In Situ Burning and Phytoremediation Studies for Onshore Oil Spills

Jeff B. Hillard, Ph.D.

Stephanie Farrell, Ph.D.

Maureen McCurdy, Ph.D.

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Abstract

Phytoremediation and *in situ* burning are emerging technologies that can remediate crude oil contaminated upland sites. Phytoremediation of upland oil spills requires plants that are capable of thriving in oiled soil. Furthermore, the effectiveness of *in situ* burning and phytoremediation in restoring oil contaminated soil needs to be evaluated under controlled conditions. The objectives of this study were to: (1) identify potential phytoremediators that are adapted to the soils and climate of northern Louisiana, and (2) assess the effectiveness of *in situ* burning and phytoremediation in greenhouse pots under controlled conditions. The first objective was addressed by: (1) observing vegetation growing in existing upland oil spill sites, and (2) screening plants for oil tolerance in the greenhouse. The second objective will be evaluated during the second year of this study by measuring the residual hydrocarbon content and components in oiled soil subjected to *in situ* burning, phytoremediation, or both over a 300 day period.

Over 40 different species of native plants were observed growing in oil contaminated soil at existing spill sites in northern Louisiana. These observations indicated that a variety of plants might be able to persist in crude oil contaminated soil under field conditions. This suggested that the plants may have the potential to phytoremediate. In greenhouse studies, 27 different types of plants were screened for oil tolerance by growing transplants in soil containing 0, 30, or 60 grams of North Louisiana Sweet Crude oil per kg of typical north Louisiana upland soil (0, 30, or 60 g oil kg^{-1} soil). Plant height, dry matter, and mortality were determined after a minimum growing period of 28 days. Dry matter yields and plant height were reduced gradually in response to increasing rates of crude oil for all plants tested, although some plants appeared to tolerate oiled soil better than others. Plant height generally was not influenced as strongly by crude oil as was dry matter yield. Gazania (a drought tolerant ground cover) exhibited the least decline in dry matter yield and height in response to crude oil. Plant mortality was zero for most plants. Based on these studies, it appears feasible to establish vegetation in soil containing up to approximately 6 % crude oil. Germination studies were conducted in soil containing either 0 or 30 g oil kg^{-1} soil. Germination rates were very low in oiled soil, indicating that transplanting may be the best option for establishing vegetation in oiled soil.

In order to assess *in situ* burning and phytoremediation quantitatively and qualitatively, the following eight treatments were established in greenhouse pots: (1) soil contaminated with 30 g oil kg^{-1} soil, (2) soil with 30 g oil kg^{-1} soil followed by burning, (3) oiled soil with bermudagrass, (4) oiled soil with tall fescue, (5) burned oiled soil with bermudagrass, (6) oiled soil containing 2 g kg^{-1} lime with bermudagrass, (7) soil with bermudagrass, and (8) soil with tall fescue. The treatments were established in greenhouse pots on April 6, 1999. Soil will be sampled at 0, 50, 100, 200, and 300 days and analyzed for hydrocarbon utilizing bacteria (HUB) by most probable number (MPN) technique, hydrocarbon content by GC/FID, and hydrocarbon fingerprinting by GC/MS.

1.0 Introduction

Numerous low volume crude oil spills occur on upland sites in Louisiana. These spills can damage the environment through their toxic effects on soil, water, and native vegetation. Phytoremediation and *in situ* burning are technologies that have the potential to restore crude oil contaminated upland sites. Phytoremediation involves using plants to reduce the level of either inorganic or organic contaminants in soil and groundwater (Salt *et al.* 1998). This emerging technology has shown promise in remediating crude oil contaminated upland environments (Banks and Schwab 1998; Wiltse *et al.* 1998). *In situ* burning involves the combustion of some of the flammable components in crude oil to lower the hydrocarbon content. It has been investigated extensively for marine oil spills, but has not been studied in conjunction with small, upland sites (Allen and Ferek 1993). Although *in situ* burning appears promising, its effectiveness alone and in combination with phytoremediation has not been studied under controlled conditions.

Phytoremediation has been used successfully to facilitate *in situ* bioremediation of soil contaminated with compounds such as heavy metals and nonhydrophobic organic contaminants. The primary function of plants in restoring oil contaminated soil is to increase the rate of organic biodegradation within the rhizosphere by stimulating microbiological activity. An added benefit is that plant roots create a porous soil matrix that encourages air and water to move into and through the soil, thereby enhancing aeration and water availability (Rock 1996). Phytoremediation has several advantages: it is *in situ*, passive, solar driven, and its cost is about 10 to 20 % less than costs associated with mechanical or chemical treatments. Moreover, phytoremediation is faster than natural (unassisted) remediation, aesthetically pleasing, and has high public acceptance (Rock 1996).

The presence of oil in soil is, however, toxic to plants, and establishing vegetation can be difficult (Amakiri and Onoreghara 1983; Baker 1979; Udo and Fayemi 1975). Several plant species may be able to remediate oil contaminated soil (Aprill and Sims 1990; Gunther *et al.*1996; Klokk 1984; Lee and Banks 1993). Aprill and Sims (1990) reported an increase in the disappearance of polycyclic aromatic hydrocarbons (PAHs) in soil columns planted with prairie grasses. The first successful demonstration of phytoremediation of petroleum contaminated soil on a Gulf Coast agricultural site occurred in 1993 (Betts 1997). Over a 21 month period, 41 and 50 % of petroleum compounds were removed from Saint Augustine and ryegrass vegetated plots, respectively. Only 21% of petroleum compounds were removed from nonvegetated plots. Banks and Schwab (1998) reported that the levels of residual hydrocarbons were statistically lower in plots planted with white clover, tall fescue, or bermudagrass compared to control plots. After three growing seasons, approximately 50 % of the residual hydrocarbons had been removed from the vegetated plots while only 33 % had been removed from the control plots.

The effectiveness of phytoremediation is affected by both plant species and cultivars within a species (Wiltze *et al.*1998). The success of some studies was achieved using plant species that were not well suited to conditions found in northern Louisiana. Successful phytoremediation requires plants that will tolerate oil and thrive in the infertile, acidic soils typical of the region.

In situ burning has been used as a treatment technology for marine oil spills for many years, and the advantages of this remediation technique have been thoroughly analyzed (Allen and Ferek 1993). Some of the advantages of *in situ* burning include: (1) high elimination rate, (2) reduction of petroleum compounds to primary combustion products of carbon dioxide and water, (3) minimal environmental impact, and (4) minimal cleanup. Although *in situ*burning has been investigated as a method of removing oil from wetland environments (Baker *et al.* 1987; Bruney and Trimm 1993), there is little information about its applicability to small, upland oil spills. May and Wolfe (1997) presented a synopsis of field experiences (not formal research studies) using controlled burning on inland oil spill sites in Illinois. Only one case involved a small oil spill on a fallow cornfield which was free from standing water prior to the spill. This site was burned the same day of the oil spill and then tilled before establishing normal farming activity. Two years later, representative soil samples from the site met the Illinois Tier I Cleanup Objectives.

The overall goal of this project was to evaluate the potential for using *in situ* burning and phytoremediation to restore oil contaminated upland sites in northern Louisiana. The objectives of this project were to:

1. Observe and identify native vegetation in existing upland oil spill sites in Louisiana. This may provide clues about the types of plants that can tolerate oil in soil and that may be effective phytoremediators.
2. Screen a variety of plants for oil tolerance under greenhouse conditions. Plant screening will improve understanding of how plants respond to oil in soil and provide additional insights about the types of plants that may persist in oiled soil in the field.
3. Evaluate the effectiveness of *in situ* burning and phytoremediation quantitatively and qualitatively over time in the greenhouse under controlled conditions.

2.0 Materials and Methods

2.1 Observations of Vegetation at Existing Oil Spill Sites

Five visits to the oil producing region of northern Louisiana were made during the summer of 1998. These observation sites were located near Oil City, Caddo Parish. The sites consisted of areas associated with some aspect of crude oil production (storage tanks, pipelines, wells, etc.) where crude oil had been spilled (Figure 1). Plants found growing in oiled soil were photographed for future reference.

Figure 1. *Typical observation site for plants growing in crude oil contaminated soil.*

2.2 Greenhouse Screening for Oil Tolerance

2.2.1 Preparation of Oiled Soil

Soil for the plant screening and germination studies was obtained from the Louisiana Tech University Arboretum located in Lincoln Parish. Soil was collected from the surface horizon of a Sacul fine sandy loam (clayey, mixed, thermic Aquic Hapludult). A sample of this soil was analyzed by the Louisiana State University Soil Testing Laboratory (Table 1). Soil used in these experiments was air dried and passed through a 2 mm mesh screen prior to applying crude oil.

Table 1. Soil test results for Sacul fine sandy loam.

Properties	**Value**	**Soil Test Interpretation**
pH	5.5	
Phosphorus, mg kg^{-1}	11	low
Potassium, mg kg^{-1}	3	very low
Calcium, mg kg^{-1}	176	very low
Magnesium, mg kg^{-1}	25	very low
Exchangeable bases, cmole kg^{-1}	1.1	
Texture	fine sandy loam	

To prepare oiled soil for the plant screening studies, 1500 g of sieved, air dried Sacul topsoil was added to a stainless steel mixing bowl and treated with 0, 45, or 90 g of north Louisiana Sweet Crude oil (Calumet Lubricants Company, API gravity of 38.3). Oil spilled at these rates produced soil containing 0, 30, or 60 g crude oil kg^{-1} soil. The oil and soil were mixed thoroughly using a hand held electric mixer. The oiled soil was divided into three round (10 cm diameter) plastic pots, such that each pot contained approximately 500 grams of oiled soil. This allowed the oil spill rate for each plant to be replicated three times. The bottom of each pot was lined with a layer of Weed-X fabric. The pots were aged for seven to ten days in a greenhouse to allow the volatile hydrocarbons to evaporate.

2.2.2 Plant Screening

Seeds were germinated in Pro-Mix potting media in plug trays [1.5 cm (w) x 4 cm (h)]. Each pot received five transplants (Figure 2) and was watered with 100 ml of tap water. The pots were placed randomly on an ebb and flow watering table where they were watered automatically twice per day. On warm, clear days when evapotranspiration rates were high, the pots were top misted. The pots were housed in a heated and cooled greenhouse where the air temperature was maintained between 10^{o} C to 35^{o} C. Each pot was fertilized by adding four g of *Osmocote*. Insects were controlled with insecticide sprays when necessary. Plants that died from transplant shock during the first week were replaced with fresh transplants. After a minimum 28 day growing period, plant heights, mortality, and dry weights were measured.

Figure 2. *Greenhouse pot containing oiled soil and a wild oats transplant.*

2.2.3 Germination Study

Seventy grams of soil containing either 0 or 30 g crude oil kg^{-1} soil (prepared as described in the previous section) were added to plastic bathroom cups (5 cm diameter) with holes punched in the bottom. Twenty seeds were placed on the top of the soil and pressed into the soil with another cup. Each treatment was replicated twice. The cups were maintained on an ebb and flow watering table in the greenhouse (as described above) and misted occasionally. Seedlings were removed as they germinated, and the number of germinated seeds was recorded over a 28 day period.

2.3 *In Situ* Burning and Phytoremediation Greenhouse Study

2.3.1 Preparation of Oiled, Oiled/Limed, and Oiled/Burned Soil

The following soil treatments were prepared using air dried, sieved (2 mm) Sacul topsoil and North Louisiana Sweet Crude oil: (1) oiled soil, (2) oiled/burned soil, and (3) oiled/limed soil. The soil was contaminated in small batches by applying 60 g of crude oil to two kg of soil (30 g oil kg^{-1}) in a stainless steel mixing bowl. The soil and oil were mixed thoroughly using a hand held electric mixer and transferred to a 40 l galvanized steel tub. Twenty-five two kg batches of oiled soil were prepared in this manner. After all of the small batches had been prepared and transferred to the tub, they were mixed thoroughly using an electric mixer. The oiled/burned soil was prepared in one batch by applying 750 g of crude oil to 25 kg of soil in a 25 l galvanized steel pail. The oil was allowed to seep into the soil for about 15 minutes until approximately a 1 cm thickness of oil remained on the soil surface. The oil was ignited with a propane torch and burnt itself out over approximately 30 minutes (Figure 3). The batches of oiled and oiled/burned soil were stored uncovered in a greenhouse for seven days. Following this aging period, the oiled/limed soil was prepared in four separate batches by mixing 3 kg of oiled soil with 6 g of hydrated lime [$Ca(OH)_2$] using the electric mixer.

Figure 3. *In situ burning of crude oil contaminated soil.*

2.3.2 Establishing Treatments

One kg of untreated soil, oiled soil, oiled/limed soil, or oiled/burned soil was added to a square plastic pot [11 cm (w) x 12.5 cm (h)] that was lined with Weed-X fabric. The pots that received phytoremediation treatments had four transplants added per pot. These transplants were established in plug trays (1.5 cm x 4 cm) using untreated soil as the growing medium. To summarize, the following treatments were established in the pots:

1. soil + 30 g crude oil kg^{-1}
2. soil + 30 g crude oil kg^{-1} + bermudagrass
3. soil + 30 g crude oil kg^{-1} + bermudagrass + 2 g lime kg^{-1}
4. soil + 30 g crude oil kg^{-1} + tall fescue
5. soil + 30 g crude oil kg^{-1} + burning
6. soil + 30 g crude oil kg^{-1} + burning + bermudagrass
7. soil + bermudagrass
8. soil + tall fescue

Sufficient pots were prepared to allow for three replications of each treatment over four sampling periods (total of 12 pots per treatment). These sampling periods were set at 50, 100, 200, and 300 days after the oil was spilled. Samples of oiled and oil/burned soil used to generate these treatments were used for Day 0 (April 6, 1999) samples. To date, Day 0 and Day 50 soil samples have been obtained; Day 100, 200, and 300 samples will be taken during the second year of this study.

The pots were kept in a heated and cooled greenhouse in which the temperature was maintained between 10^{o}C and 30^{o} C. The pots were placed on an ebb and flow watering table that was flooded twice a day and top misted as needed. Four grams of *Osmocote* fertilizer granules were added to each pot, and the plants were treated with insecticides as needed. The plants were harvested periodically by clipping the grasses at 10 cm above the soil surface. The clippings were dried in an oven (105^{o} C), weighed, and stored for future nutrient analyses.

2.3.3 Sampling Technique

Prior to soil sampling, the grasses were clipped (10 cm height above the soil surface), and the clippings were dried, weighed, and retained. Next, the soil was removed from each plastic pot in one large plug and placed in a paper bag that had been cut to the height of the soil. Bags containing the soil plugs were stored in the greenhouse and allowed to dry for two days. Drying the soil plugs was necessary in order to remove the soil from the plant roots; the soil could not be separated from the plant roots while the soil plugs were still moist. For those treatments containing plants, soil was separated from the root mass by placing the soil plug in a one quart plastic bag with the stems protruding out of the bag. The soil was kneaded carefully away from the roots, sieved through a 2 mm screen, and retained for analysis.

2.3.4 Microbial and Hydrocarbon Analyses

Soil samples were analyzed for hydrocarbon utilizing bacteria (HUB) by the most probable number (NPN) technique using North Louisiana Sweet Crude oil as the carbon source. (Chaîneau *et al.*1996). The soil samples were extracted with dichloromethane prior to GC/FID analysis for hydrocarbon content and GC/MS analysis for hydrocarbon fingerprinting (Roques *et al.*1994)

3.0 Results And Discussion

3.1 Observations at Existing Spill Sites

Over 40 different plant species were observed at oil spill sites in northern Louisiana. Many of these plants were identified as either native grasses, sedges, or other herbaceous plants (Figure 4). A number of plants were found growing in heavily oiled soil, indicating that some plants might persist in oiled soil under field conditions. The investigators were unable to identify any of the observed plant species with complete certainty. A more concerted effort to identify oil tolerant plants will be undertaken during the second year of the project.

Figure 4. *Native plants found growing on existing oil spill sites.*

3.2 Greenhouse Studies

3.2.1 Oil Tolerance Screening Study

Increasing levels of crude oil gradually reduced the amount of plant dry matter yield (Table 2 and Figures 5 to 23) and plant height (Figures 5 to 20, 22, and 23) of all plants relative to plants grown in the control pots. Texas bluebonnet (Figure 21) and crimson clover (Figure 12) were affected most severely by the level of oil in soil; gazania (Figure 14) appeared to be the least affected. The other plants exhibited a moderate response to crude oil. The response of the plants to crude oil in soil suggests several important possibilities. First, there were noticeable differences in the overall vigor of plants cultivated in oiled soil. This difference in vigor indicates that screening additional plants for oil tolerance may identify plants that have an even higher probability of persisting in crude oil contaminated soils. Based on this study, gazania, yellow nutsedge, and bermudagrass would be suitable phytoremediation candidates for field trials because of their relative tolerance to oil in soil and their suitability for cultivation in Louisiana's upland oil polluted sites. Secondly, the plants' responses suggest that the upper limit of crude oil tolerance may be on the order of 5 to 6 % crude oil in soil (weight oil/weight of soil). In addition to the standard rates of 0, 30, and 60 g oil kg^{-1} soil (Figure 5), wild oats were screened at 90 g oil kg^{-1} soil (9 % oil). The relative dry matter yield and plant height for wild oats were essentially zero at 90 g oil kg^{-1} soil; its response to crude oil between 0 and 60 g oil kg^{-1} soil was typical for most plants screened. The best performing plants (gazania and others) should be evaluated at oil spill rates greater than 60 g oil kg^{-1} soil to see whether they can tolerate oil levels in soil beyond 5 to 6 %. It should be noted, however, that a plant's ability to tolerate crude oil in soil might not translate into long-term persistence under actual field conditions.

All plants exhibited a good fit between their relative dry matter yields and the rate of spilled oil by second order, polynomial regression equations. The coefficient of determinations (R^2) was usually greater than 0.90. The investigators had expected to use confidence intervals to separate the plants into groups of similarly responding plants. Unfortunately, the confidence intervals for relative dry matter yield and plant height were too wide to group the plants definitively.

Dry matter yields appeared to represent the overall plant response to crude oil better than plant height. In many instances, the heights of plants in oiled soil were similar to heights in the controls, even though the visual appearance and dry matter yields were affected significantly by crude oil. While crude oil suppressed dry matter yields, it generally was not lethal to the plants at the levels tested. Texas bluebonnet and rape were the only two plants that experienced greater than 20 % mortality at 60 g oil kg^{-1} soil. The mortality rate of most plants was usually zero, but a few had less than 10 % mortality. Plant mortality, like plant height, was found to be correlated less with overall plant growth and vigor than with dry matter yields.

The investigators attempted to screen a variety of wildflowers, but were unsuccessful in producing viable transplants. During the second year, attention will be focused on screening additional grasses and perennial species, as well as attempting to produce viable wildflower transplants.

Table 2. Mean relative dry matter yield in soil containing 30 and 60 g oil kg^{-1} soil.

	% Relative Yield	
Plant	**30 g oil kg^{-1}**	**60 g oil kg^{-1}**
Annual bluegrass	34	24
Annual ryegrass	40	22
Anza Wheat	64	38
Austrian winter pea	58	41
Barley	62	35
Barnyardgrass	52	29
Bermudagrass	40	41
Cowpea	68	49
Crimson clover	27	15
Elbon rye	52	17
Gazania	96	50
Hairy vetch	43	25
Matua prairiegrass	32	19
Millet	74	52
Mt. Barker clover	34	9
Novella English pea	57	32
Oats	52	25
Piper sudangrass	55	27
Rape	52	21
Rough bluegrass	44	20
Sorghum sudangrass	78	54
Sweet pea	50	37

Tall fescue	36	22
Texas bluebonnet	25	12
Wild oats	47	18
Winter wheat	68	43
Yellow nutsedge	60	58

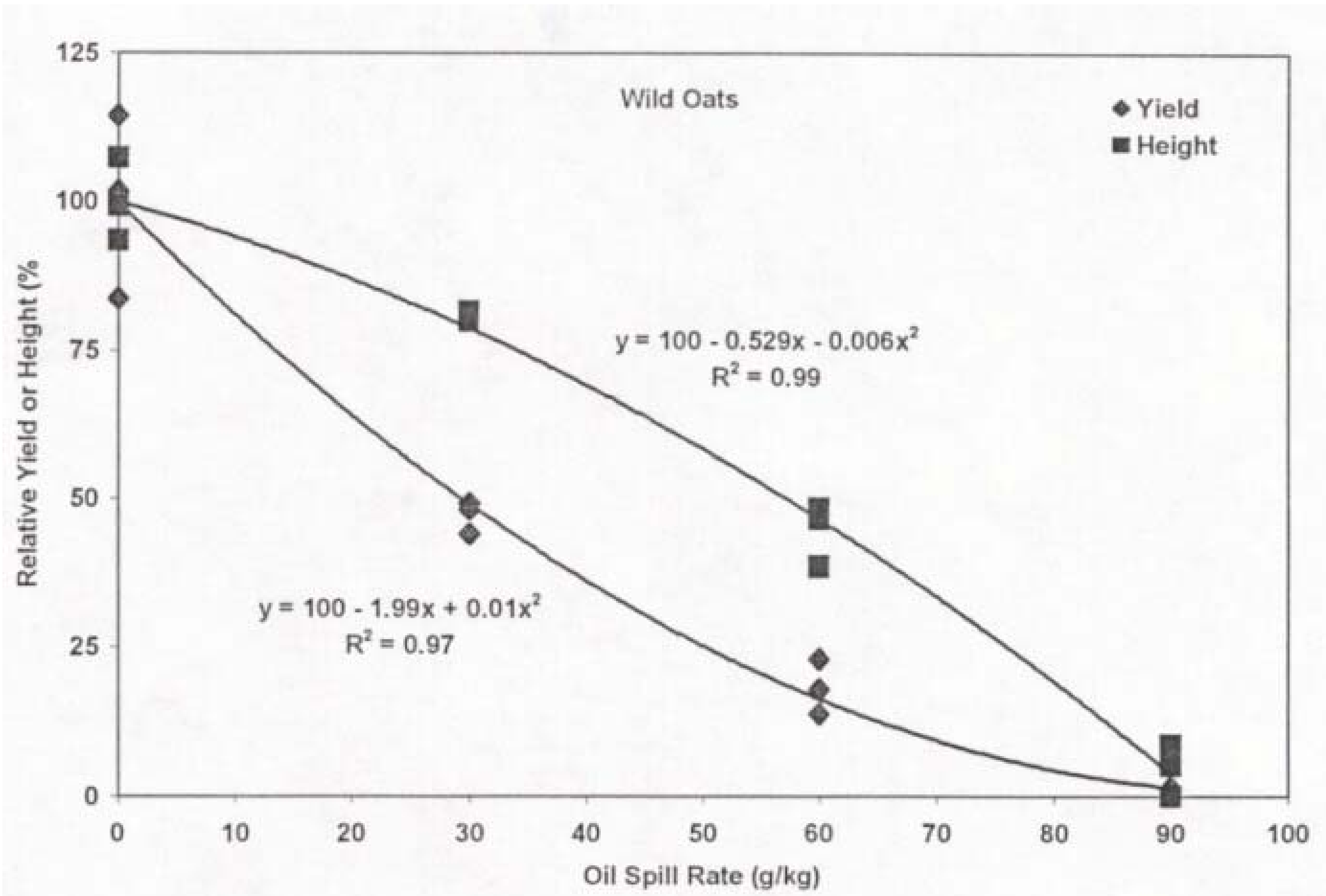


Figure 5. *Relative dry matter yield and plant height of wild oats cultivated in soil containing 0, 30, 60, or 90 g crude oil kg^{-1} soil.*

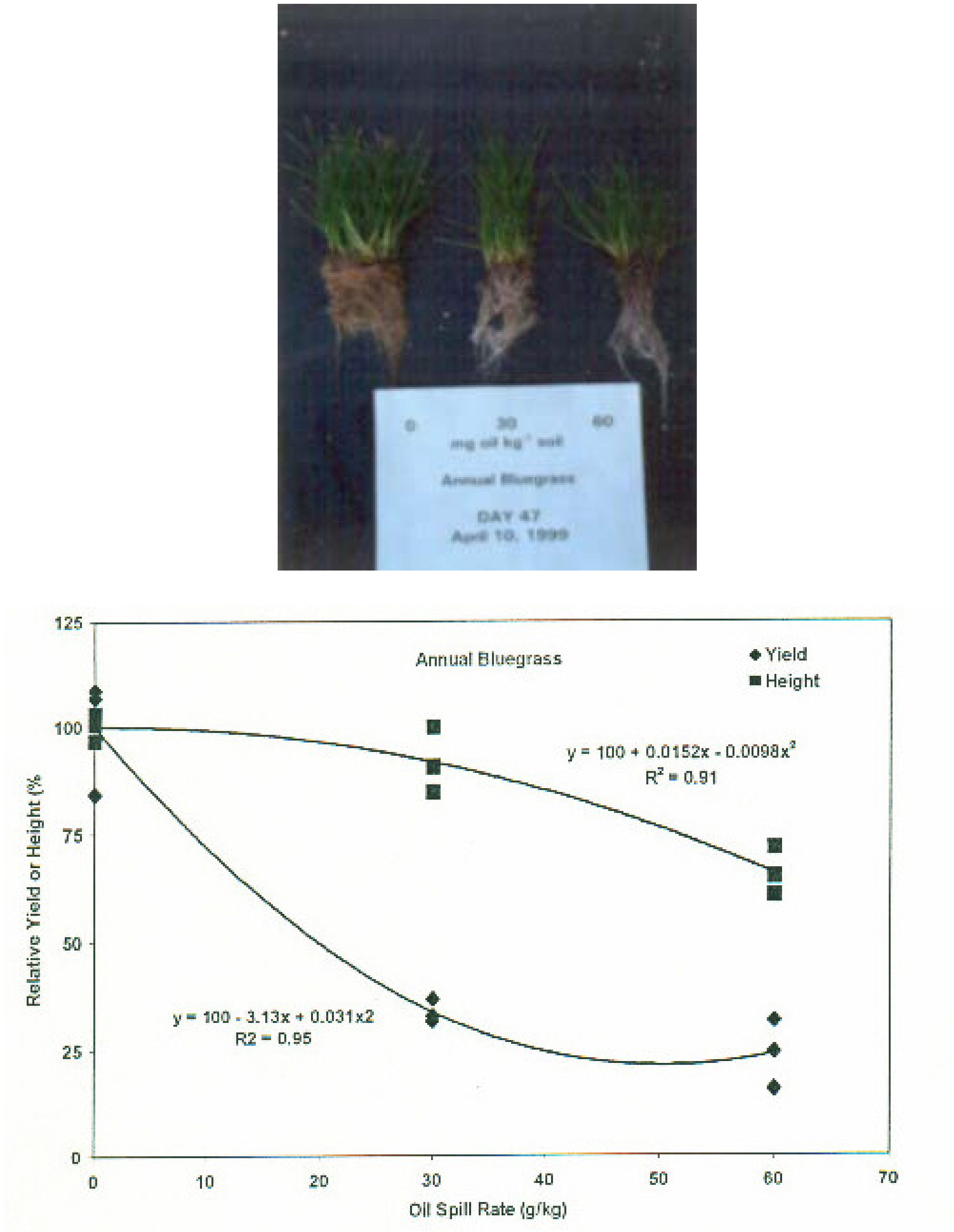


Figure 6. *Relative dry matter yield, plant height, and photograph of annual bluegrass cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

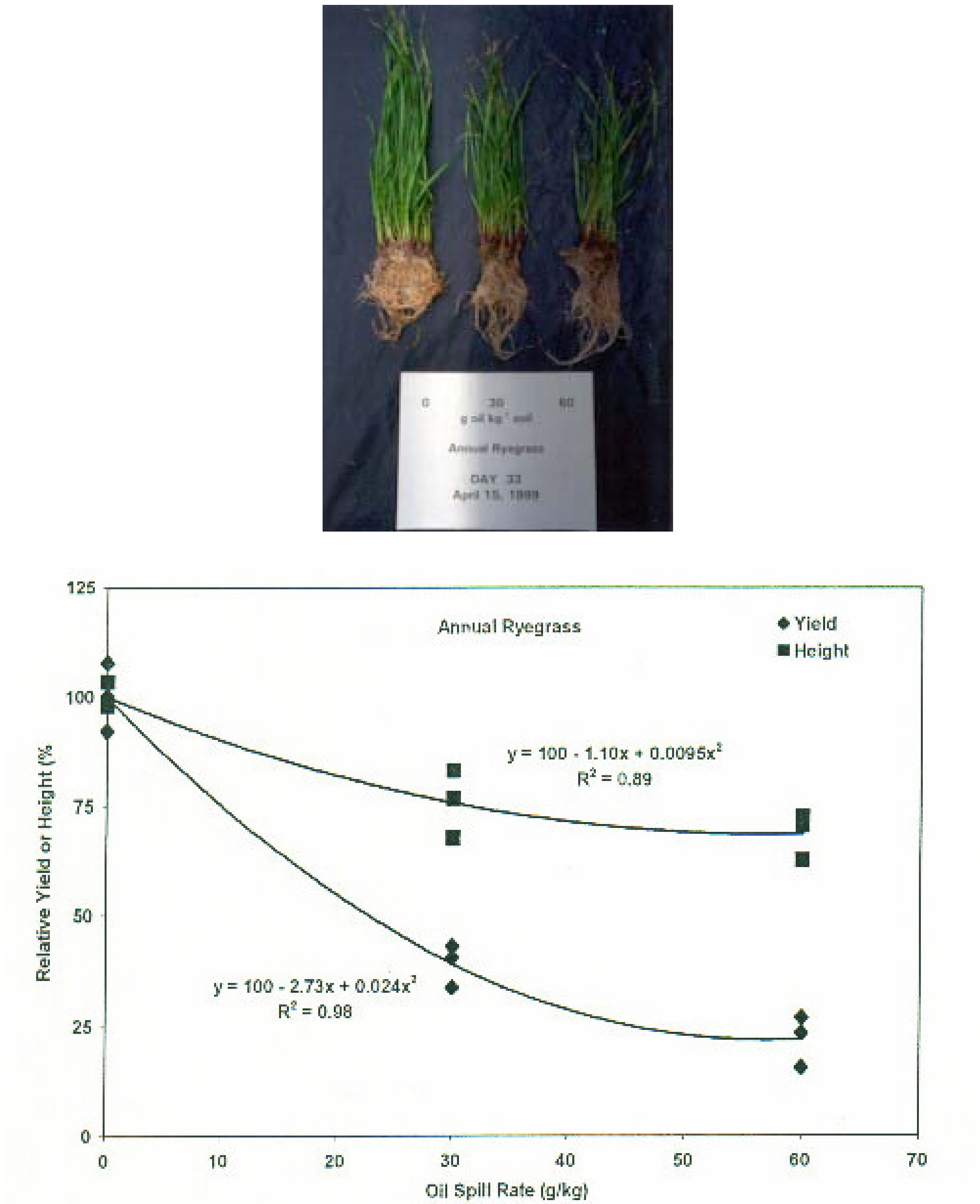


Figure 7. *Relative dry matter yield, plant height, and photograph of annual ryegrass cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

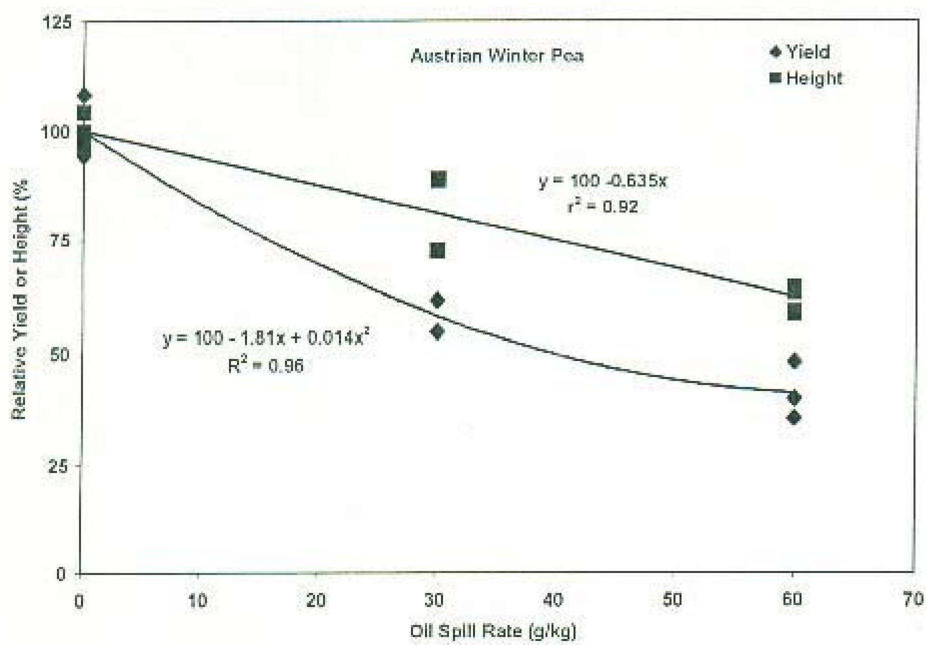


Figure 8. *Relative dry matter yield, plant height, and photograph of Austrian winter pea cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

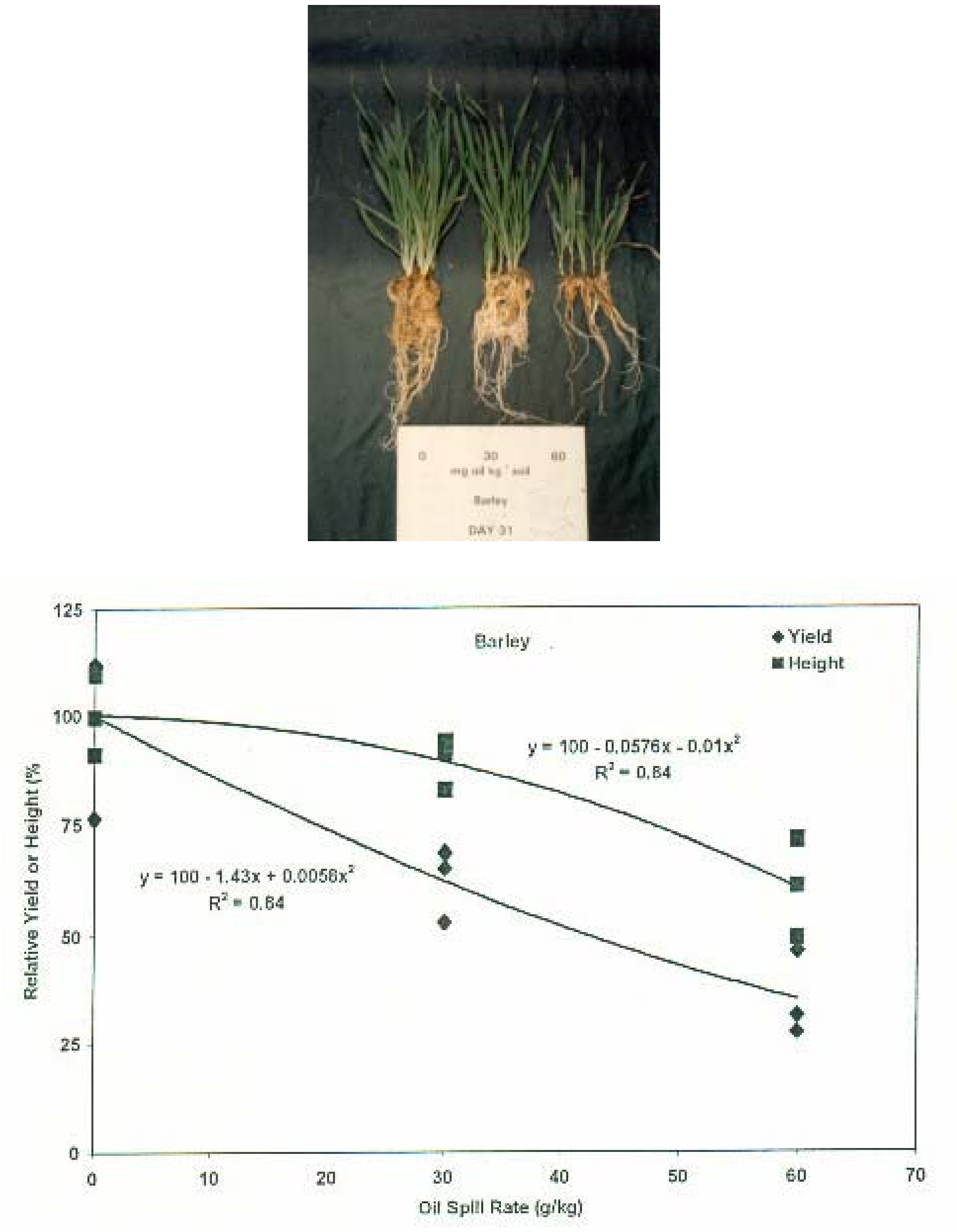


Figure 9. *Relative dry matter yield, plant height, and photograph of barley cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

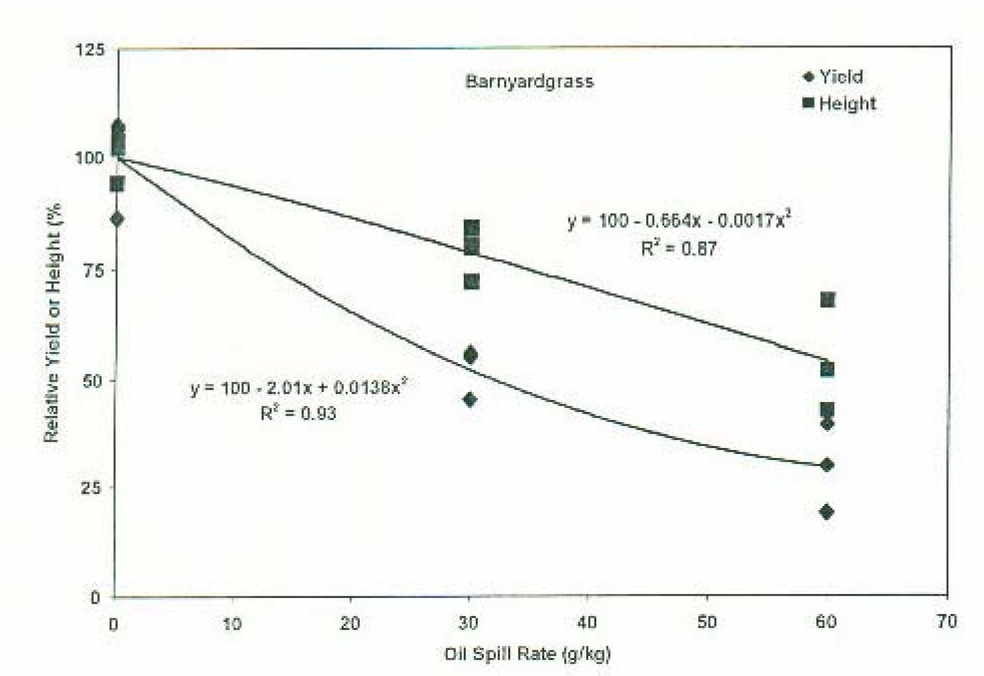


Figure 10. *Relative dry matter yield, plant height, and photograph of barnyardgrass cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

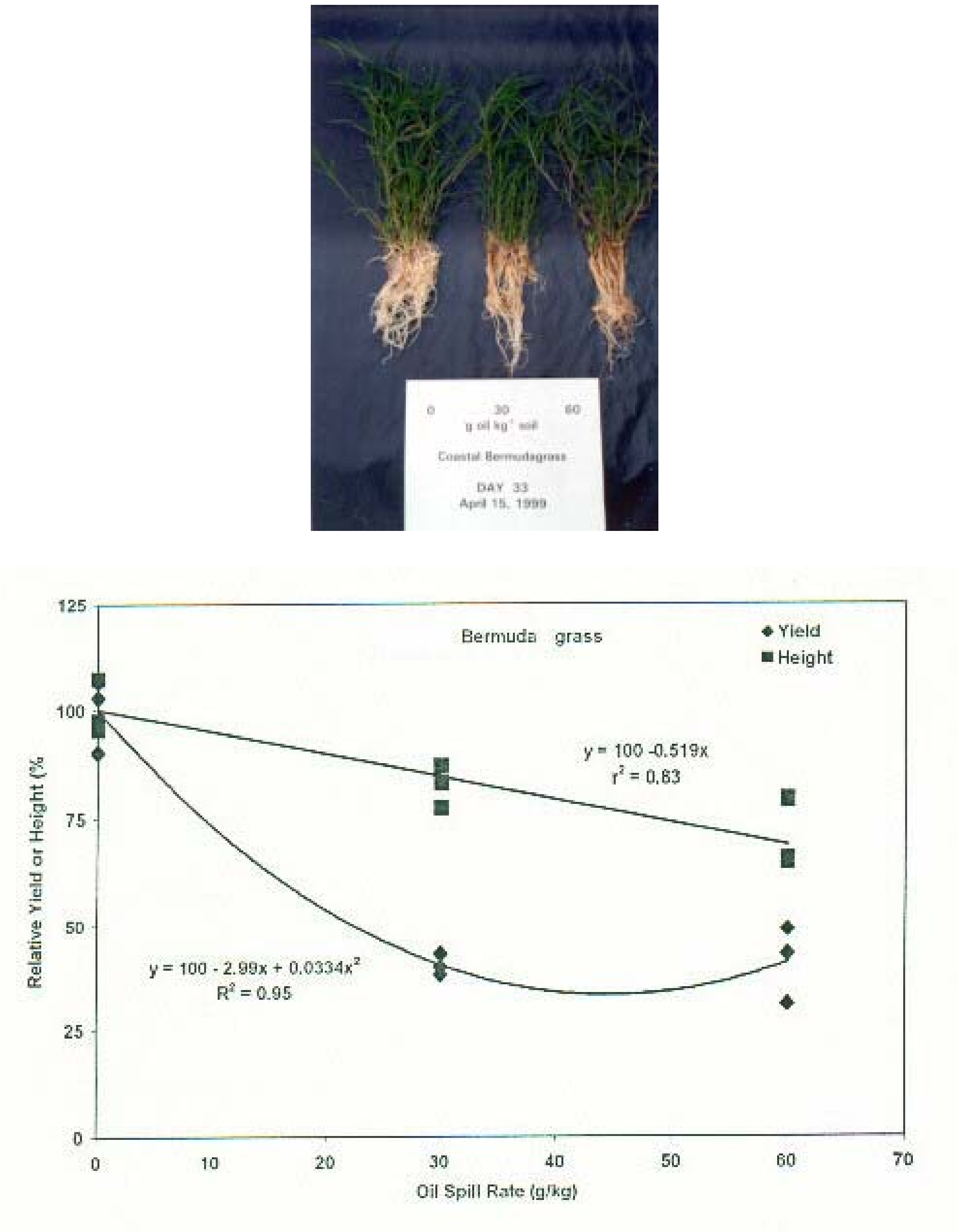


Figure 11. *Relative dry matter yield, plant height, and photograph of bermudagrass cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

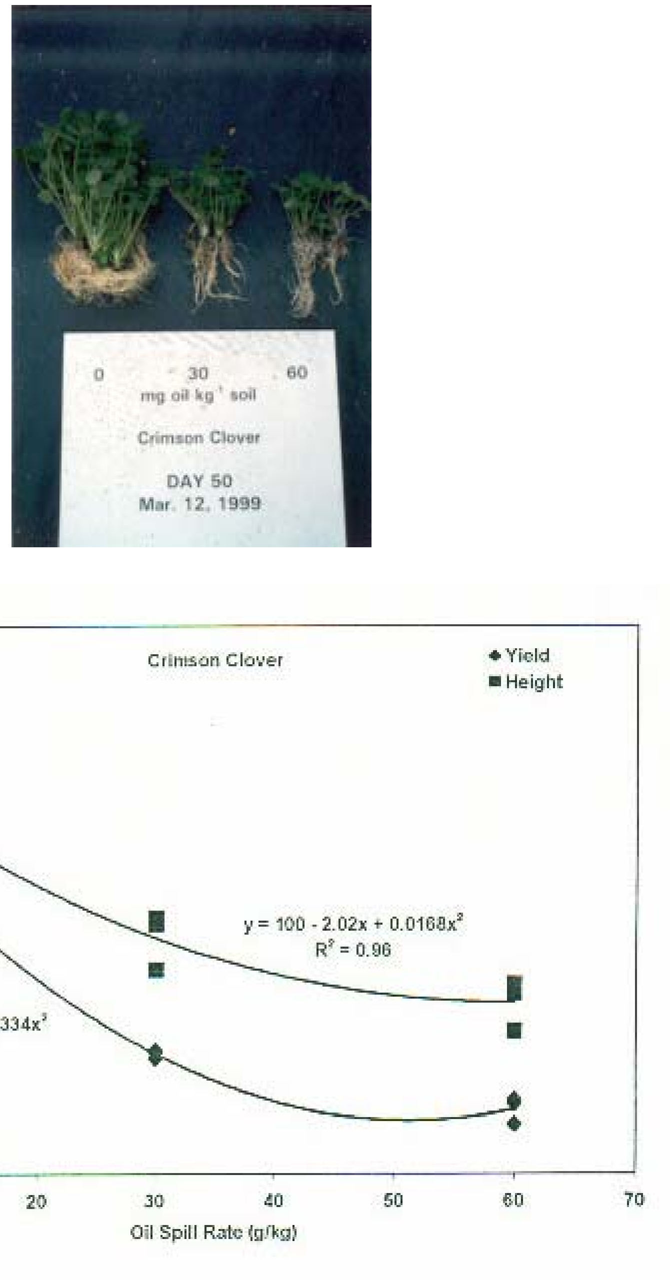


Figure 12. *Relative dry matter yield, plant height, and photograph of crimson clover cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

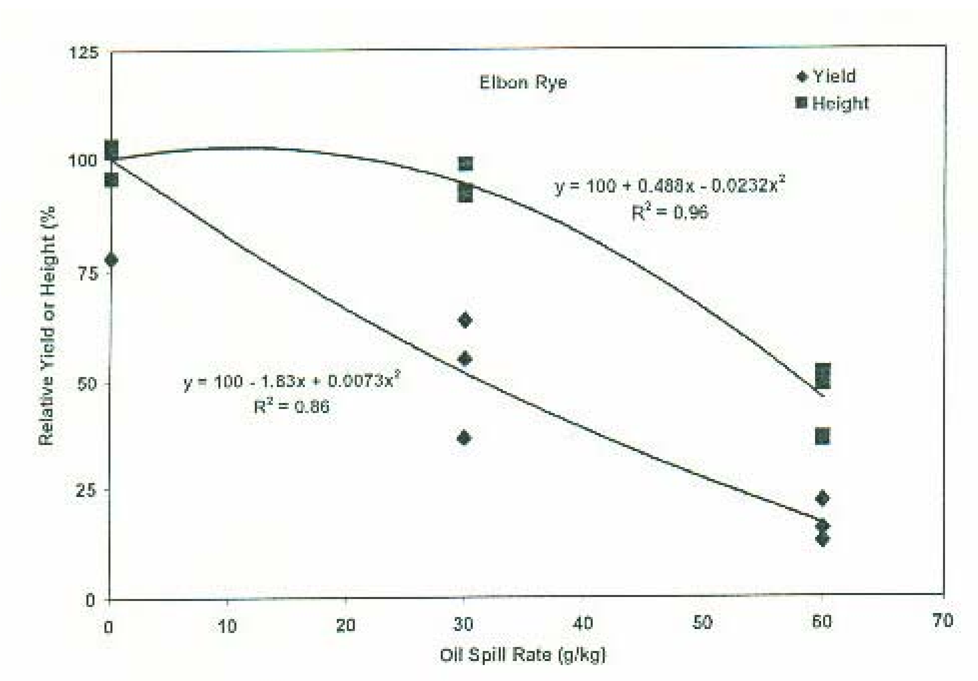


Figure 13. *Relative dry matter yield, plant height, and photograph of elbon rye cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

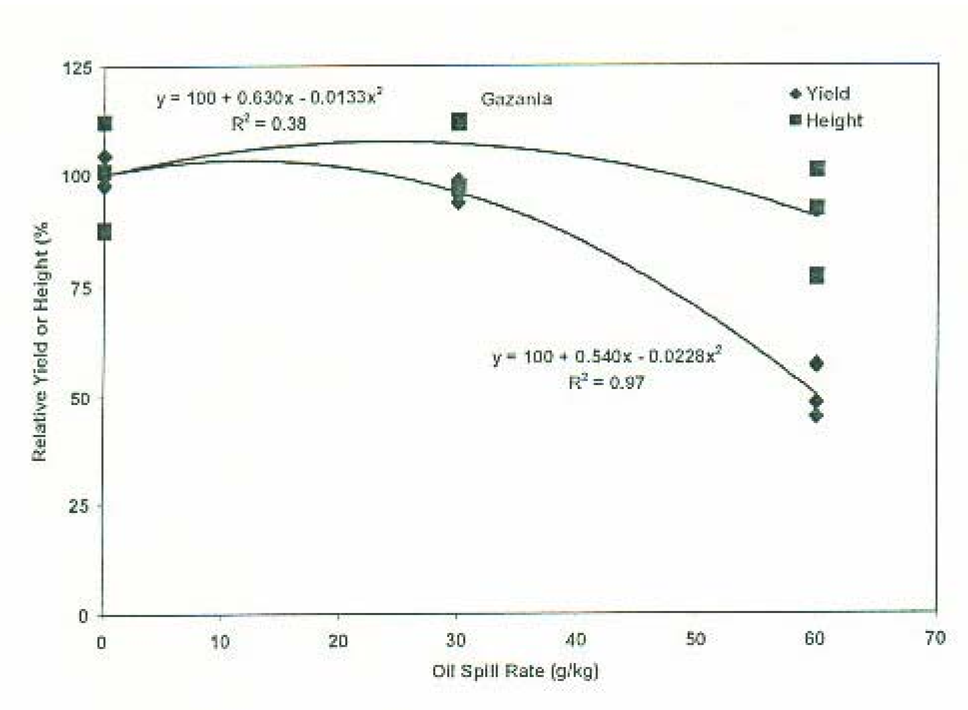
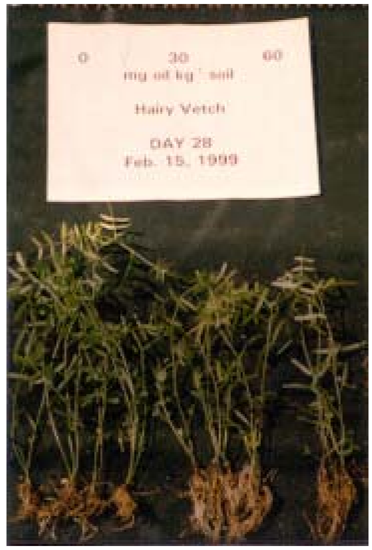


Figure 14. *Relative dry matter yield, plant height, and photograph of gazania cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*



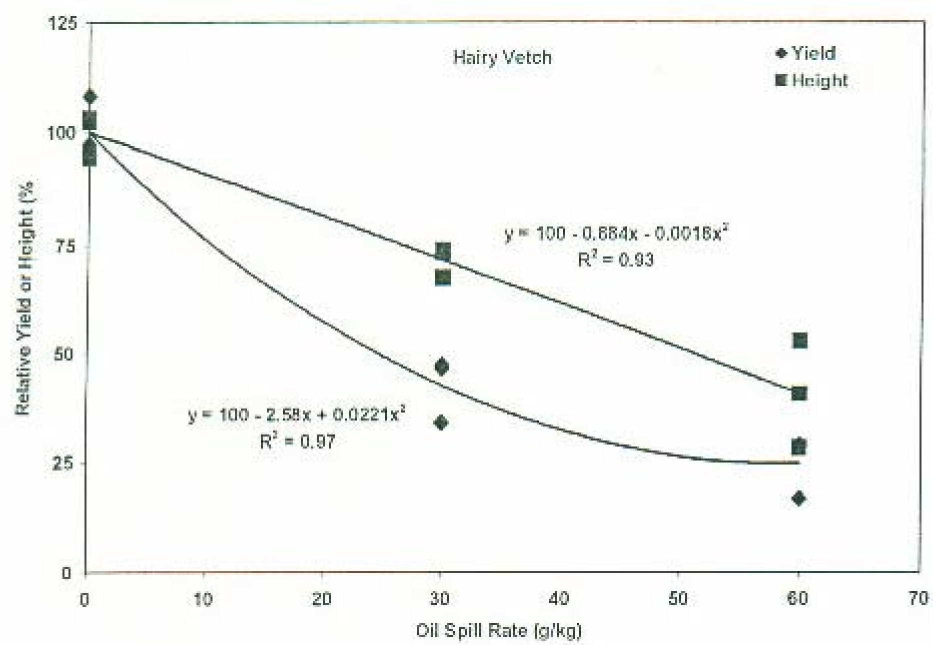


Figure 15. *Relative dry matter yield, plant height, and photograph of hairy vetch cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

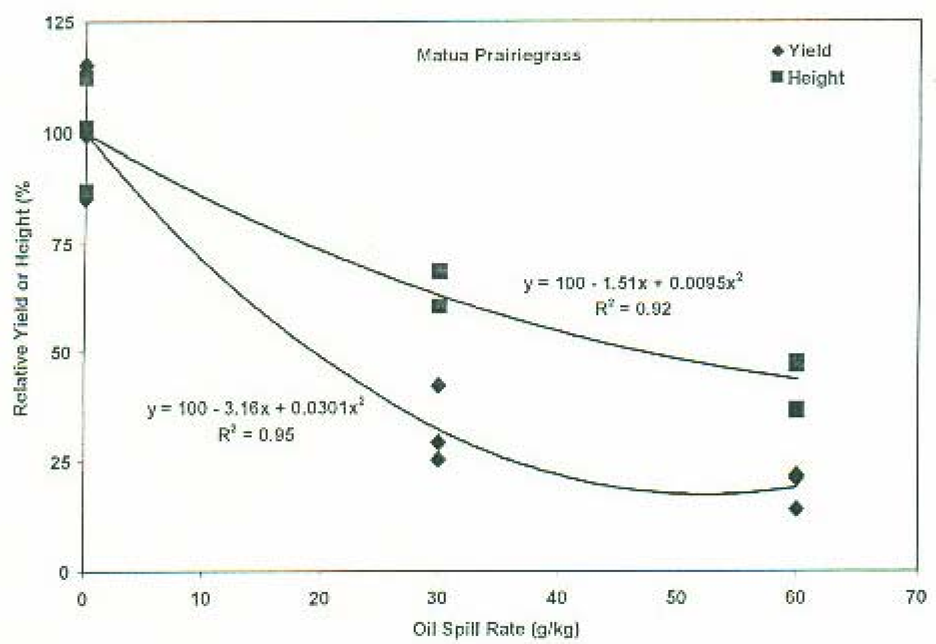


Figure 16. *Relative dry matter yield, plant height, and photograph of matua prairiegrass cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

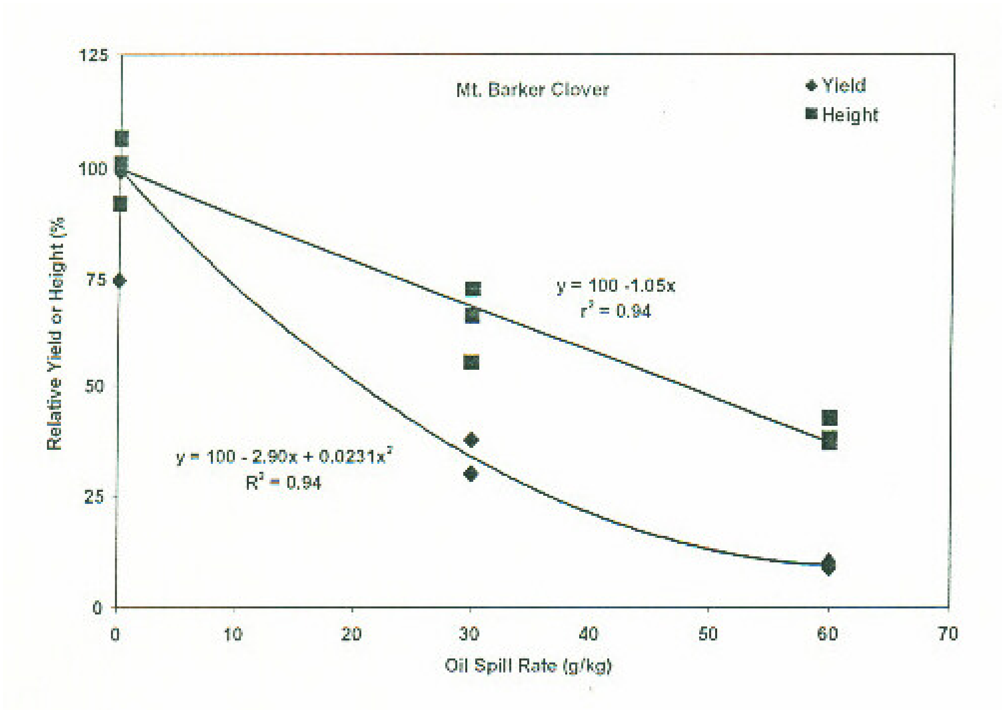


Figure 17. *Relative dry matter yield, plant height, and photograph of Mt. Barker clover cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

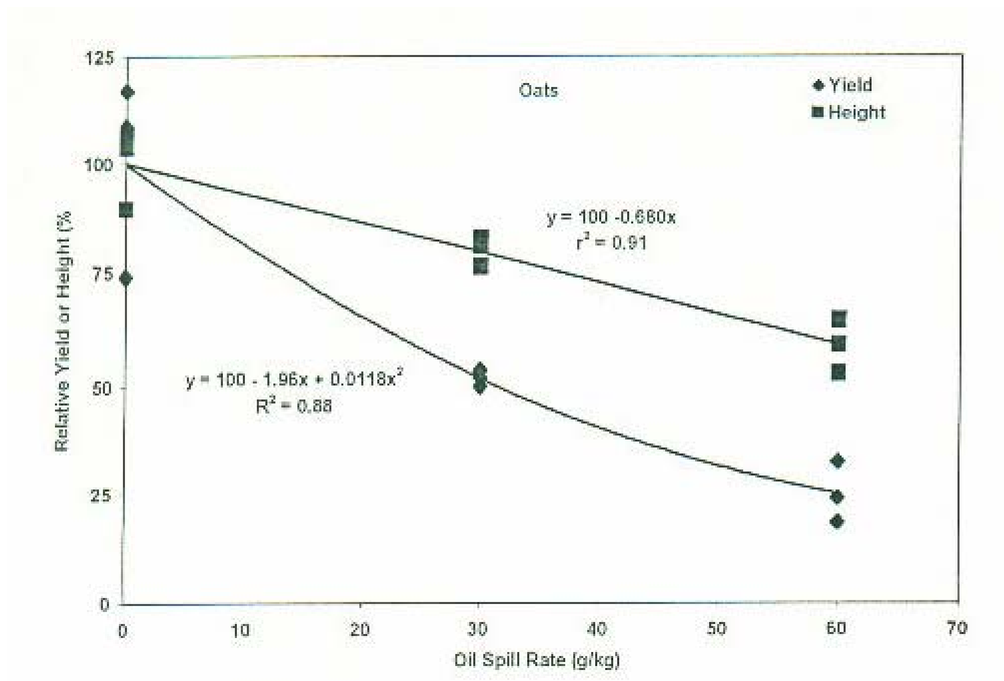


Figure 18. *Relative dry matter yield, plant height, and photograph of oats cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

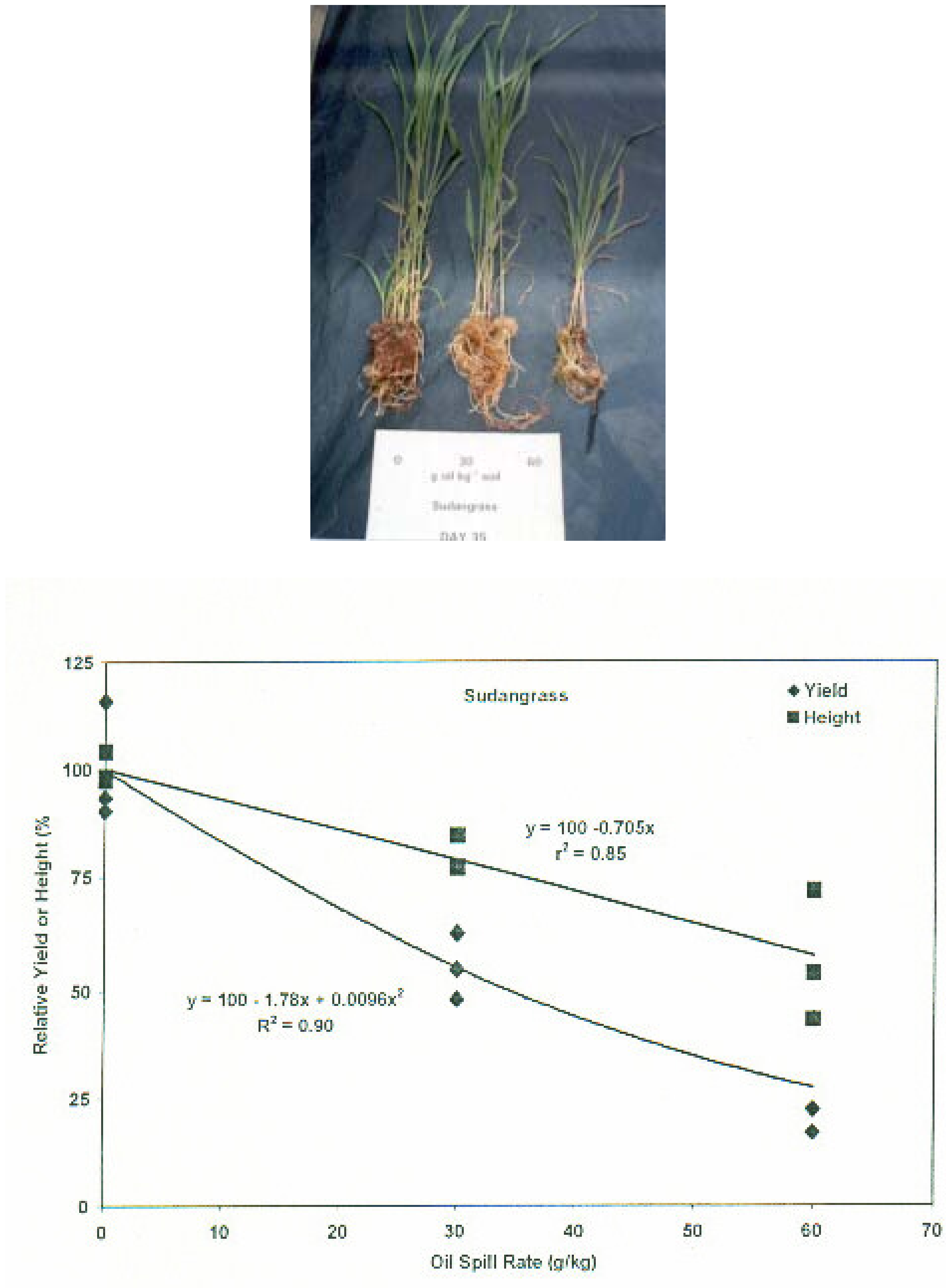


Figure 19. *Relative dry matter yield, plant height, and photograph of sudangrass cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

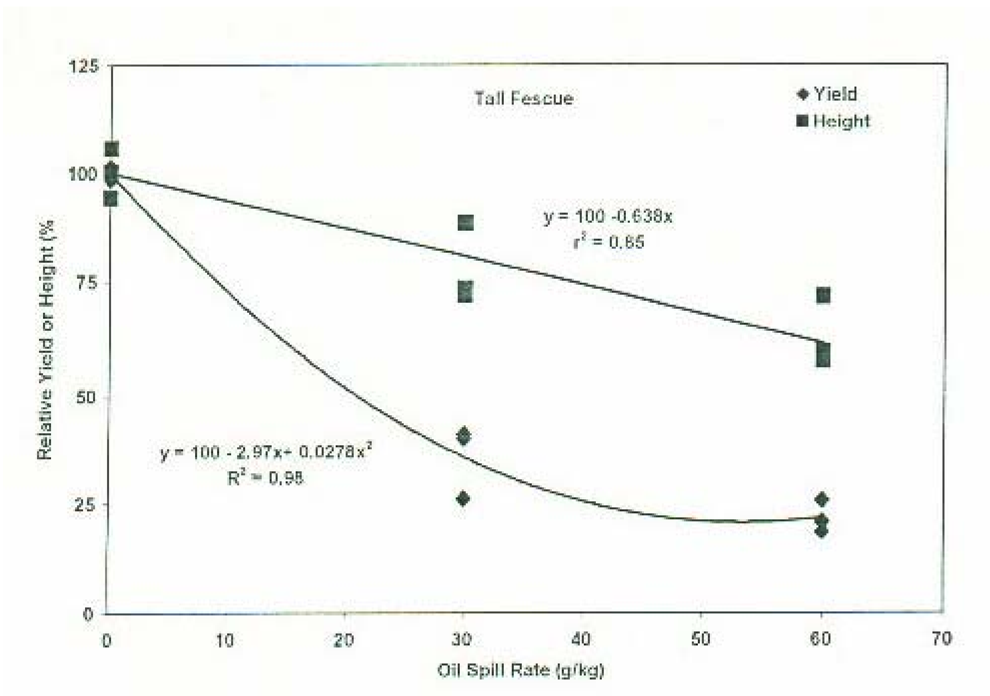
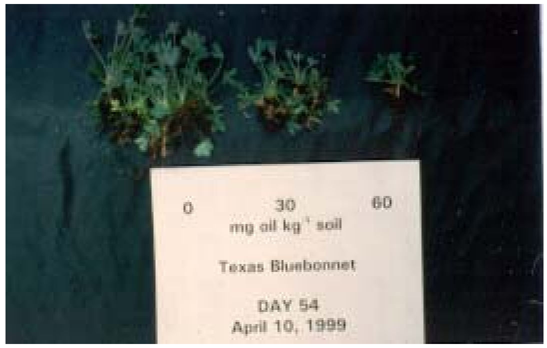


Figure 20. *Relative dry matter yield, plant height, and photograph of tall fescue cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*



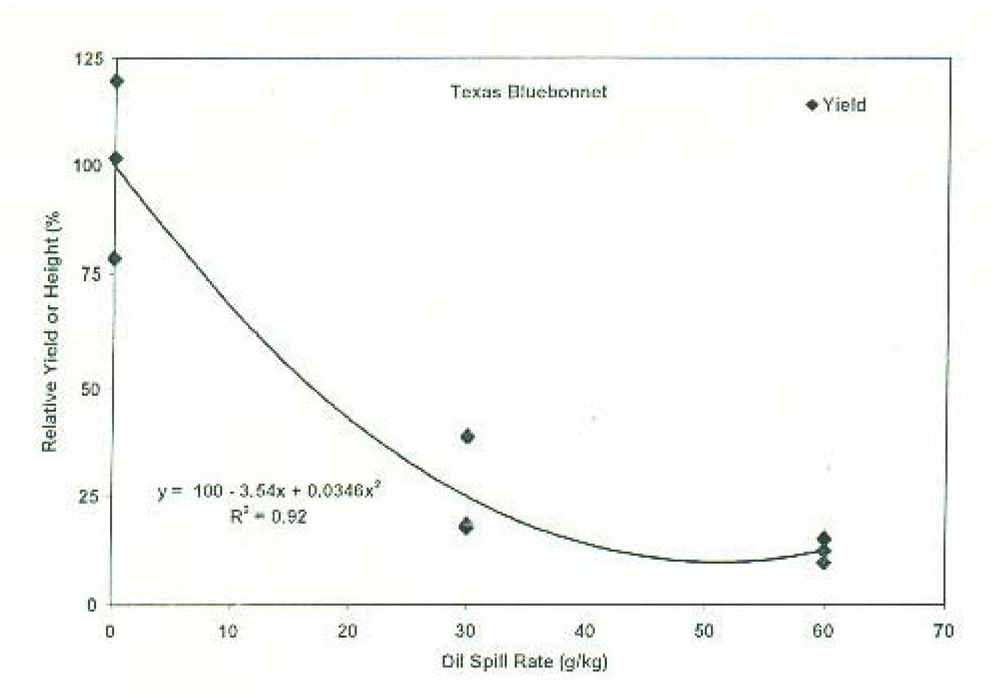


Figure 21. *Relative dry matter yield and photograph of Texas blubonnet cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

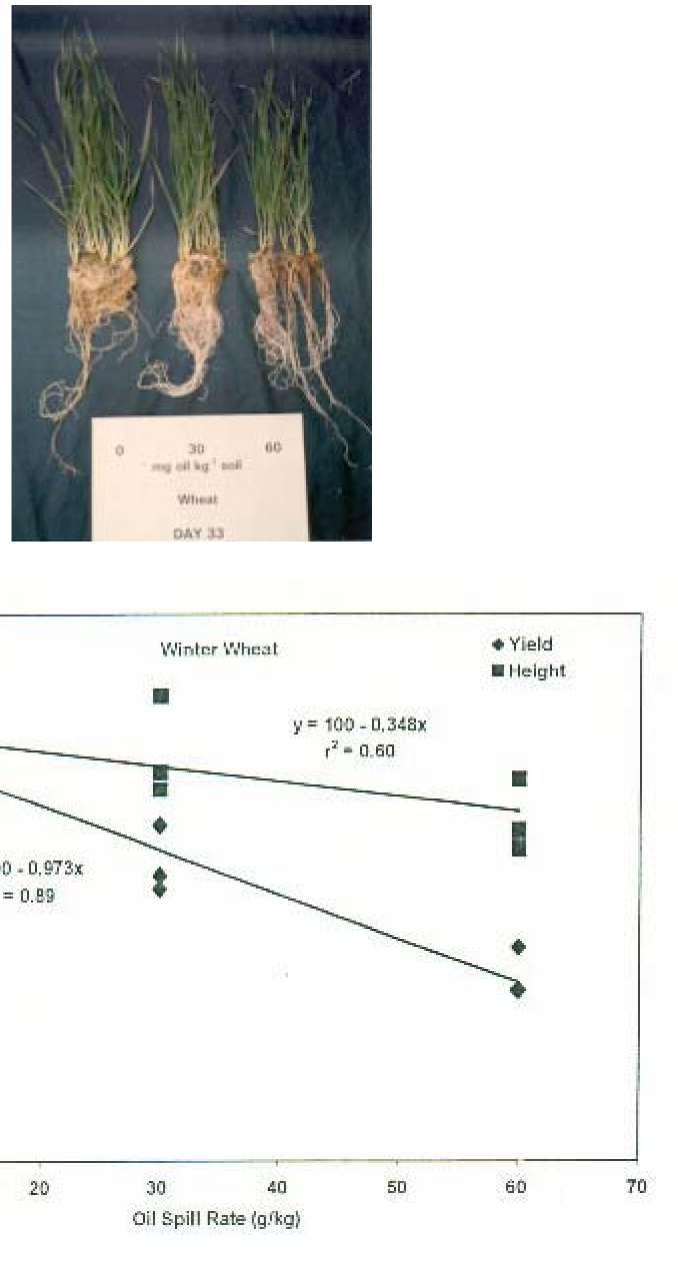


Figure 22. *Relative dry matter yield, plant height, and photograph of winter wheat cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

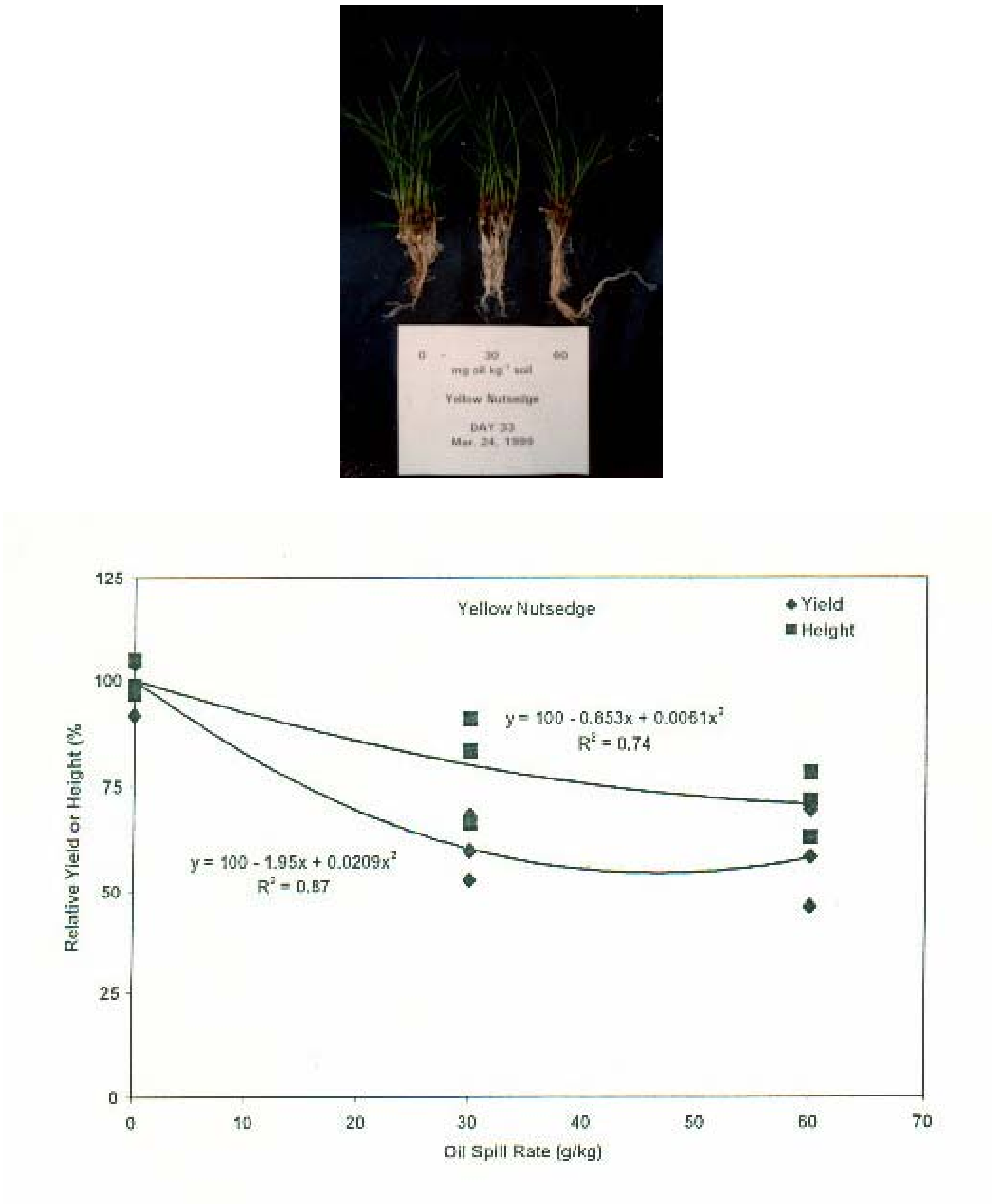


Figure 23. *Relative dry matter yield, plant height, and photograph of yellow nutsedge cultivated in 0, 30, and 60 g crude oil kg^{-1} soil.*

3.2.2 Germination Study

Crude oil in soil suppressed seed germination in all plants tested (Table 3). Most plants had zero germination in oiled soil and only one species (cowpea) had a germination rate close to the germination rate in the control. These findings imply that establishing vegetation in oiled uplands may require the use of transplants rather than direct seeding.

3.2.3 *In Situ* Burning and Phytoremediation Greenhouse Study

To date, samples from Days 0 and 50 have been obtained and are being analyzed for hydrocarbon utilizing bacteria and residual oil content. This information will be published in the final report for Year Two of this study.

Table 3. Percent seed germination in the unoiled and oiled soil.

	% Germination	
Plant	**0 g oil kg^{-1}**	30 g oil kg^{-1}
Annual bluegrass	95	0
Annual ryegrass	90	0
Austrian winter pea	100	0
Anza Wheat	90	5
Barley	95	0
Bermudagrass	42	0
Cowpea	32	25
Crimson clover	97	12
Elbon rye	80	0
Hairy vetch	75	0
Matua prairiegrass	97	0
Millet	50	0
Mt. Barker clover	60	7

Novella English pea	97	0
Oats	92	0
Piper sudangrass	82	0
Rape	97	10
Rough bluegrass	77	0
Sorghum sudangrass	87	0
Sweet pea	50	0
Tall fescue	82	0
Texas bluebonnet	47	0
Wild oats	20	0
Winter wheat	92	0
Yellow nutsedge	32	0

4.0 Conclusions

Observations at existing oil spill sites in northern Louisiana indicated that a variety of native plants appear to persist under field conditions. The investigators will attempt to identify some of these plant species during the second year of this study. In greenhouse screening studies, plant response to crude oil in soil (within the range of 0 to 60 g oil kg^{-1} soil) was somewhat variable. All plants showed a gradual reduction in growth and vigor in response to increasing rates of spilled oil, however, some plants appeared to tolerate up to 60 g oil kg^{-1} soil. Plant mortality was low for all of the 27 plants tested. Seed germination was reduced severely in soil containing as little as 30 g oil kg^{-1} soil, indicating that the establishment of vegetation by seed could be impractical. Greenhouse studies to evaluate phytortemediation and *in situ* burning were initiated and will be completed during the second year of this study.

5.0 References

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