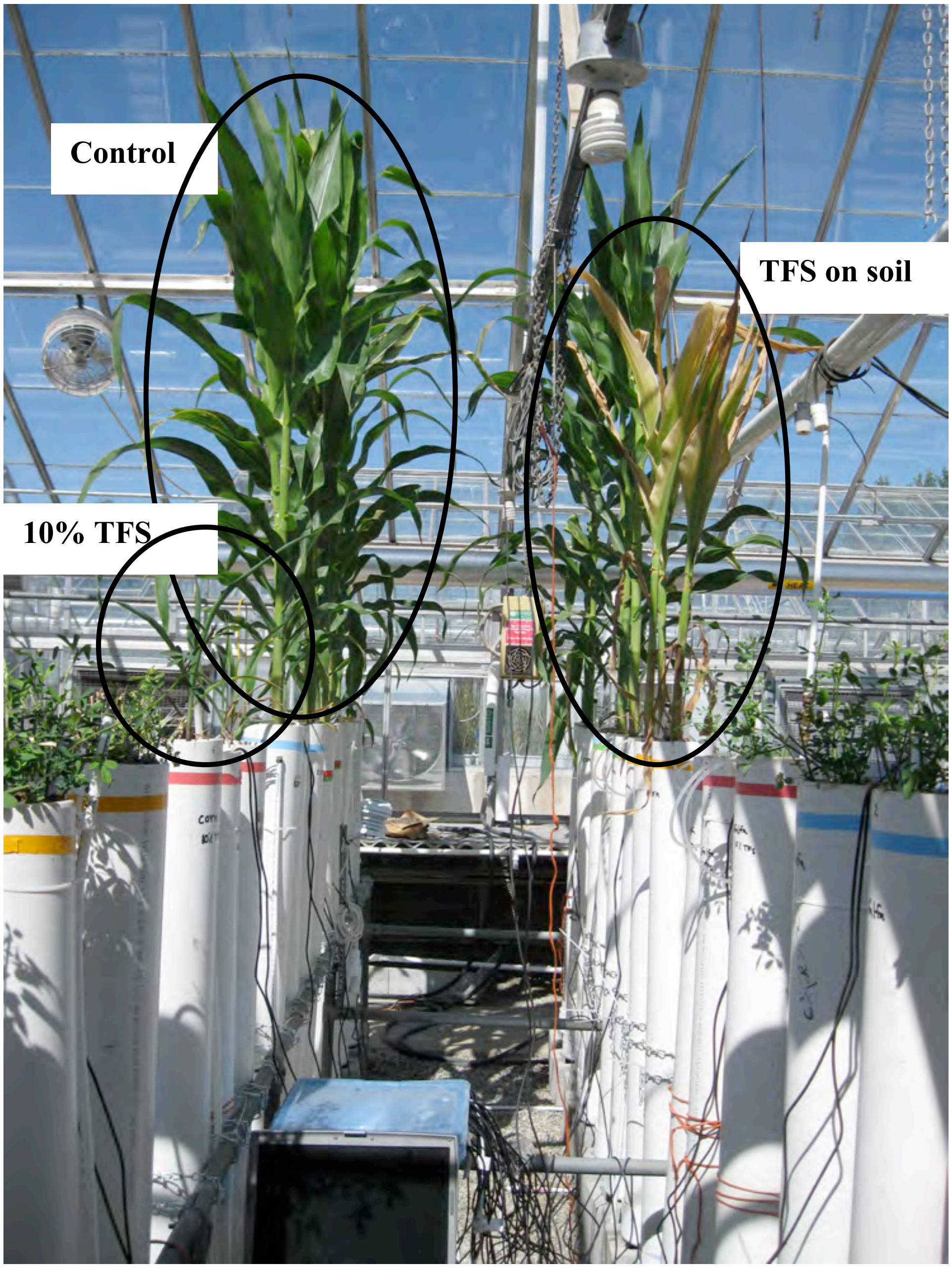

Fig. 7 Growth comparisons of corn grown in soil, treated with TFS on soil, or grown in 10% TFS

Fig. 8 Corn leaves treated with TFS

Table 4 Biomass by treatment: average dry weight of triplicate corn plants

Treatment Type	Average Mass (g)	St. Dev (g)
Control (soil)	99.4[a]	11.2
10% TFS	4.8[b]	4.3
TFS on soil	43.9[c]	16.9
Soil Deposition	113.0[a]	11.8
Soil Wash	92.2[a]	1.8
TFS Deposition	105.2[a]	7.5
TFS Wash	118.9[a]	4.3
Field Corn	92.1[a]	22.2

Note: Average values followed by the same lower case letter are not significantly different ($p<0.05$) according to ANOVA and Tukey's test.

Table 5 Yield production by treatment: average dry weight of triplicate corn ears

Treatment Type	Average Mass (g)	St. Dev (g)
Control (soil)	117.6[a]	15.5
10% TFS	0.5[b]	1.1
TFS on soil	0[b]	0
Soil Deposition	122.8[a]	10.6
Soil Wash	115.5[a]	9.8
TFS Deposition	130.2[a]	17.1
TFS Wash	119[a]	9.1
Field Corn	138.4[a]	69.6

Note: Average masses followed by the same lower case letter are not significantly different ($p<0.05$) according to ANOVA and Tukey's test.

The plants treated with TFS in or on the soil produced no significant yield. One plant grown in 10% TFS produced an ear containing 1.6 g of kernels. The other plants grown in 10% TFS did not produce any kernels, nor did corn treated with TFS on top of the soil. Reduction in yield is one result of highly saline soil. In the concentrations used for this study, the TFS produces a highly saline soil environment. The results for the corn grown in 10% TFS or treated with TFS on the soil are consistent with the effect of salinity on yield production. More results are shown Table B2.

3.2.2 Metals

Corn leaf tissue was analyzed for total metals and nutrients (results in Table B3). Several elements appear in higher concentrations in plants grown in 10% TFS or treated with TFS on the soil compared to the other treatment conditions. Statistical difference from controls is shown in Table 6. Results no different than the controls are indicated by NS (not significant), whereas arrows denote if a treatment contained higher or lower levels compared to controls.

Statistical differences were also compared between treatments. Corn grown in 10% TFS and with TFS on the soil contained concentrations of potassium and magnesium not statistically different from each other, but higher than foliar treated plants and controls. Moreover, corn with TFS on soil was higher than all other treatments, including 10% TFS, for total nitrogen, barium, calcium, cadmium, phosphorus, sulfur, and strontium. Although increased metals uptake was noted for plants exposed to TFS in the root zone, the metals concentration in DM-1 TFS was not higher than in the soil, except for aluminum.

Plants treated with TFS foliar deposition (unwashed) contained more aluminum than controls and other treatments, including TFS that was washed off after one week. Iron was also elevated in plants treated with TFS deposition (unwashed), but similarly increased iron content was also observed in plants with foliar soil deposition. Increased iron may result from foliar contact with soil, as well as TFS.

The National Resource Council (NRC) (2005) identifies the limits of several elements that can be fed to livestock without impairing animal health. These limits are called maximum tolerable levels (MTL). The MTL for calcium and potassium were exceeded for corn tissue grown in 10% TFS or treated with TFS on soil. Other treatments did not elevate metal concentrations above the recommended MTL.

Corn kernels were analyzed for metals and nutrients (results shown in Table B4). Table 7 shows significant differences in metals of kernels from treated corn compared to controls. Plants treated with foliar TFS deposition (washed and unwashed) produced kernels containing significantly higher zinc than controls. They also produced more potassium than controls or field corn. Plants treated with foliar soil or TFS deposition

Table 6 Significant metal differences between control and soil treatments (10% TFS and TFS on soil), foliar treatments (soil deposition washed and unwashed and TFS deposition washed and unwashed), and field corn.

Element	Control	10% TFS	TFS on soil	Soil (unwashed)	Soil (washed)	TFS (unwashed)	TFS (washed)	Field Corn
Total Nitrogen	NS	↑	↑	NS	NS	NS	NS	NS
Aluminum	NS	NS	NS	NS	NS	↑	NS	NS
Arsenic	<	<	<	<	<	<	<	<
Boron	NS	NS	NS	NS	NS	NS	NS	↓
Barium	NS	NS	↑	NS	NS	NS	NS	NS
Calcium	NS	↑	↑	NS	NS	NS	NS	NS
Cadmium	NS	NS	↑	NS	NS	NS	NS	NS
Cobalt	<	<	<	<	<	<	<	<
Chromium	NS	NS	NS	NS	NS	NS	NS	NS
Copper	NS	NS	NS	NS	NS	NS	NS	NS
Iron	NS	NS	NS	↑	NS	↑	NS	NS
Potassium	NS	↑	↑	NS	NS	NS	NS	NS
Magnesium	NS	↑	↑	NS	NS	NS	NS	NS
Manganese	NS	↓	NS	NS	NS	NS	NS	NS
Molybdenum	<	<	<	<	<	<	<	<
Sodium	NS	NS	NS	NS	NS	↑	NS	NS
Nickel	NS	NS	NS	NS	NS	NS	NS	NS
Phosphorous	NS	↑	↑	NS	NS	NS	NS	NS
Lead	<	<	<	<	<	<	<	<
Sulfur	NS	NS	↑	NS	NS	NS	NS	NS
Selenium	<	<	<	<	<	<	<	<
Silicon	NS	NS	NS	NS	NS	NS	NS	NS
Strontium	NS	↑	↑	NS	NS	NS	NS	NS
Zinc	NS	NS	↑	NS	NS	NS	NS	NS

Note: NS is not statistically different from control, ↑ is above control, ↓ is below control, and < is below detection limit.

(unwashed) contained higher phosphorous and calcium than control plants. This suggests that foliar exposure to TFS may change kernel composition (as in the case of zinc), but foliar exposure to soil may also contribute to elevated concentrations (like phosphorus and calcium). Although concentrations of calcium, potassium, phosphorous, and zinc were elevated by treatment, the concentrations are well below the MTL for consumption by cattle recommended by the NRC (2005).

3.2.3 Anions

Plant tissue was analyzed for chloride, sulfate, nitrate, and phosphate. The results of the corn plant tissue are summarized in Table 8 (results in Table B5). There were no significant differences between corn tissue from controls, plants treated with foliar soil deposition (washed and unwashed) or foliar TFS deposition (washed and unwashed), and field corn for phosphate or nitrate. Field corn contained less sulfate than the controls.

Corn plant tissue grown in 10% TFS or treated with TFS on the soil contained significantly higher levels of chloride than all other treatments and more phosphate than controls. Corn treated with TFS on the soil also contained more nitrate than all other treatments.

Plants often contain chlorine contents ranging from 2-200 mg/g (2000-200,000 mg/kg) dry weight, and corn may be chlorine-deficient at levels below 106 ug Cl/g (106 mg/kg) dry plant matter (Marschner 1995). Taiz and Zeiger (2006) suggest that 100 mg/kg may be a reasonable chlorine concentration in plant tissue. Although the corn with TFS on the soil had at least an order of magnitude more chloride than all other plants, the observed chloride concentrations were well within the previously reported ranges. The plants were certainly not chlorine deficient.

Table 7 Significant metal differences between control kernels and foliar treatments (soil deposition washed and unwashed and TFS deposition washed and unwashed), and field corn.

Element	Control	Soil deposition	Soil wash	TFS deposition	TFS wash	Field Corn
Total Nitrogen	NS	NS	↓	NS	NS	NS
Aluminum	NS	NS	NS	NS	NS	NS
Arsenic	<	<	<	<	<	<
Boron	NS	NS	NS	NS	NS	NS
Barium	NS	NS	NS	NS	NS	NS
Calcium	NS	↑	NS	↑	NS	NS
Cadmium	NS	NS	NS	NS	NS	NS
Cobalt	<	<	<	<	<	<
Chromium	NS	NS	NS	NS	NS	NS
Copper	NS	NS	NS	NS	NS	NS
Iron	NS	NS	NS	NS	NS	NS
Potassium	NS	NS	↑	↑	↑	NS
Magnesium	NS	NS	NS	NS	NS	NS
Manganese	NS	NS	NS	NS	NS	NS
Molybdenum	<	<	<	<	<	<
Sodium	NS	NS	NS	NS	NS	NS
Nickel	NS	NS	NS	NS	NS	NS
Phosphorous	NS	↑	NS	↑	NS	NS
Lead	<	<	<	<	<	<
Sulfur	NS	NS	NS	NS	NS	NS
Selenium	<	<	<	<	<	<
Silicon	NS	NS	NS	NS	NS	↓
Strontium	NS	NS	NS	NS	NS	NS
Zinc	NS	NS	NS	↑	↑	NS

Note: No kernels developed on corn grown in 10% TFS or with TFS on the soil. NS is not statistically different from control, ↑ is above control, ↓ is below control, and < is below detection limit.

Field corn and plants whose foliage was treated with TFS (washed and unwashed) produced kernels containing significantly more chloride than plants whose foliage was treated with soil (washed and unwashed), shown in Table 9, but only plants whose leaves were treated with TFS and washed off produced kernels with significantly more chloride than controls. Other differences between treatments were not significant, and the range in chloride levels for kernels is much smaller than the range in chloride for plant tissue. No results are shown for corn grown in 10% TFS or TFS on soil because no kernels were produced. Results are shown in Table B6.

There were no significant differences in sulfate between treatments except that field corn kernels contained less sulfate than kernels whose foliage was treated with TFS deposition (unwashed) or soil deposition (washed). None of the treatments resulted in significantly different nitrate and phosphate levels, seen in Table 9. Plant composition is affected by the application of TFS. Chloride was two orders of magnitude higher in plants grown in 10% TFS or treated with TFS on the soil. Chloride is also present in concentrations orders of magnitude higher in TFS than in soil. Increased metals uptake was noted, although the metals content of DM-1 TFS is not significantly different than soil, with the exception of elevated aluminum. The increased metals uptake did not result from exposure to higher concentrations of metals, except for plants that accumulated aluminum after foliar treatment with TFS. Increased uptake of metals may instead result from accumulation of chloride in plant tissue. Excessive chloride levels results in ionic imbalance, countered by uptake of cations, such as barium, calcium, cadmium, potassium, strontium, and zinc.

3.3 Alfalfa Plant Study

Plant growth was mildly to severely affected by TFS. Biomass production decreased after plants were treated with TFS on the soil surface, but increased slightly by the third cutting. One column appeared to be especially affected by the addition of TFS, but the other two triplicates did not appear visually to be affected (Fig. 9) other than some

Table 8 Average concentrations of anions in corn plant tissue

Treatment	Chloride (mg/kg)	Sulfate (mg/kg)	Nitrate (mg/kg)	Phosphate (mg/kg)
Control	481^{b}	926^{b}	68^{a}	256^{a}
10% TFS	69644^{e}	229^{ab}	98^{a}	900^{c}
TFS on soil	70127^{e}	1633^{b}	2109^{b}	2432^{bc}
Soil Deposition	138^{a}	924^{b}	67^{a}	275^{a}
Soil wash	201^{ab}	702^{ab}	150^{a}	428^{ab}
TFS Deposition	4795^{d}	724^{ab}	42^{a}	531^{ab}
TFS wash	1564^{c}	609^{ab}	43^{a}	481^{ab}
Field Corn	1857^{cd}	214^{a}	85^{a}	425^{ab}

Note: Within columns, values followed by the same lower case letter are not significantly different ($p<0.05$) according to ANOVA and Tukey's test.

Table 9 Average concentrations of anions in corn kernels

Treatment	Chloride (mg/kg)	Sulfate (mg/kg)	Nitrate (mg/kg)	Phosphate (mg/kg)
Control	511^{ab}	93^{ab}	58^{a}	1046^{a}
Soil Deposition	379^{a}	86^{ab}	94^{a}	989^{a}
Soil wash	431^{a}	157^{b}	42^{a}	1633^{a}
TFS Deposition	656^{bc}	132^{b}	75^{a}	1792^{a}
TFS wash	772^{c}	66^{ab}	66^{a}	1809^{a}
Field Corn	606^{bc}	23^{a}	75^{a}	1819^{a}

Note: No kernels were produced in 10% TFS or TFS on soil treatments. Within columns, values followed by the same lower case letter are not significantly different ($p<0.05$) according to ANOVA and Tukey's test.

spotting (Fig. 10). Although soil oxygen levels were not measured, the recovery of plants in two columns treated with TFS on the soil suggest that oxygen deficiency may not have resulted from the layer of TFS. Alfalfa grown in 10% TFS produced significantly lower biomass than control alfalfa. Field alfalfa was not collected in a comparable manner, therefore no field results are shown.

Fig. 9 Alfalfa treated with TFS on soil. One column (far right) appeared especially affected after application of TFS and nearly ceased production of biomass

Fig. 10 Spotting of alfalfa treated with TFS on the soil surface

3.3.1 Biomass

Alfalfa production was notably affected by TFS exposure in the root zone, as shown in Table 10. Alfalfa did not sprout in 10% TFS. One-week-old alfalfa plants germinated on paper at the time of planting survived transplanting into 10% TFS, but did not produce plant material in excess of 10.2 cm (4 inches) by the first cutting, so none was sampled then, as seen in Table 10, 52 days after planting. TFS was not applied to the soil surface until 54 days, so the first cutting includes only untreated alfalfa. The mass produced pre-treatment is not significantly different from the control plants.

Production of alfalfa decreased significantly after TFS was applied to the soil surface (54 days after planting). By the second sampling event (87 days after planting), control alfalfa grown in soil produced roughly four times the mass of alfalfa treated with TFS on soil. Alfalfa grown in 10% TFS produced still significantly less plant matter.

In the third cutting (119 days after planting), the mass of the untreated alfalfa was still significantly higher than that of the alfalfa grown in 10% TFS. However, the difference in mass between the control plants grown in soil and those treated with TFS on the soil surface was not significant at the third cutting. The difference between alfalfa treated with TFS on the soil and 10% TFS treatment was not significant either ($p>0.05$). See Table C1 for complete results.

As with corn, a reduction in yield occurred in alfalfa treated with TFS in the root zone. TFS contributes to highly saline soil conditions, reducing the alfalfa yield. At the second sampling, alfalfa treated with TFS on the soil produced 25.3% the mass of the

Table 10 Average alfalfa dry weights by treatment

Treatment Type	First Cutting (g)	Second Cutting (g)	Third Cutting (g)
Control (soil)	6.0^{a}	17.8^{a}	23.2^{a}
10% TFS	0.0^{b}	2.5^{b}	2.1^{b}
TFS on soil	6.2^{a}	4.5^{b}	11.7^{ab}

Note: Within columns, values followed by the same lower case letter are not significantly different ($p<0.05$) according to ANOVA and Tukey's test.

controls while plants grown in 10% TFS produced 14.0% the mass of controls. By the third cutting, plants treated with TFS on soil produced half the mass of the controls, whereas the production in plants grown in TFS dropped to 9%. The results for the alfalfa treated with TFS are consistent with the effect of salinity on biomass production.

Application of foliar soil and TFS treatments occurred in a second alfalfa study. The alfalfa was grown in the winter and produced little biomass for analysis. Biomass production was not significantly different between treatments for any of the sampling events (more results in Table C2). The first sampling (late November) provided sufficient mass for metals and anions analysis; however the second and third samplings of foliar treated alfalfa did not produce enough mass for all the samples to be analyzed. Treatment had not been applied at the first sampling time (following the sampling and treatment procedure of the previous alfalfa study), so metals and anions results of the first sampling of foliar treated alfalfa will not be presented.

3.3.2 Metals

The first cutting of control alfalfa from the root exposure experiment found no statistical difference in metals between controls and the plants which were to receive TFS on the soil. By the second and third cuttings of alfalfa (after TFS was added to soil), changes were evident. Table 11 shows the differences in treatments compared against controls for the third cutting (see Table C3).

Alfalfa grown in 10% TFS or treated with TFS on soil contained significantly higher concentrations of calcium and zinc than control plants by the third cutting. Alfalfa grown in 10% TFS also contained higher levels of barium, copper, manganese, nickel,

Table 11 Significant differences in metal concentrations between control alfalfa and treatments 10% TFS and TFS on soil for the third cutting

Element	Control	10% TFS	TFS on soil
Total Nitrogen	NS	NS	NS
Aluminum	NS	NS	NS
Arsenic	<	<	<
Boron	NS	NS	↑
Barium	NS	↑	NS
Calcium	NS	↑	↑
Cadmium	NS	NS	NS
Cobalt	<	<	<
Chromium	NS	NS	NS
Copper	NS	↑	NS
Iron	NS	NS	NS
Potassium	NS	NS	NS
Magnesium	NS	NS	NS
Manganese	NS	↑	NS
Molybdenum	<	<	<
Sodium	NS	NS	NS
Nickel	NS	↑	NS
Phosphorous	NS	NS	NS
Lead	<	<	<
Sulfur	NS	NS	NS
Selenium	<	<	<
Silicon	NS	NS	NS
Strontium	NS	↑	NS
Zinc	NS	↑	↑

Note: NS is not statistically different from control, ↑ is above control, ↓ is below control, and < is below detection limit.

and strontium compared to controls. Boron was significantly higher in alfalfa treated with TFS on the soil surface compared to controls. Although levels of boron, copper, manganese, and zinc concentrations were elevated, they were still within adequate plant nutrition ranges tabulated by Marschner (2012) and below the MTL for livestock consumption (NRC 2005). Calcium levels in alfalfa grown in 10% TFS or treated with TFS on the soil exceeded the MTL for consumption by cattle and sheep, but so did the controls. However, the calcium levels are not high enough to reduce plant growth considerably (Marschner 1995).

3.3.3 Anions

Alfalfa was analyzed for chloride, sulfate, nitrate, and phosphate at each of three cuttings. Results for the third cutting are shown in Table 12. More results are shown in Table C4.

Alfalfa grown in 10% TFS or treated with TFS on the soil surface contained significantly more chloride than controls. There was no significant difference between treatments for sulfate, nitrate, or phosphate.

Metals were not significantly higher in TFS than in soil, except for aluminum, so the increased uptake of metals such as barium, calcium, copper, manganese, strontium, and zinc does not result from more exposure to these metals. Instead, the accumulation of these metals may be explained by the increase in chloride content of the plant tissue. The metals would provide the necessary positive charge to counter the excessive chloride and maintain ionic balance.

Table 12 Average concentrations of anions in alfalfa tissue at the third cutting

Treatment	Chloride (mg/kg)	Sulfate (mg/kg)	Nitrate (mg/kg)	Phosphate (mg/kg)
Control	627^a	3402^a	140^a	329^a
10% TFS	15044^b	2820^a	40^a	720^a
TFS on soil	11743^b	1913^a	63^a	384^a

Note: Within columns, values followed by the same lower case letter are not significantly different ($p<0.05$) according to ANOVA and Tukey's test.

3.4 Leachate

The leachate contained high levels of calcium and had to be diluted 1:100 for analysis, and few metals were measured about the detection limit. Manganese, copper, arsenic, and barium were detected, but aluminum was not, except for in one soil treatment collected after 48 hours and in one column packed with TFS on soil, detected after 44 hours but not after 48 hours. The aluminum appears to be immobile, as expected for alkaline soil. Metal results of the leachate analysis are shown in Tables D1-D3.

As expected, TFS produces leachate with elevated chloride concentrations. Control leachate contained 1300 mg/L chloride at 40 hours and dropped to 1020 mg/L chloride by the end of the experiment at 48 hours (see Tables D4-D6), and chloride levels were consistently lower than leachate from 10% TFS and TFS on soil treatments. The leachate collected from the 10% TFS treatment initially contained 55300 mg/L chloride, but dropped an order of magnitude to 5730 mg/L by the end of the experiment. Leachate from columns containing TFS on soil had initial chloride concentrations of 23300 mg/L chloride (less than the first 10% TFS concentrations) that did not appear to decrease by the end of the experiment.

Germination of corn and alfalfa was improved by leaching of the TFS from the soil. After 5 days, 80-90% of the corn and alfalfa in leached soil or leached 10% TFS had sprouted. Germination was near 40-50% in leached TFS. By 7 days, there was no statistical difference between leached soil profiles for corn germination, although alfalfa germination was statistically lower in leached TFS than in soil or 10% TFS. Results are shown in Table D7.

Although the germination percentage of corn in leached TFS was no different than in leached soil or 10% TFS after seven days, the seedlings were much smaller (Fig. 11; photo taken after 10 days). Growth in leached TFS may still be impacted.

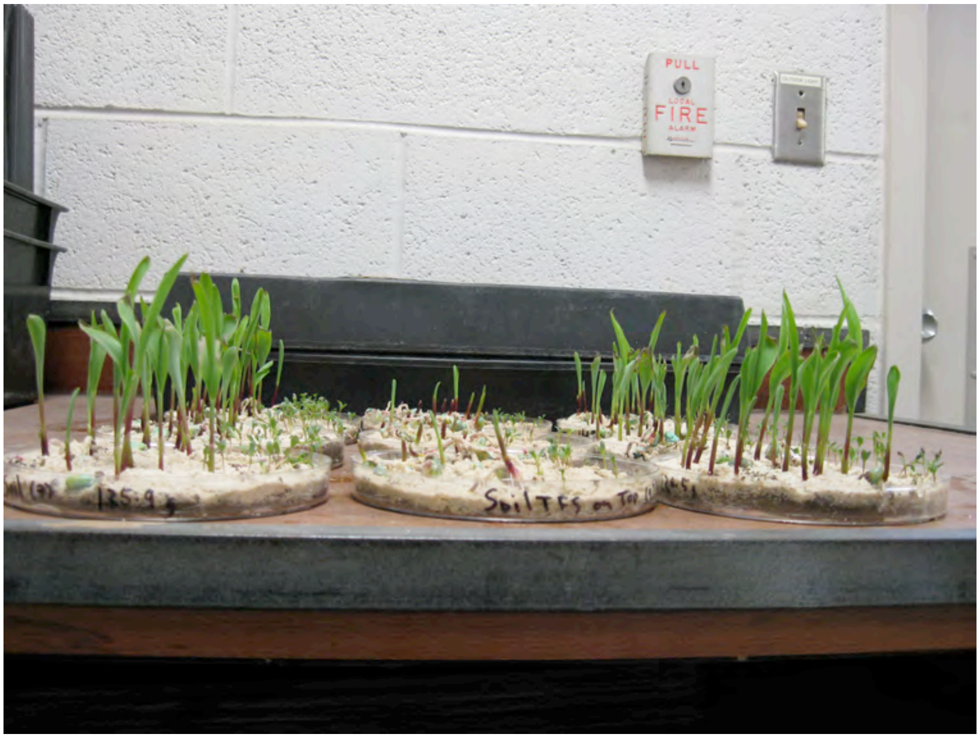

Fig. 11 Leached germination study. From left to right, control (leached soil), leached TFS, and leached 10% TFS. After 10 days, corn germination was not significantly different between treatments, but seedlings in leached TFS were smaller and less developed than controls or those in leached 10% TFS.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Exposure to TFS affects the germination, growth, and contaminant concentration of corn and alfalfa, but the degree of impact depends on the type and concentration of exposure.

Germination is inhibited by high concentrations of TFS. Germination was completely inhibited in 50% TFS, and greatly reduced by 10% TFS for both corn and alfalfa. TFS concentrations below 2% had no effect on corn germination. Alfalfa germination may be more sensitive to TFS, with reduced germination observed as low as 0.4% TFS.

Germination in high concentrations of TFS can be at least partially restored if the TFS is leached. Percent germination of corn in leached TFS was not statistically different than germination in leached soil after 7 days. Although alfalfa germination in leached soil was only slightly lower (about 10% less than controls), its difference was significant.

Growth of plants may be affected by TFS, depending on the type of exposure. Corn grown in 10% TFS or treated with TFS on the soil surface did not develop normally, producing less biomass than controls and no kernels. Alfalfa grown in 10% TFS produced significantly less biomass than control plants grown in soil. Biomass production of alfalfa dropped to roughly 25% of control production after treatment with TFS on the soil surface. In contrast, foliar treatments of TFS did not significantly reduce biomass production in corn or alfalfa.

Uptake of metals was affected by exposure to TFS. Plants treated with TFS on soil had significantly higher levels of total nitrogen, barium, calcium, cadmium, potassium, magnesium, phosphorous, sulfur, strontium, and zinc than control plants grown in soil or plants receiving foliar treatment. Plants grown in 10% TFS also contained significantly higher total nitrogen, calcium, potassium, manganese, phosphorus, and strontium than controls. Foliar applications of TFS and soil were significantly different for aluminum, sodium, and iron. Plants whose foliage was exposed to TFS (but not washed off) contained more aluminum and sodium than controls, and levels of iron were elevated in plants with foliar application of soil or TFS that was not washed off. Foliar application may increase uptake of metals.

TFS contains high levels of chloride and produces saline leachate, leading to reduced germination and plant growth. Furthermore, high levels of chloride in TFS may contribute to elevated levels of metals in plant tissue, as a result of increased osmotic potential. Some of the defense mechanisms that exclude uptake of certain metals may be bypassed to increase the amount of water uptake, resulting in accumulation of metals in plant tissue. The metals may also be required to counter the excessive chloride content of the leaves that accumulate chloride ions.

As expected, aluminum did not have an effect on germination and was not found in leachate. Foliar treatment of TFS to corn affected aluminum levels, but that did not change biomass production. Aluminum is not bioavailable in alkaline soil conditions and should not impact plant growth. If aluminum toxicity was causing damage, lower biomass and metal concentrations would be expected, because aluminum toxicity interferes with root development and uptake of nutrients and water.

CHAPTER 5

ENGINEERING SIGNIFICANCE

This study helps to assess the impact of TFS from ATK's static test fires on crop production in the area of southwest Box Elder County, Utah. Results can be used to develop Best Management Practices and test fire protocols that will reduce impacts of static test fires on crop growth.

Results of the study indicate that germination is hindered above 1% TFS. However, germination is not permanently hindered, as leaching of TFS alleviates germination inhibition. Nevertheless, this suggests that care should be taken to avoid TFS deposition in planting season, and ATK may consider scheduling static test fires so they do not occur during planting season. If deposition does occur during the planting season, irrigation may mitigate the impact of TFS on germination.

Results of the growth study indicate that TFS does have yield implications for the corn and alfalfa, depending on the time and type of application. Growth in TFS – amended soil reduced biomass production for both corn and alfalfa and prevented development of corn. Plants did not grow well in high concentrations of TFS or when TFS was applied to the soil of established plants. Although exposure to TFS damaged foliage, new leaves were not marred, and foliar treatment did not affect total biomass. This suggests that test-fires should not be conducted during times of young plant growth.

Analysis of plant composition shows increased uptake of several metals and a few nutrients in plants exposed to TFS. Calcium and potassium exceeded the maximum tolerable level for consumption by cattle and sheep reported by the National Research Council (2005) in corn tissue exposed to TFS in the root zone, but kernels were well below the recommended levels. Alfalfa treated with TFS in the root zone also had calcium levels in excess of the MTL. Because TFS exposure appears to increase accumulation of some metals, ATK may further reduce the risk of damaged crops by conducting test fires post-harvest.

CHAPTER 6

SUGGESTIONS FOR FUTURE RESEARCH

In germination studies, the detrimental effects of TFS were alleviated if the TFS was leached using a low-ionic strength solution of $CaCl_2$; however seedling size was impacted in TFS (Section 3.4). The next step is to consider growth of plants in leached TFS. This experiment would be similar to the plant growth study described in Chapter 2, but soil treatments 10% TFS and TFS on soil should be leached with artificial rainwater before planting. Plant tissue would be sampled and analyzed for metals, anions, and nutrients to determine if leaching the TFS eliminates the impact to corn and alfalfa crops.

Leachate analysis shows mobile chloride. This may result in chloride intrusion of groundwater. Aluminum is not expected to be found in the groundwater because of alkaline pH, but the hydrochloric acid from the exhaust cloud may mobilize aluminum temporarily (Nowak and Friend 2006). Groundwater should be tested to monitor for saline or brackish water and abnormal levels of aluminum.

Leachate columns attempted to simulate movement of aluminum and chloride through a soil column, but actual soil column data are limited. Collection of soil cores and analysis of aluminum and chloride contents are recommended to confirm the results of the leaching study.

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APPENDICES

APPENDIX A

GERMINATION DATA

Table A1 Percent germination of alfalfa in chloride based on the type of chloride exposure: TFS in soil, hydrochloric acid in soil, hydrochloric acid and aluminum oxide in soil, and aluminum oxide in soil

Treatment	**<100 mg/kg**	**100-1000 mg/kg**	**1000-3500 mg/kg**	**>6000 mg/kg**
DM-1 TFS	85	82.5	52.5	0.0
DM-1 TFS	90	82.5	50.0	0.0
DM-1 TFS	77.5	85.0	70.0	0.0
Average	**84.2**	**83.3**	57.5	**0.0**
Hydrochloric Acid	82.5	82.5	47.5	--
Hydrochloric Acid	87.5	95.0	50.0	--
Hydrochloric Acid	90	85.0	62.5	--
Average	**86.7**	**87.5**	**53.3**	--
Aluminum and Chloride	82.5	82.5	42.5	--
Aluminum and Chloride	85	82.5	40.0	--
Aluminum and Chloride	85	95.0	50.0	--
Average	**84.2**	**86.7**	**44.2**	--
Aluminum Oxide	82.5	--	--	--
Aluminum Oxide	85	--	--	--
Aluminum Oxide	82.5	--	--	--
Average	**83.3**	--	--	--
Soil	80	--	--	--
Soil	82.5	--	--	--
Soil	80	--	--	--
Average	**80.8**	--	--	--

Table A2 Percent germination of corn in chloride based on the type of chloride exposure: TFS in soil, hydrochloric acid in soil, hydrochloric acid and aluminum oxide in soil, and aluminum oxide in soil

Treatment	**<100 mg/kg**	**100-1000 mg/kg**	**1000-3500 mg/kg**	**>6000 mg/kg**
DM-1 TFS	100.0	19.0	85.0	5.0
DM-1 TFS	95.0	20.0	75.0	0.0
DM-1 TFS	100.0	20.0	80.0	5.0
Average	98.3		80.0	3.3
Hydrochloric Acid	100.0	20.0	5.0	--
Hydrochloric Acid	95.0	20.0	0.0	--
Hydrochloric Acid	100.0	20.0	15.0	--
Average	98.3	100.0	6.7	--
Aluminum and Chloride	95.0	20.0	35.0	--
Aluminum and Chloride	100.0	19.0	0.0	--
Aluminum and Chloride	100.0	20.0	5.0	--
Average	98.3	98.3	13.3	--
Aluminum Oxide	100.0	--	--	--
Aluminum Oxide	100.0	--	--	--
Aluminum Oxide	100.0	--	--	--
Average	100.0	--	--	--
Soil	100.0	--	--	--
Soil	100.0	--	--	--
Soil	100.0	--	--	--
Average	100.0	--	--	--

APPENDIX B

CORN PLANT STUDY

Table B1 Dry weight of corn plant tissue collected from three sampling events. The total mass is a summation of mass from the three sampling events.

Treatment Type	First Event (g)	Second Event (g)	Third Event (g)	Total Mass (g)
Control (soil)	2.69	2.43	107	112.12
Control	4.53	3.48	87	95.01
Control	3.23	3.84	84	91.07
Average	3.48	3.25	92.67	99.40
10% TFS	0.00	0.00	8.3	8.30
10% TFS	0.00	0.00	0.00	0.00
10% TFS	0.00	0.00	6.00	6.00
Average	0.00	0.00	4.77	4.77
TFS on soil	3.30	6.39	51.8	61.49
TFS on soil	4.42	2.62	35.5	42.54
TFS on soil	3.09	6.72	18	27.81
Average	3.60	5.24	35.10	43.95
Soil Deposition	4.64	3.77	115	123.41
Soil Deposition	3.89	3.60	108	115.49
Soil Deposition	2.29	2.94	95	100.23
Average	3.61	3.44	106.00	113.04
Soil Wash	3.84	3.01	84	90.85
Soil Wash	3.54	2.71	88	94.25
Soil Wash	3.66	2.88	85	91.54
Average	3.68	2.87	85.67	92.21
TFS Deposition	4.16	2.89	104	111.05
TFS Deposition	3.68	4.25	100	107.93
TFS Deposition	5.10	2.64	89	96.74
Average	4.31	3.26	97.67	105.24
TFS Wash	3.44	4.62	107	115.06
TFS Wash	2.98	4.19	111	118.17
TFS Wash	4.50	4.02	115	123.52
Average	3.64	4.28	111.00	118.92
Field Corn				84.6
Field Corn				74.6
Field Corn				117.1
Average				92.1

Table B2 Dry weight of corn kernels produced from plant study

Treatment Type	Kernel Mass (g)
Control (soil)	133
Control	117.8
Control	102
Average	117.6
10% TFS	1.6
10% TFS	0
10% TFS	0
Average	0.5
TFS on soil	0
TFS on soil	0
TFS on soil	0
Average	0
Soil Deposition	124.2
Soil Deposition	132.7
Soil Deposition	111.6
Average	122.8
Soil Wash	123.3
Soil Wash	118.7
Soil Wash	104.4
Average	115.5
TFS Deposition	110.5
TFS Deposition	138.7
TFS Deposition	141.3
Average	130.2
TFS Wash	119.6
TFS Wash	109.6
TFS Wash	127.8
Average	119
Field Corn	147.5
Field Corn	208.9
Field Corn	42.4
Field Corn	154.8
Average	138.4

Table B3 Metals analysis for corn tissue collected at time of harvest

Treatment	Total N	Al	As	B	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Se	Si	Sr	Zn
Control	0.69	255	<	42.3	9.35	0.8	0.18	<	0.35	24.5	93.4	1.29	0.24	119	<	35.6	2.64	0.03	<	0.09	<	2731	28.7	35.7
Control	0.7	147	<	43.5	9.06	0.759	0.17	<	0.51	27.2	78.3	1.3	0.29	137	<	20.8	1.77	0.04	<	0.11	<	2526	28.7	43.6
Control	0.3	49.5	<	42.2	8.53	0.66	0.16	<	<	25.3	50	1.12	0.24	105	<	49.1	3.22	0.02	<	0.08	<	2380	25	42.5
Average	0.6	150.5	<	42.7	9.0	0.7	0.2	<	0.4	25.7	73.9	1.2	0.3	120.3	<	35.2	2.5	0.0	<	0.1	<	2545.7	27.5	40.6
10% TFS	0.9	61.5	<	17.5	13.2	1.49	0.21	<	0.37	17.4	76.4	2.03	0.35	43.8	<	33.9	1.5	0.12	<	0.07	<	1992	43.8	50.9
10% TFS	1.41	48.4	<	15.9	22.1	2.32	0.29	<	0.48	9.59	68.9	2.44	0.38	55.7	<	40.5	1.51	0.16	2.59	0.1	<	1779	69.5	47.6
Average	1.2	55.0	<	16.7	17.7	1.9	0.3	<	0.4	13.5	72.7	2.2	0.4	49.8	<	37.2	1.5	0.1	2.6	0.1	<	1885.5	56.7	49.3
TFS on Soil	1.78	32.8	<	56.2	45	2.774	0.38	<	<	13.9	58.2	1.76	0.35	161	<	35.6	0.69	0.36	<	0.18	<	2721	87.9	79.6
TFS on Soil	1.99	28.2	<	43	58	3.468	0.47	<	<	12	54.5	2	0.38	146	<	30.6	0.89	0.38	<	0.18	<	2808	105	65.9
TFS on Soil	2.3	19.1	<	14.3	58.6	4.042	0.46	<	<	10.5	47.6	2.6	0.34	90.4	<	41.4	0.81	0.29	<	0.14	<	1736	116	55.4
Average	2.0	26.7	<	37.8	53.9	3.4	0.4	<	<	12.1	53.4	2.1	0.4	132.5	<	35.9	0.8	0.3	<	0.2	<	2421.7	103.0	67.0
Soil Deposition	0.47	148	<	37.2	7.53	0.63	0.22	<	0.35	35.4	157	1.05	0.19	82	<	22.8	2.81	0.03	<	0.07	<	2439	22.1	33.3
Soil Deposition	0.53	382	<	44	9.83	0.7	0.22	<	0.82	54.5	375	1.14	0.22	113	<	39.5	6.38	0.03	<	0.08	<	2259	25.1	50.5
Soil Deposition	0.56	460	<	52.7	11.4	0.79	0.2	<	1.01	24.3	419	1.18	0.27	119	<	38.7	3.12	0.05	<	0.09	<	2337	27.5	35.7
Average	0.5	330.0	<	44.6	9.6	0.7	0.2	<	0.7	38.1	317.0	1.1	0.2	104.7	<	33.7	4.1	0.0	<	0.1	<	2345.0	24.9	39.8
Soil Wash	0.52	174	0.51	40.3	9.54	0.71	0.14	<	0.35	30.9	168	1.16	0.24	85.4	<	18.1	2.49	0.05	<	0.08	<	2610	25.1	37.2
Soil Wash	0.54	169	<	32.7	9.65	0.63	0.16	<	0.5	34	168	1.36	0.22	92.6	<	66.9	3.06	0.05	2.51	0.08	<	2710	24.1	40.7
Soil Wash	0.62	227	<	47.3	10.2	0.74	0.14	<	0.43	34.5	185	1.18	0.25	99.6	<	30.9	2.45	0.05	<	0.08	<	2594	26.8	45.5
Average	0.6	190.0	0.5	40.1	9.8	0.7	0.1	<	0.4	33.1	173.7	1.2	0.2	92.5	<	38.6	2.7	0.1	2.5	0.1	<	2638.0	25.3	41.1
TFS Deposition	0.55	933	<	32.1	10.9	1.183	0.12	<	0.59	29.9	198	1.17	0.25	84.6	<	74.9	1.18	0.06	<	0.07	<	2756	34.6	36
TFS Deposition	0.77	1778	<	35.1	10.9	1.39	0.11	<	0.82	26.6	326	1.17	0.24	88.85	<	94.6	2.75	0.09	<	0.09	<	2681	36.4	38.3
TFS Deposition	0.55	1298	<	38.9	12.2	1.44	0.12	<	0.93	29.8	237	1.17	0.25	93.3	<	95.7	2.87	0.05	<	0.08	<	2989	40.5	37.5
Average	0.6	1336.3	<	35.4	11.3	1.3	0.1	<	0.8	28.8	253.7	1.2	0.2	88.9	<	88.4	2.3	0.1	<	0.1	<	2808.7	37.2	37.3
TFS Wash	0.89	178	<	45.8	9.34	0.894	0.2	<	0.34	27.6	97.1	1.46	0.22	113	<	60.7	1.16	0.06	<	0.1	<	2954	29.8	39.8
TFS Wash	1	199	0.51	41.6	7.29	0.94	0.15	<	0.31	25.3	127	1.36	0.23	119	<	49.8	2.8	0.05	<	0.11	<	2698	28.7	40
TFS Wash	0.85	278	<	38.4	9.48	0.833	0.2	<	<	26.9	104	1.33	0.26	125	<	45.9	1.2	0.05	<	0.1	<	2714	29.1	42
Average	0.9	218.3	0.5	41.9	8.7	0.9	0.2	<	0.3	26.6	109.4	1.4	0.2	119.0	<	52.1	1.7	0.1	<	0.1	<	2788.7	29.2	40.6
Field Corn	0.89	225	<	16.6	13.3	0.63	0.26	<	0.59	28.8	243	1.01	0.23	165	<	63.3	2.49	0.06	<	0.09	<	3002	29.6	34.1
Field Corn	0.95	225	<	15.2	12.2	0.58	0.28	<	0.54	49.1	244	0.84	0.21	146	<	45.3	2.71	0.07	<	0.09	<	3089	27.4	65.7
Field Corn	0.83	229	<	15.2	11.2	0.51	0.16	<	0.45	42.1	220	0.85	0.18	113	<	48.9	2.77	0.07	1.51	0.07	<	3124	23.4	49
Average	0.9	226.3	<	15.7	12.2	0.6	0.2	<	0.5	40.0	235.7	0.9	0.2	141.3	<	52.5	2.7	0.1	1.5	0.1	<	3071.7	26.8	49.6

Note: Below detection limit denoted by "<". See Table 2 in Section 2 for detection limits.

Table B4 Metals analysis for corn kernels. No kernels were produced by corn grown in 10% TFS or treated with TFS on soil.

Treatment	Total N	Al	As	B	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Se	Si	Sr	Zn
Control	1.26	<	<	2.27	0.13	0.006	<	<	<	1.71	14.8	0.29	0.09	3.64	<	<	0.91	0.18	<	0.1	<	40	<	15.8
Control	1.52	<	<	2.14	0.1	0.006	<	<	<	1.49	13.2	0.31	0.1	3.85	<	<	0.66	0.2	<	0.11	<	39.6	<	14.9
Control	1.52	<	<	1.76	0.1	0.006	<	<	<	2.44	15	0.27	0.1	4.59	<	<	0.66	0.2	<	0.11	<	40.3	<	15
Average	1.4	<	<	2.1	0.1	0.0	<	<	<	1.9	14.3	0.3	0.1	4.0	<	<	0.7	0.2	<	0.1	<	40.0	<	15.2
Soil Deposition	1.32	<	<	2.09	0.21	0.01	<	<	<	1.54	14.8	0.36	0.11	4.03	<	<	0.84	0.27	<	0.09	<	39.7	<	16.6
Soil Deposition	1.18	<	<	2.17	0.12	0.007	<	<	<	1.75	12.7	0.33	0.1	3.81	<	<	0.68	0.22	<	0.09	<	35.2	<	16
Soil Deposition	1.32	<	<	2.52	0.14	0.01	<	<	<	2.72	18.6	0.39	0.12	4.41	<	<	1.22	0.29	2.66	0.11	<	39.2	<	19.5
Average	1.3	<	<	2.3	0.2	0.0	<	<	<	2.0	15.4	0.4	0.1	4.1	<	<	0.9	0.3	2.7	0.1	<	38.0	<	17.4
Soil Wash	1.02	<	<	2.14	0.14	0.008	<	<	<	1.79	12.3	0.35	0.1	3.57	<	<	1.14	0.25	2.83	0.09	<	36.5	<	16.5
Soil Wash	1.07	<	<	2.22	0.11	0.007	<	<	<	1.52	11.9	0.38	0.1	3.5	<	<	1.68	0.24	<	0.09	<	35.4	<	15.1
Soil Wash	1.08	<	<	2.15	0.1	0.007	<	<	<	1.56	13.2	0.36	0.11	3.68	<	<	0.74	0.25	2.46	0.09	<	29.4	<	16.4
Average	1.1	<	<	2.2	0.1	0.0	<	<	<	1.6	12.5	0.4	0.1	3.6	<	<	1.2	0.2	2.6	0.1	<	33.8	<	16.0
TFS Deposition	1.07	<	<	2.57	0.16	0.01	<	<	0.51	2.89	20.7	0.45	0.12	4.32	<	<	0.69	0.31	<	0.09	<	33.7	<	19.3
TFS Deposition	1.31	<	<	2.19	0.15	0.009	<	<	<	1.96	15.2	0.41	0.12	4.45	<	<	1.27	0.3	<	0.1	<	26.2	<	19.7
TFS Deposition	1.17	<	<	2.29	0.16	0.009	<	<	<	2.49	16.9	0.38	0.1	3.79	<	<	1.19	0.28	<	0.09	<	36.9	<	17.9
Average	1.2	<	<	2.4	0.2	0.0	<	<	0.5	2.4	17.6	0.4	0.1	4.2	<	<	1.1	0.3	<	0.1	<	32.3	<	19.0
TFS Wash	1.56	<	<	2.25	0.11	0.007	<	<	<	2.61	21.1	0.37	0.1	4.84	<	<	1.36	0.25	5.62	0.1	<	30.6	<	19.2
TFS Wash	1.48	<	<	1.86	0.12	0.008	<	<	<	2.21	14.2	0.37	0.1	4.5	<	<	1.06	0.22	4.28	0.11	<	33	<	18.4
TFS Wash	1.66	<	<	2.01	0.14	0.008	<	<	<	2.74	18	0.4	0.11	5.41	<	<	0.98	0.26	3.46	0.12	<	36.5	<	20.3
Average	1.6	<	<	2.0	0.1	0.0	<	<	<	2.5	17.8	0.4	0.1	4.9	<	<	1.1	0.2	4.5	0.1	<	33.4	<	19.3
Field Corn	1.2	<	<	1.65	0.15	0.006	0.38	<	<	1.62	13	0.28	0.09	3.92	<	<	0.62	0.19	<	0.08	<	24.2	<	14.4
Field Corn	1.22	<	<	1.8	0.11	0.005	<	<	<	1.47	21.5	0.35	0.1	3.41	<	<	0.9	0.25	<	0.09	<	28.3	<	16.4
Field Corn	1.39	<	<	1.62	0.14	0.006	<	<	<	1.61	19.8	0.29	0.1	4.32	<	5.05	1.12	0.22	<	0.1	<	29	<	15.7
Field Corn	1.09	<	<	1.8	0.13	0.006	<	<	0.34	6.18	14.4	0.31	0.1	3.28	<	<	0.66	0.23	1.86	0.08	<	33.9	<	18.7
Average	1.2	<	<	1.7	0.1	0.0	0.4	<	0.3	2.7	17.2	0.3	0.1	3.7	<	5.1	0.8	0.2	1.9	0.1	<	28.9	<	16.3

Note: Below detection limit denoted by "<". See Table 2 in Section 2 for detection limits.

Table B5Anions results for corn tissue collected at final sampling/harvest

Treatment	Chloride (mg/kg)	Sulfate (mg/kg)	Nitrate (mg/kg)	Phosphate (mg/kg)
Control	691.7	471.4	45.6	210.8
Control	486.7	1457.9	134.5	409.7
Control	264.5	848.7	24	148.3
Average	481	926	68	256
10% TFS	49212.7	290.3	73.6	805.2
10% TFS	90076.1	167.3	121.7	993.9
Average	69644	229	98	900
TFS on soil	45319.1	1844	836.9	2340.4
TFS on soil	73768.9	2473	1954.6	3002.2
TFS on soil	91293.2	581.4	3534.1	1954.6
Average	70127	1633	2109	2432
Soil Deposition	72.8	880.5	43	191.4
Soil Deposition	86.5	988.2	31.5	238.9
Soil Deposition	254.5	903.1	127.1	393.8
Average	138	924	67	275
Soil wash	171.9	804.7	230.9	434.4
Soil wash	215	682.2	157.9	389.7
Soil wash	216.8	620.1	59.8	461
Average	201	702	150	428
TFS Deposition	5447.8	892	59.1	544.8
TFS Deposition	4805.4	590.5	36	680.9
TFS Deposition	4132.2	688	30	367.8
Average	4795	724	42	531
TFS wash	1699.4	537.3	34	483.3
TFS wash	1916.4	537.2	0	420
TFS wash	1076.5	752.6	93.5	539.2
Average	1564	609	43	481
Field Corn	2543.4	37.8	95	178.8
Field Corn	1437.8	469.4	145.6	516.7
Field Corn	1590.7	133.6	14.8	579
Average	1857	214	85	425

Table B6 Anions results for corn kernels

Treatment	Chloride (mg/kg)	Sulfate (mg/kg)	Nitrate (mg/kg)	Phosphate (mg/kg)
Control	520.3	74.3	na	888
Control	554.3	161	25.2	1478.9
Control	457.3	42.7	90.3	771.8
Average	511	93	58	1046
Soil Deposition	366.1	87.9	110.7	1447.8
Soil Deposition	399.4	53.3	64.1	87.8
Soil Deposition	370	118	108	1430
Average	379	86	94	989
Soil wash	372.8	180.9	41.7	2037.8
Soil wash	452.5	146.8	15.5	1672.8
Soil wash	466.3	144	69.5	1188.3
Average	431	157	42	1633
TFS Deposition	721.8	185.1	46.5	1633.9
TFS Deposition	621	118.8	56.7	1349
TFS Deposition	626.4	92.9	122.8	2394.2
Average	656	132	75	1792
TFS wash	753.8	54.2	15.2	2319.4
TFS wash	792.2	72	109.1	1635.8
TFS wash	770.2	71.2	74.1	1472
Average	772	66	66	1809
Field Corn	642.9	40.6	86.5	1700.2
Field Corn	594.5	7.5	116.7	2096.9
Field Corn	744.9	11.4	18.6	1291.8
Field Corn	477.3	50.1	90	2067.9
Average	606	23	75	1819

APPENDIX C

ALFALFA PLANT STUDY

Table C1 Dry weight of alfalfa treated with TFS in or on soil

Treatment Type	First Cutting (g)	Second Cutting (g)	Third Cutting (g)
Control (soil)	5.6	17.9	20.0
Control	4.6	18.5	29.1
Control	7.7	17.0	20.4
Average	6.0	17.8	23.2
10% TFS	0.0	2.5	1.7
10% TFS	0.0	2.3	2.0
10% TFS	0.0	2.6	2.5
Average	0.0	2.5	2.1
TFS on soil	7.9	3.9	4.6
TFS on soil	6.0	4.3	15.1
TFS on soil	4.6	5.4	15.4
Average	6.2	4.5	11.7

Alfalfa for a foliar treatment study was grown in the winter. Little biomass was produced, especially for the second and third sampling times. Application of treatments to foliage did not occur until after the first sampling.

Table C2 Biomass of alfalfa grown in winter and exposed to foliar treatments

Treatment Type	First Sampling (g)	Second Sampling (g)	Third Sampling (g)
Control (soil)	4.7	0.7	0
Control	3.7	0.4	0.3
Control	3.7	0.1	0
Average	4.0	0.4	0.1
Soil Deposition	3.3	1.4	0.1
Soil Deposition	3.1	2.1	0.6
Soil Deposition	3	0.5	0.2
Average	3.1	1.3	0.3
Soil Wash	3.8	0.2	0.9
Soil Wash	4	0.9	0
Soil Wash	6.3	1.7	0
Average	4.7	0.9	0.3
TFS Deposition	3.7	0.5	0.6
TFS Deposition	5	1.3	0.1
TFS Deposition	4.1	3.3	0
Average	4.3	1.7	0.2
TFS Wash	4.4	2.4	0
TFS Wash	4.7	2.6	1.1
TFS Wash	5.7	2.6	0.9
Average	4.9	2.5	0.7

Table C3 Metals analysis of alfalfa exposed to TFS in the root zone, collected at third sampling

Treatment	Total N	Al	As	B	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Se	Si	Sr	Zn
Control	3.73	23.3	<	37.6	6.27	1.19	<	<	0.43	5.27	75.9	2.34	0.18	33.5	<	66.3	0.97	0.27	<	0.22	<	199	17.3	16.3
Control	3.58	13.5	<	40.4	6.24	1.33	0.06	<	<	4.51	63.4	2.35	0.17	34	<	23.5	0.57	0.25	<	0.23	<	148	19.3	16.5
Control	3.88	10	<	42.8	7.53	1.2	0.06	<	0.31	4.59	85.3	2.29	0.16	50.1	<	37.2	0.6	0.34	<	0.29	<	123	19	17.7
Average	3.7	15.6	<	40.3	6.7	1.2	0.1	<	0.4	4.8	74.9	2.3	0.2	39.2	<	42.3	0.7	0.3	<	0.2	<	156.7	18.5	16.8
10% TFS	4.38	17	<	39.7	11.3	2.31	<	<	0.23	9.18	75.8	2.37	0.16	78.6	<	16.2	4.06	0.18	<	0.32	<	164	36.4	26.6
10% TFS	3.95	21.2	<	41.1	10.2	2.08	0.08	<	0.64	8.93	82	2.12	0.23	80.6	<	23.2	2.85	0.2	3.31	0.27	<	161	31.9	31.5
10% TFS	4.73	17.6	<	43.5	9.42	1.87	<	<	0.53	6.75	75.6	2.15	0.22	64.4	<	32	1.96	0.18	<	0.35	<	148	27.5	25.3
Average	4.4	18.6	<	41.4	10.3	2.1	0.1	<	0.5	8.3	77.8	2.2	0.2	74.5	<	23.8	3.0	0.2	3.3	0.3	<	157.7	31.9	27.8
TFS on soil	4.94	9.34	<	45.7	10.2	1.68	0.2	<	<	4.87	62.4	3.37	0.18	49.7	<	44.6	1.2	0.41	<	0.29	<	213	27.1	25.8
TFS on soil	3.98	14.9	<	56	7.25	1.58	0.14	<	<	4.59	70.6	2.47	0.18	32.4	<	66.3	0.68	0.3	<	0.31	<	195	23.1	20.7
TFS on soil	4.25	14.3	<	60.1	8.67	1.72	0.27	<	<	5.63	66.1	2.77	0.2	42.8	<	56.6	0.83	0.33	<	0.33	<	173	27.5	26.5
Average	4.4	12.8	<	53.9	8.7	1.7	0.2	<	<	5.0	66.4	2.9	0.2	41.6	<	55.8	0.9	0.3	<	0.3	<	193.7	25.9	24.3

Note: Below detection limit denoted by "<". See Table 2 in Section 2 for detection limits.

Table C4 Anions analysis of alfalfa tissue exposed to TFS in the root zone, harvested at the third sampling

Treatment	Chloride (mg/kg)	Sulfate (mg/kg)	Nitrate (mg/kg)	Phosphate (mg/kg)
Control	629.9	3224	5.2	200.3
Control	593.9	4527.9	404.1	55.1
Control	655.7	2453.5	9.3	732.1
Average	627	3402	140	329
10% TFS	23697.8	2844.5	37.3	0
10% TFS	10912.9	2313.4	56	1399.3
10% TFS	10519.8	3303.2	27.2	759.9
Average	15044	2820	40	720
TFS on soil	11454.6	194	2	714.8
TFS on soil	12032	3631.8	123.6	53.4
Average	11743	1913	63	384

APPENDIX D

LEACHATE RESULTS

Results for four leached columns are shown on the following pages, with Tables D1-3 and D4-6 corresponding to collection at times 40, 44, and 48 hours after starting the study. Columns 1 and 2 were run at the same time (for all three treatments) and columns 3 and 4 were run at the same time (again for all three treatments), but 1 and 2 were run on different days than columns 3 and 4. Leachate was not produced at 48 hours for one soil treatment and both TFS on soil treatments in the first run. Anions analysis was not performed for leachate sampled from the first column after 44 hours because the entire sample was acidified before an aliquot was removed for the analysis.

Table D1 Metals analysis of leachate collected after 40 hours

Treatment	Be	Al	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Cd	Sb	Ba	Tl	Pb
	Ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	Ug/L	Ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Control 1	<	<	<	<	388.2	<	<	45.4	65.0	<	25.6	<	<	<	1361	<	<
Control 2	<	<	<	<	387.3	<	<	40.9	58.9	<	23.9	<	<	<	1311	<	<
Control 3	<	<	<	<	933	<	<	<	42	<	25	<	<	<	1772	<	<
Control 4	<	<	<	<	793	<	<	<	35	<	23	<	<	<	1651	<	<
Average	<	<	<	<	625	<	<	43.2	50.2	<	24.4	<	<	<	1524	<	<
10% TFS 1	<	<	<	<	223.2	<	<	<	136.5	<	39.7	<	23.5	<	14047	<	<
10% TFS 2	<	<	<	<	183.6	<	<	<	132.1	<	41.0	<	22.2	<	13417	<	<
10% TFS 3	<	<	<	<	589	<	<	<	239	<	54	37	58	<	23980	<	<
10%TFS 4	<	<	<	<	509	141	<	<	218	<	46	37	62	<	26640	<	<
Average	<	<	<	<	376	141	<	<	181.4	<	45.2	37	41.4	<	19521	<	<
TFS on Soil 1	<	<	<	<	2307	<	<	137.7	57.6	<	21.7	<	38.1	<	10323	<	<
TFS on Soil 2	<	<	<	<	2964	505	<	40.6	55.6	<	21.4	<	30.8	<	8657	<	<
TFS on Soil 3	<	<	<	<	7151	<	<	<	62	<	24	<	72	<	13210	<	<
TFS on Soil 4	<	<	<	<	7778	<	<	<	67	<	24	<	74	<	13990	<	<
Average	<	<	<	<	5050	505	<	89.2	60.6	<	22.8	<	53.7	<	11545	<	<

Note: Below detection limit denoted by "<".

Table D2 Metals analysis of leachate collected after 44 hours

Treatment	Be	Al	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Cd	Sb	Ba	Tl	Pb
	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	Ug/L	Ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Control 1	<	<	<	<	95.6	<	<	44.7	67.2	<	22.2	<	<	<	350.2	<	<
Control 2	<	<	<	<	170	<	<	<	57	<	24.6	<	<	<	646.4	<	<
Control 3	<	<	<	<	396	<	<	<	<	<	26	<	<	<	485	<	<
Control 4	<	<	<	<	574	<	<	<	51	<	32	<	<	<	798	<	<
Average	<	<	<	<	309	<	<	44.7	58	<	26	<	<	<	570	<	<
10% TFS 1	<	<	<	<	113.6	<	<	<	130.4	<	25.2	<	<	<	4949	<	<
10% TFS 2	<	<	<	<	126.1	<	<	<	127.3	<	25.2	<	<	<	7410	<	<
10% TFS 3	<	<	<	<	135	<	<	<	135	<	22	<	<	<	1785	<	<
10% TFS 4	<	<	<	<	199	<	<	<	195	<	27	20	<	<	3461	<	<
Average	<	<	<	<	143	<	<	<	146.9	<	24.9	20	<	<	4401	<	<
TFS on Soil 1	<	<	<	<	1968	<	<	51.4	35	<	18.1	<	39	<	9747	<	<
TFS on Soil 2	<	<	<	<	2830	<	<	<	53.9	<	18.6	<	32.9	<	8686	<	<
TFS on Soil 3	<	<	<	<	10440	<	<	<	59	<	26	<	107	<	18370	<	<
TFS on Soil 4	<	333	<	<	6620	<	<	<	36	<	21	<	76	<	12300	<	<
Average	<	<	<	<	5465	<	<	51.4	46.0	<	20.9	<	64	<	12276	<	<

Note: Below detection limit denoted by "<".

Table D3 Metals analysis of leachate collected after 48 hours

Treatment	Be ug/L	Al ug/L	V ug/L	Cr ug/L	Mn ug/L	Fe ug/L	Co ug/L	Ni ug/L	Cu Ug/L	Zn Ug/L	As ug/L	Se ug/L	Cd ug/L	Sb ug/L	Ba ug/L	Tl ug/L	Pb ug/L
Control 1	<	<	<	<	161.3	<	<	57.8	61.7	<	22.5	<	<	<	394.7	<	<
Control 3	<	<	<	<	165	<	<	<	<	<	27	<	<	<	435	<	<
Control 4	<	651	<	<	194	<	<	<	25	<	26	<	<	<	647	<	<
Average	<	651	<	<	173	<	<	57.8	43	<	25.2	<	<	<	492	<	<
10% TFS 1	<	<	<	<	32.3	<	<	<	92.4	<	18.6	<	<	<	535.7	<	<
10% TFS 2	<	<	<	<	28.4	<	<	<	82.1	<	17	<	<	<	534.3	<	<
10% TFS 3	<	<	<	<	<	<	<	<	70	<	18	<	<	<	886	<	<
10% TFS 4	<	<	<	<	<	<	<	<	91	<	30	<	<	<	1683	<	<
Average	<	<	<	<	30	<	<	<	84	<	21	<	<	<	910	<	<
TFS on Soil 3	<	<	<	<	6828	<	<	<	<	<	20	<	79	<	12830	<	<
TFS on Soil 4	<	<	<	<	3684	<	<	<	<	<	<	<	43	<	7276	<	<
Average	<	<	<	<	5256	<	<	<	<	<	20	<	61	<	10053	<	<

Note: Below detection limit denoted by "<".

Table D4 Anions analysis of leachate collected after 40 hours

Treatment	Chloride mg/L	Sulfate mg/L	Nitrate mg/L	Phosphate mg/L
Control 1	1151.4	359.0	1000.6	<
Control 2	852.75	55.2	38.6	<
Control 3	1464.1	503.6	1445.2	<
Control 4	1958	498	1247	<
Average	1357	354	933	<
10% TFS 1	51848	466	700	<
10% TFS 2	49648	440	678	<
10% TFS 3	53200	475	795	<
10% TFS 4	66645	560	990	<
Average	55335	485	791	<
TFS on Soil 1	16150	199	434	<
TFS on Soil 2	23603	329	676	<
TFS on Soil 3	26898	421	958	<
TFS on Soil 4	26546	316	658	<
Average	23299	316	682	<

Note: Below detection limit denoted by "<".

Table D5 Anions analysis of leachate collected after 44 hours

Treatment	Chloride mg/L	Sulfate mg/L	Nitrate mg/L	Phosphate mg/L
Control 1	--	--	--	--
Control 2	982.7	134.75	336.55	<
Control 3	995.6	150.8	226.2	<
Control 4	1120.6	158	241	<
Average	1033	148	268	<
10% TFS 1	25443	365	435	<
10% TFS 2	27992	316	458	<
10% TFS 3	5567.8	228.4	78.6	<
10% TFS 4	9163.8	319.8	173.4	<
Average	17042	307	286	<
TFS on Soil 1	15975	70	106	<
TFS on Soil 2	21758	188	329	<
TFS on Soil 3	32631	164	267	<
TFS on Soil 4	22978	91	99	<
Average	23336	128	200	<

Note: Below detection limit denoted by "<".

Table D6 Anions analysis of leachate collected after 48 hours

Treatment	Chloride mg/L	Sulfate mg/L	Nitrate mg/L	Phosphate mg/L
Control 1	958.7	34.4	91.1	<
Control 3	1027.3	126.1	158.3	<
Control 4	1084.3	125.5	182.3	<
Average	1023	95	144	<
10% TFS 1	11545	694	194	<
10% TFS 2	2338.2	132.1	32.8	<
10% TFS 3	3747	206	38.2	<
10% TFS 4	5295.4	266	50.4	<
Average	5731	325	79	<
TFS on Soil 3	37180	160	254	<
TFS on Soil 4	22121	83	85	<
Average	29651	122	170	<

Note: Below detection limit denoted by "<".

Table D7 Percent germination of corn and alfalfa in leached TFS

Treatment	Corn			Alfalfa		
	5 days	7 days	10 days	5 days	7 days	10 days
Control	80	90	90	85	85	87.5
Control	80	95	95	80	77.5	77.5
Control	75	85	90	82.5	87.5	85
Average	78.3	90.0	91.7	82.5	83.3	83.3
10% TFS	70	80	100	77.5	85	82.5
10% TFS	90	100	100	75	82.5	77.5
10% TFS	100	100	90	80	77.5	87.5
Average	86.7	93.3	96.7	77.5	81.7	82.5
TFS on soil	50	95	95	52.5	67.5	72.5
TFS on soil	50	90	95	35	50	60
TFS on soil	30	95	100	55	72.5	77.5
Average	43.3	93.3	96.7	47.5	63.3	70.0

Note: The top 3 cm of soil treatment from the leached columns were collected and used for the leached germination experiment.