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# Trace Metal Concentrations across Trophic Levels in Cotton Fields of Xinjiang Province, China

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Trace Metal Concentrations across Trophic Levels in Cotton Fields of  
Xinjiang Province, China

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B.S., Governors State University, 2007

THESIS

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## ABSTRACT

Trace metal concentrations across trophic levels in cotton fields of Xinjiang Province, China

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Trace metals become concentrated in urban and peri-urban soils with the use of agricultural practices and industrial emissions. Fertilizers, liming, sewage sludge, and irrigation water contain metals which accumulate in agricultural fields and pose a risk to humans and wildlife. Coal plants and brickyards release metals into the atmosphere which are deposited on soil and plant surfaces. This research quantifies the concentrations of nine trace metals in three different soil types. A total of 116 rodents were sampled in cotton fields and a desert. Cotton plants and triplicate soil samples were collected with each rodent capture. Soil samples were analyzed for organic carbon content, pH, soil texture, and trace metal concentrations. Soil, cotton plants, and rodents were digested and trace metal concentrations determined. Significant differences of nine trace metals, As, Ca, Cd, Cr, Cu, Ni, Pb, Se, and Zn, were found across three different soil types. Rodent tissue metal concentrations were found to be significantly different across soil types; As and Se were highest in loam soils. The lowest concentration of Cr in rodent tissue was found in fields with loam soil. Nine trace metal concentrations were not significantly different across five different species of rodents. Soil texture can influence the availability of trace metals; High clay soils can bind to metals decreasing their bioavailability.

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## CHAPTER ONE

### Background & Significance

*Overview of heavy metals.* — A heavy metal is defined as an inorganic element, having a high specific gravity, one greater than 5.0 relative to water. In addition, heavy metals are described as having a lustrous appearance, good conductivity, and good malleability (Newman and Unger, 2003). Metals, such as Mercury have been considered poisons since the time of Aristotle (Clarkson, 1987). Heavy metals are non-biodegradable and cannot be transformed or destroyed (Walker et al., 2001). After entering an organism, metals generally have long biological half-lives (Radha et al., 1997). Metals have a geological origin, occurring naturally in the earth's crust (He et al., 2005). Trace metals can be released from the parent material through weathering. The geological occurrence of a specific metal is referred to as the background value. Heavy metals in worldwide soils were provided by Xie and Lu (2000) in 2005: As (9.36 ppm), Cd (0.06 ppm), Cr (20-200 ppm), Co (10-40 ppm), Cu (20 ppm), Hg (0.03 ppm), Pb (10-150 ppm), Mo (1-5 ppm), Ni (40 ppm), Se (0.20 ppm), and Zn (10-300 ppm). They are of concern since they remain in the soil for long periods of time (Alloway, 1995). Heavy metals are often ill defined in environmental literature, more attention being given to the chemistry of the element and its potential to become a pollutant through anthropogenic activity. Therefore some heavy metals, metals, metalloids, and even nonmetals are considered

environmental pollutants. Arsenic, a metalloid often included in environmental studies, is an element in the periodic table that displays intermediate properties. Selenium is considered a non-metal but because of its properties is often considered a borderline element.

Micronutrients, such as As, Ca, Cl, Cr, Co, Cu, F, Fe, I, K, Mg, Mn, Mo, Na, Ni, Se, Si, Sn, V, and Zn are essential for animal growth at low concentrations, but can produce adverse effects above certain concentrations. Al, B, Br, Ca, Cl, Co, Cu, F, Fe, I, K, Mg, Mn, Mo, Na, Ni, Rb, Si, Ti, V, and Zn are essential to plant growth (Alloway, 1995). Trace metals such as As, Cd, Pb, and Hg are non-essential elements for humans and are considered toxic at relatively low levels (Shi et al., 2010). The deficiency of essential elements to animals and plants can also cause health problems. As deficiency has led to reproductive problems and impaired growth in rats, hamsters, goats, and chicks (NAS, 2001). Deficiency of micronutrients in plants may cause deformities or a lowered photosynthetic rate (Masoni et al., 1996).

#### Sources of Heavy Metal Contaminants/Pollutants

*Arsenic.*— Since ancient times, As contaminated humans via food, water, and soil (ATSDR, 2005; WHO, 2001). In the 1970's As contaminated drinking water claimed over 20,000 lives in Bangladesh and is recognized as one of the worst mass poisonings in history (Chaudhuri, 2004). Arsenic has a geological origin, often found in volcanic rock, and can be released during mining

(Robertson, 1989; Cao et al., 2009; WHO, 2001). Gold mines in Nebraska have the largest amount of As in the United States (Bowell and Parshley, 2001). Arsenic is considered an atmophile metal, being released into the atmosphere during events such as burning coal and smelting activities (Bolton et al., 1975; Wood, 1974). According to Loebenstein (1994) the last smelting operation closed in 1985. Forest fires release As into the atmosphere (EPA, 1998). Crop fields can be irrigated with As contaminated irrigation water and sprayed with As based pesticides (Cao et al., 2009; Folkes et al., 2001). Until 2004, chromated copper arsenate was a compound used for wood preservation (National Toxicology Program, 2005). Tobacco smoke also emits small concentrations of As into the atmosphere (EPA, 1998). A synthetically derived arsenic compound was released in the early 1900's to treat syphilis (Yarnell, 1983). In 2000, the US FDA approved use of arsenic trioxide for treatment of leukemia (Antman, 2001). Other insignificant sources of arsenic include: production of glass, coloration of fireworks, production of round lead bullets, as an alloy for certain products, and in lead acid batteries (Jones, 2007).

*Cadmium.*— Cd is an atmophile element, released by activities like smelting and mining (Dudka et al., 1995; Wood, 1974). Cd is commonly found in urban and rural soils surrounding coal burning plants, however does not have a long residence time in the atmosphere (Fishbein, 1981). Cd is also found in building siding and accumulates in engine oil during use (Davis et al., 2001). It is used as an alloy and is found in Ni-Cd batteries (Fishbein, 1981). Phosphate

fertilizers, fungicides, and some pesticides contain Cd and are an important source in soils (Fishbein, 1981; Li et al., 2001). During the 1970's, it was estimated that 30% to 50% of Cd in soils came from phosphate fertilizer application in Sweden (Anon, 1979). Sewage sludge is capable of accumulating significant sources of Cd, Cu, and Zn (Moolenaar and Beltrami, 1998).

*Copper.*— Cu is considered an atmophile element, released during activities such as mining and smelting (Wood, 1974; Davis et al., 2001). A large source of Cu comes from automobile brake pads, vehicle exhaust, and engine oil (Mielke et al., 2000; Imperato et al., 2003; Davis et al., 2001). Cu and Zn are both commonly used in galvanized products such as metal roofs. Cu has been found in soils adjacent to railroads suggesting Cu may be released from line abrasion (Imperato et al., 2003). Cu is a component used in the Bordeaux mixture which is commonly used as a fungicide (Moolenaar and Beltrami, 1998). Wood preservatives also contain Cu (Davis et al., 2001).

*Chromium.*— Cr has geological origin and is primarily a lithophile element, being primarily released into streams (Alemayehu, 2006; Biasioli et al., 2006; Wood, 1974). Due to its natural occurrence in rock, Cr is also released in the atmosphere during the production of cement (Denton et al., 1954). The metallurgical industry accounts for the vast use of Cr during the production of stainless steel and other metal alloys (NAS, 1974). Small concentrations of Cr are used in the production of tanning animal hides, wood preservatives, paints,

printing inks, and corrosion inhibitors (NAS, 1974). Tobacco leaves have been found to contain small concentrations of Cr (Frank et al., 1977).

*Nickel.*— Ni occurs naturally in rock, usually in combination with Cr (Alemayehu, 2006). Along with Cr, Ni is also considered a lithophile element (Wood, 1974). Ni can be released from primary minerals during mining and smelting (Biasioli et al., 2006). Ni is also used in electroplating and the productions of alloys. Both coal and fly ash contain small concentrations of Ni. Exhaust fumes, primarily from diesel, release Ni particulates into the atmosphere (NAS, 1975).

*Lead.*— Pb is a very common element in the environment and is primarily released into the atmosphere (Wood, 1974). It is also one of the less mobile elements in soils (Biasioli et al., 2006). Pb is found in roadside soils and street dusts from brake pads, vehicle exhaust, and lead based gasoline (Davis et al., 2001; Nriagu, 1990; Imperato et al., 2003; Li et al., 2001). Old buildings are a significant source of Pb contamination with Pb based paint and Pb in bricks (Nriagu, 1990).

*Selenium.*— Se is an atmophile element, released during anthropogenic activities such as burning coal (Bolton et al., 1975; Wood, 1974).

*Zinc.*— Zn is often found in urban areas since a large source of pollution

is from automobiles. Zn is found in brake pads, tires, vehicle exhaust, and oil (Hewitt and Rashed, 1990; Mielke et al., 2000; Imperato et al., 2003; Davis et al., 2001). Mining and smelting activities release Zn into the atmosphere. Along with Cu, Zn is also used in galvanized products such as metal roofs and siding (Kabata and Pendias, 1992; Davis et al., 2001). Fertilizers often contain high concentrations of Zn and can be found in soils (Imperato et al., 2003).

### Agrochemicals

*Overview of Pesticides.*— A pesticide is a broad term for a substance that kills pests, such as fungi, microorganisms, insects, or other animals. Pesticides, types of agrochemicals, include: organochlorines, organophosphates, carbamates, and pyrethroids. Several pesticides were used before World War II. At this time, the deleterious effects of pesticides had not yet been recognized. Pesticides were viewed as extremely beneficial, increasing crop production and decreasing diseases transmitted by pests. Public awareness of the detrimental effects of pesticides grew when Rachel Carson's *Silent Spring* was published in 1963. Most developed countries responded by attempting to regulate pesticide manufacturing, distribution, and application. However, developing countries, such as China and India are two exceptions. Since both of these countries are relatively large in area, have the two largest populations, and attempt to produce large quantities of food, this led to a plethora of environmental concerns and health problems.

*Inorganic compounds.*— Inorganic elements are often ingredients in chemical compounds used in agriculture. Copper (Cu), Chromium (Cr), Arsenic (As), and Lead (Pb), are often found in agricultural soils due to their agrochemical uses (Chen et al., 2001). Arsenic was the most widely used metal in agrochemicals during most of the 20<sup>th</sup> century. Paris green, a copper acetoarsenite pigment, was used as an insecticide for moths, mosquitoes, and beetles throughout the early 1900's and its use declined with the introduction of lead arsenate. It was also used to kill plant fungi. Lead arsenate was also used as an insecticide until it was banned throughout the United States and Europe in 1988 due to its toxicity (Peryea, 1998). Some arsenate compounds are still being used as insecticides on vineyards in France. The Bordeaux mixture (CuSO<sub>4</sub>) was used as a fungicide on fruits and vegetables and is still applied to grapes in Italy (Eckel et al., 2001). Cu, As, Pb, and Zn are used in sprays applied to apple, citrus, grape, cherry, and peach orchards. Soil As levels of up to 2500 ppm have been found in orchards where arsenic based pesticides were used (WHO, 2000). High concentrations of Cu were found in grape orchards in China and as of 2003 were still used in Florida on oranges (Xie and Lu, 2000; Michaud and Grant, 2003). Cadmium was used in a phosphorus fertilizer on agricultural soils until it was banned. Copper and zinc were added to pig and poultry feed and therefore found in manure, which can subsequently be applied to crop fields (Chen et al., 2001). Trace metals, such as As, Pb, or Hg are still found in several pesticides including lindane, chlordane, dieldrin, and toxaphene (Barnum, 2005). Fungicides containing Cu are still used in the USA to prevent crop diseases

(Timmer et al., 2004).

*Organic Compounds.* — Although organochlorines have not been used for decades in the United States and have been banned in China since 1983, their persistence in the environment continues to cause detrimental effects on wildlife (Zhu et al., 2005). Despite this ban, organochlorines are still used in China, posing serious health implications and long-term pollution due to their persistence, chronic toxicity, bioaccumulation, and suspected carcinogenicity (Wei et al., 2007; Lang, 2003). Several organochlorines are considered persistent organic pollutants (POPs), of which 12 are listed under the Stockholm Convention treaty of 2004. The Stockholm Convention is an internationally bound agreement among 128 countries restricting the use of POPs (Stockholm Convention, 2008). Nine of the twelve POPs are pesticides and several of them are used on cotton (Wei et al., 2007). Two of the twelve POPs are industrial by-products and the other is an industrial chemical. Exceptions have been made in developing countries where safer, more effective alternatives are not available. The World Health Organization approved the use of DDT in Africa in 2006 where malaria poses more of a threat to the population than the pesticide itself (WHO, 2006). Organochlorines are effective against their target organisms, but also have proven to be toxic to non-target organisms, such as birds of prey (Drooge et al., 2005). After exposure to DDE, eggshell thickness of hawks and falcons decreased up to 25%, resulting in a deleterious effect on their reproductive success (Cade et al., 1972).

Organophosphates have been used since the early 1960's and were first introduced as nerve gases in World War II. Organophosphates eventually replaced many organochlorines, such as DDT (Grue et al., 1997). They are still some of the most widely used pesticides today, largely due to their effectiveness at low doses (Lang, 2003). Organophosphates do not pose as great of a risk as organochlorines since they have higher water solubility. Furthermore, they tend not to persist in the environment as long as organochlorines. Microbial remediation assists with the degradation of organophosphate pesticides in soil, decreasing their retention time (Lamoreaux and Newland, 1977). They also are known to cause acute toxicity and are usually not magnified across trophic levels since they are metabolized within 24 hours (Hill, 1995). Depending on exposure and the biological species, organophosphate exposure may be followed by recovery within hours or death (Hoffman et al., 2002). Organophosphates, such as diazinon, chlorpyrifos, and methyl parathion cause death by inhibiting acetylcholinesterase (Newman and Unger, 2003). As a result, the neurotransmitter acetylcholine cannot be degraded, accumulates and leads to muscular paralysis and eventually death.

Two other classes of organic pesticides include carbamate pesticides and pyrethroid pesticides. Carbamate pesticides, along with organophosphates, work by disrupting acetylcholinesterase in the nervous system that controls the neurotransmitter acetylcholine. However, unlike organophosphates, the effects on the enzyme can often be reversed since they are not metabolized (EPA, 2008). Pyrethroid pesticides are derived from pyrethrum, a chrysanthemum extract, and

are manufactured synthetically (EPA, 2008). Pyrethroid pesticides serve numerous purposes, being used on several agricultural crops and fruits. Pyrethroid pesticides are used as mosquito repellents that can be applied to clothing. Permethrin, which is a neurotoxin, is also used in the form of a cream to control body lice.

*Overview of agricultural practices.*— Heavy metals become concentrated in soils through the use of agricultural practices, such as application of sewage sludge, pesticides, fertilizers, manure, irrigation water, and liming. Direct application of these substances to agricultural fields has the potential to expose wildlife, livestock, and humans to heavy metals. Industrial wastewater, containing heavy metals, is often used as irrigation water and can contaminate agricultural fields with adverse consequences (He et al., 2005). Crops grown on one contaminated field were consumed and adversely affected human health (Kobayashi, 1978). Cd and Pb were found in soils and cattle feed at concentrations 10 to 40 times higher than acceptable standards (Cai et al., 2009). Industrial activity also has an impact on heavy metal concentrations in agricultural soils and has been shown to adversely affect crop yields (Dudka et al., 1996; Cao et al., 2009).

*Industrial and anthropogenic sources*

*Overview of industrial sources.*— Industrial activity and other anthropogenic sources influence heavy metal concentrations in agricultural soils. Heavy metal pollution and contamination has been a known problem historically, but has become a more prominent issue within the last century due to increasing urbanization and industrialization. The main sources of anthropogenic activity include industrial emissions and waste, traffic, and fossil fuel (Biasioli et al., 2005). Several countries have set standards due to problems associated with agricultural practices and human health. For example, Imperato et al. (2003) found Pb levels in Naples, Italy exceeding the 100 ppm limit in 76% of public, private, and residential areas. Atmospheric deposition of heavy metals accounts for a large proportion (25-85%) of metals in soils (Nicholson et al., 2003). The majority of As particles eventually adsorb to soil particles; As resides in the atmosphere for about 9 days prior to soil deposition (EPA, 1998). Coal plants release As, Se, Pb, Zn, Cu, Ni, Cr, Mg, Al, and Fe into the atmosphere (Hulett et al., 1980). In areas surrounding brickyards, trace metal concentrations of Pb, Zn, Cd, Hg, Tl, and Bi were found in grasses and soils (Brumsack, 2006).

Lead was first found to be detrimental to human health as early as the 1980's (Needleman, 2004). It became widely distributed in the environment after being used in gasoline and lead-based paint (Nriagu, 1990). Peak use of leaded gasoline occurred in the early 1970's and was banned in the United States in 1978, whereas its use continued in China until 2000 (Mielke and Gonzales, 2008).

Peak use of lead-based paint occurred in the 1920's (Mielke and Reagan, 1998). Lead is most commonly found in paint as lead carbonate and is released over time as particles are dissolved (Davis et al., 2001). Consumption of Pb contaminated soil particles is a risk to children and wildlife (Chaney and Ryan, 1994). Lead poisoning is another relevant problem, especially to children in urban areas where lead concentrations are greater and children are in closer proximity to urban soils (Mielke and Reagan, 1997). In addition to paint and gasoline, Pb can be found in vehicle exhaust (EPA, 2009). Environmental concentrations of Pb have decreased over time with the discontinued use of lead based gasoline (Berthelson et al., 1995). Soil Pb concentrations are significantly different between urban and rural areas (Biasioli et al., 2005; Harrison et al., 1981; Mielke et al., 2000). In urban areas and areas near older housing, Pb concentrations occurred between 500 to 1000 ppm compared to less than 75 ppm in rural areas (Kelly et al., 1996). Imperato et al. (2003) found Pb, Zn, Cu, and Cr to be most abundant in soils near roadside fields. Cu, Pb, and Zn soil concentrations exceeded limits for residential areas in Seville, Italy (Madrid et al., 2002). These four heavy metals (Cu, Cr, Pb, and Zn) usually occur jointly in roadside soils and street dusts due to the increased volume of traffic within urban areas (Li et al., 2001). Pollutants, such as Cu, Cr, Pb, and Zn are greater in urban areas and then decrease as the distance from the city center increases (Biasioli et al., 2005). The density of automobiles in a specific area has an influence on soil heavy metal concentrations (Davis et al., 2001). Vehicle brake pads contain Cd, Cu, Pb, and Zn, with approximately 5% of the brake pad being Cu (Davis et al., 2001; Hewitt and Rashed, 1990). These four

metals are also found in stormwater runoff (Davis et al., 2001).

*Factors influencing heavy metal availability*

*Bioavailability.*— Bioavailability is defined by Newman and Jago (1994) as the extent to which a contaminant in a source is free for uptake. In mammalian ecotoxicology, total metal content is primarily measured compared to available metal content. However, total metal content is not a good indicator of heavy metal availability (Alloway et al., 1988). Metal speciation also affects the availability of the metal. Unlike organic chemicals, inorganic chemicals have a non-biodegradable nature allowing them to persist in the environment unchanged (Hoffman, 2002). Heavy metals contaminate ecosystems through dust, soil, water, or air. Several factors influence availability such as soil clay content, soil organic carbon content, and soil pH (Dube et al., 2000; Walker et al., 2001; Zhu et al., 2005). Cation exchange capacity (CEC), which is correlated with organic carbon content can also influence availability. Heavy metals can bind to organic carbon and clay particles, decreasing bioavailability. Organic carbon is low in agricultural soils due to a small amount of the vegetation returning to the soil (Biasioli et al., 2005). The soil pH indirectly affects the retention of a metal in the soil. A higher soil pH will have a much higher affinity for heavy metals (Alloway et al., 1988). Specifically, Alloway et al. (1988) found Cd and Pb to be less bioavailable at higher pH values. In more acidic soils, Fuller (1977) found Cd,

Ni, and Zn to have high bioavailability; in neutral/alkaline soils Cr has high bioavailability. Biasioli et al. (2005) concluded that a wide range of soil pH indicates agricultural practices. Agricultural practices such as liming increases pH, which inadvertently decreases Zn availability to the plant (Marschner, 1995). Other factors have also been found to have an impact on the retention of the metal such as weathering, seasonal changes, and anthropogenic activities (Alemayehu, 2006; Dube et al., 2000; Matthews, 1982). Plant species and different parts of the plant have different rates of uptake by trace metals (Angelova et al., 2004).

*Bioaccumulation.*— Bioaccumulative substances, such as many heavy metals, enter an organism's body through respiratory, digestive, and dermal exposure routes. After exposure, a heavy metal can sequester itself in certain organ(s) of an organism. The primary site of As metabolism is the liver where As is usually excreted within 48 hours (Cohen et al., 2006). The target organ for Cd and Pb is usually the liver or kidney (Wren, 1984). For example, Pb primarily affects the central nervous system, specifically by interfering with neurotransmitters. Historically, Pb toxicity has been associated with neurobehavioral disorders (Clarkson, 1987). Whole body homogenization may be effective in analyzing Pb and Cd. However, essential elements such as Zn and Cu may not accurately reflect environmental levels (Wren, 1984). Bioaccumulation of trace metals may also vary depending on species, metal, sex, age, diet, exposure route, and metabolism (Wren, 1984). For example, small mammals feeding on insects have the ability to accumulate higher amounts of trace metals than similar herbivorous species (Quarles et al., 1977).

*Biomagnification.*— Biomagnification is defined as, “ the increase in concentration of pollutant in animal tissue in successive members of the food chain” (Moriarty and Walker, 1987). Biomagnification poses a threat to tertiary consumers such as birds and mammals. Higher level mammals and birds would show the highest concentration of the pollutant compared to lower trophic levels (Walker et al., 2001). In humans, elements like As are metabolized too quickly to biomagnify (Hamilton, 2005). There is a direct correlation between the metals half-life and biomagnification since the longer the pollutant persists in the environment the greater chance it has to accumulate across trophic levels (Walker et al., 2001).

#### *Cotton background*

*Cotton.*— In China alone, cotton fields cover about 4 million hectares of land (Clay, 2004). Cotton is an economically important and widely produced crop. Approximately 107 million 217.7 kg bales were produced during 2008 to 2009 globally (USDA, 2010). Cotton was selected for use in this study because it has one of the highest application rates of agrochemicals of any crop (USDA, 2005). Specifically, 25% of all insecticides produced are applied to cotton. However, in developing countries it is estimated that 50% of pesticides applied to crops are applied to cotton (Clay, 2004). Although China has active environmental regulations for pesticides, they are generally not enforced. Recent

field studies have shown the use of organochlorine pesticides even though they were officially banned in 1983 (Fig. 1). The majority of As is imported into the US, primarily from China (Brooks, 2004). Four different species of cotton are used commercially: upland cotton (*Gossypium hirsutum*), American Pima (*Gossypium barbadense*), tree cotton (*Gossypium arboretum*), and Levant cotton (*Gossypium herbaceum*). *Gossypium hirsutum* accounts for approximately 90% of commercially used cotton worldwide.

Cotton along with hemp and flax is considered a fiber crop. It is grown under an optimal pH of 5.8 to 7.0 (McCarty, 2009; Kamprath, 1984). Angelova et al. (2004) found the magnitude of heavy metal accumulation to decrease in cotton plants in the following order; leaves > seeds > roots > stems. This research indicates the main source of heavy metal pollution is through the atmosphere since cotton leaves readily absorb particles deposited on their leaves. Cotton has a deep complex root system that generally does not accumulate a large concentration of metals (Angelova et al., 2004; Litvinovich and Pavlova, 2000).

#### Heavy metals in plants/organisms

*Plants/Crops.*— Total metal concentration in soil does not reflect bioavailability to plants and other organisms. Different plants have different uptake rates. Bovay (1971) found smooth leaves accumulated less Pb than hairy leaves. In general, plants can accumulate as much as 3 ppm Cd before plant growth is depressed (Allaway, 1968). Metals accumulated at higher

concentrations in leafy vegetables, specifically cabbage and lettuce, compared to root or grain crops (Alloway et al., 1990; Davis and Carlton-Smith, 1980). More recent studies reported that metals accumulated at high concentrations in leafy vegetables such as leaf mustard, onion leaf, and lettuce (Huang et al., 2006; Dahal et al., 2008; Cao et al., 2009). Crop and vegetable fields introduce trace metals into the human food chain. Corn grain accumulated an average of 200 ppm Cd and 4300 ppm Zn after amendments with sewage sludge. However, corn yields increased following application (Hinesly et al., 1977). Soils from a vegetable field exceeded pollution values for Cd and Hg (Chen et al., 2009). Dudka et al. (1996) concluded that Cd concentrations in soil were not high enough to pose a risk to the food chain. However, the same study found Zn at high enough concentrations in roots to reduce barley yields. In contrast, Jung and Thornton (1996) concluded that crops contained a high enough Cd concentration to pose a risk to higher trophic levels. Rodents feed on seeds, such as acorns which were determined to have high concentrations of As, Cd, and Pb near a metallurgic plant (Rogival et al., 2007).

*Invertebrates.*— Insects are also affected by heavy metal concentrations in soils. Some families of earthworms and arthropods play a critical role in accumulation of trace metals. Sizmur and Hodson (2009) suggested that earthworms may influence soil metal availability by altering soil properties such as pH and organic carbon content. Higher trophic level organisms feed on invertebrates such as mammals and birds. Earthworms and snails obtain trace

metals through ingestion and epithelial absorption (Coeurdassier et al., 2002). Several species of earthworms have been found to accumulate high concentrations of trace metals (Rogival et al., 2007; Kennette et al., 2002). A positive correlation was found between stinging nettle leaves and herbivorous snails for Cd, Cu, Pb, and Zn, indicating metal transfer to higher trophic levels (Notten et al., 2005). Heikens et al. (2001) found concentrations of Pb, Zn, and Cu to increase in isopods as metal concentrations increased in soil. Davis and French (1969) reported that worms and slugs accumulated enough DDT to cause acute poisoning of birds.

*Vertebrates.*— Uptake of essential metals such as Zn and Cu differ from non-essential metals due to homeostatic regulation in bone and soft tissue in mammals (Sheffield et al., 2001). Small mammals, specifically mice have frequently been used as indicators of metal pollution. Small mammals feeding on insects have the ability to accumulate higher amounts of trace metals than similar herbivorous mammals (Quarles et al., 1977). *Sorex araneus* feeds on earthworms, has a large food intake and is sensitive to metal pollution (Ma et al., 1991). Wood mice were found to have high enough Cd concentrations to produce toxic effects (Rogival et al., 2007). Although Cu concentrations were higher in the environment, Hunter and Johnson (1982) showed Cd to transfer to small mammals at a higher rate. Animals at higher trophic levels are also affected by metal contamination. Great tits and blue tits demonstrated negative breeding parameters in a pollution gradient near a copper smelter (Eeva et al., 2009).

Bovine tissue contained Cd and Pb as a result of contaminated feed in Guizhou province, China (Cai et al., 2009). Humans then consume meat contaminated with trace concentrations of metals. In addition to blood of humans, Cd and Zn have been found in human teeth in mean concentrations of 0.32  $\mu\text{g}$  and 0.29  $\mu\text{g}$ , respectively (Maah et al., 2001). Metals such as arsenic can be transferred from soil to edible parts of plants, entering the human food chain.

### Objectives

Previous studies of heavy metals in trophic webs have primarily focused on the transfer of heavy metals from soil to plant (Angelova et al., 2004; Bi et al., 2006). Several studies have also been conducted in aquatic ecosystems, analyzing heavy metal content in fish or amphibians (Kumar et al., 2008). Thus, the importance of heavy metal transfer in terrestrial ecosystems (soil-plant-mammal) has for the most part been neglected. Different species of small mammals have been proven to be adequate monitors of environmental conditions. In addition, they generally have a small home range, are abundant, and are easily trapped (Wren, 1986). Mammals are important organisms in the area of ecotoxicology since they are often viewed as indicator species and can therefore be used to predict environmental conditions (Rogival et al., 2007).

The objective of the proposed work is to determine if eight heavy metals are becoming concentrated within cotton fields: Pb, Cd, Cu, Zn, Ni, Se, As, and

Cr. This study will examine the concentration of these metals in the cotton fields, specifically in the soil, cotton plants, and rodents. Four different soil types will be sampled representing different quantities of sand, silt, and clay. The primary hypothesis of this study predicts trace metal concentrations in soil, rodents, and cotton to decrease with increasing distance from the area adjacent to the city. I also predict heavy metal transfer from soil to cotton to rodent will be greatest in areas of low clay content of soil, low organic carbon content of soil, and high soil pH.

## CHAPTER TWO

### INTRODUCTION

During the previous century heavy metal pollution has received significant attention due to increasing urbanization and industrialization. Trace metals accumulate in urban and agricultural soils, allowing for uptake by plants and wildlife. Inorganic compounds containing As, Cu, Cd and Pb are often applied to agricultural fields. Several studies have been conducted in aquatic ecosystems, focusing on trace metal concentrations in water, sediment and fish (Kumar et al., 2008). The majority of ecotoxicological studies analyze metal content in soil, invertebrates and plants (Angelova et al., 2004; Bi et al., 2006). Work in terrestrial ecosystems, especially with small mammals has received little attention (Rogival et al., 2006; Wren, 1986). However, small mammals are considered useful indicator species, since they have a small home range, are abundant, and are easily trapped (Wren, 1986).

Anthropogenic activities such as industrial emissions and waste, vehicular traffic and the burning of fossil fuels are main sources of heavy metal pollution (Biasioli et al., 2005). Copper, Cr, Pb and Zn often occur jointly in roadside soils and street dusts due to the increased volume of traffic in urban areas (Li et al., 2001). Heavy metals become concentrated in soils with the use of agricultural practices, such as application of sewage sludge, pesticides, fertilizers, manure and irrigation water. Inorganic compounds such as paris green, lead arsenate and the Bordeaux mixture contain As, Cr, Cu and Pb and are often found in agricultural

soils (Chen et al., 2001; Eckel et al., 2001; Peryea, 1998). Insecticides and fungicides containing As and Cu are still being used in the U.S., China and France (Eckel et al., 2001; Timmer et al., 2004; Xie and Lu, 2000).

Several factors influence heavy metal bioavailability including soil pH, soil organic carbon content, soil clay content, and cation exchange capacity (Dube et al., 2000; Walker et al., 2001; Zhu et al., 2005). Seasonal changes, anthropogenic activities, and weathering have an impact on metal retention in soils (Alemayehu, 2006; Matthews, 1982). Wildlife can be exposed to heavy metals through consumption of soil particles, inhaling dust or drinking contaminated water. Accumulation of trace metals may also vary depending on the species, age, sex, diet, and metabolism of the animal (Wren, 1984). Plant species and different parts of the plant have different rates of uptake by trace metals (Angelova et al., 2004).

This study was conducted in Xinjiang Province, China, the top producer of cotton in the world (USDA, 2010). Cotton (*Gossypium spp.*) is an economically important and widely produced crop. In China alone, cotton fields cover about 4 million hectares of land (Clay, 2004). Approximately 107 million 217.7 kg bales were produced during 2008 to 2009 globally (USDA, 2010). Cotton was selected for use in this study because it has one of the highest application rates of agrochemicals of any crop (USDA, 2005). Specifically, 25% of all insecticides produced are applied to cotton. However, in developing countries it is estimated that 50% of pesticides applied to crops are applied to cotton (Clay, 2004).

The objective of the proposed work is to determine if eight heavy metals

are becoming concentrated within cotton fields: Pb, Cd, Cu, Zn, Ni, Se, As, and Cr. Heavy metal content in small mammal species is examined in addition to soil and different parts of the cotton plant. This work is conducted in cotton fields where soil types are categorized based on soil properties: soil texture, organic carbon content, and pH. The primary hypothesis predicts trace metal concentrations in soil, rodents, and cotton to decrease with increasing distance from the area adjacent to the city. I also predict heavy metal transfer from soil to cotton to rodent will be greatest in areas of low clay content of soil, low organic carbon content of soil, and high soil pH.

## METHODS

*Field Site.*— This investigation was conducted in the Manas River Valley located in north central Xinjiang Province, China (Fig. 1). Different topographies have been formed by the water flow and soil deposition in the valley. From higher (420 m) to lower (335 m) elevations, these topographies include alluvial fan, spring overflow belt, alluvial plain, delta, and lake shore plain. Each topographical type is characterized by specific changes in soil texture. Soil texture in the upper reaches of alluvial fan is rough, mainly gravel soil and sandy soil. The middle reaches of the alluvial fan is mainly loam soil, while the lower reaches of the alluvial fan is mainly clay soil. The general soil type distribution in the valley is gravel soil (0.25%), sandy soil (14.11%), loam soil (78.57%), and clay soil (7.07%). There are 18 farms located in the Manas River Valley; their

area ranges from  $2.18 \times 10^4$  ha to  $21.04 \times 10^4$  ha.

Four regions representing four different soil types were selected for sampling. These four regions also form an urban-rural gradient. The first region, Town 145, is situated immediately north of Shihezi City ( $44^{\circ}20'45.43''$  N,  $86^{\circ}01'45.00''$ E). The second region, Town 147, lies approximately 26 km northeast of Town 145 ( $44^{\circ}36'33.39''$ N,  $86^{\circ}07'09.18''$ E). The third region, Town 150, lies approximately 75 km northeast of Town 145 ( $45^{\circ}02'35.19''$ N,  $86^{\circ}06'32.66''$ E). The Gurbantunggut Desert, a natural desert, is the fourth region located approximately 90 km north of Town 145 ( $45^{\circ}09'50.79''$ N,  $86^{\circ}00'25.64''$ E).

*Field Methods.*— Eight cotton fields were sampled in each of the three towns. Four plots were sampled in the desert, totaling 28 fields between all four regions (Fig. 2). The desert served as a control. Each field had a  $10 \times 15$  array of snap traps sampling approximately 2.0 ha, within a cotton field ranging in size from 4 to 10 ha. Ten meters was maintained between traps and a 20-m buffer was maintained from the traps to the edge of the cotton field. Traps were baited with peanuts and checked each morning for three nights. Within 2 m of each rodent captured, leaves, stems, roots, and bolls from a cotton plant and three 50 g samples of soil were collected. In the desert, the stem and leaves of the saxaul bush (*Haloxylon ammodendron*) were obtained. Soil samples were analyzed individually for organic carbon content, texture, pH, and heavy metal concentrations.

*Laboratory Methods.*— Percent organic carbon content was estimated

using a muffle furnace. Ten grams of soil was air dried for two days and then sifted through a 2 mm sieve. Moisture was then removed from the soil by oven drying it to a constant weight. The soil was placed into a muffle furnace at 550°C for 7 hours and the pyrolyzed sample was reweighed. The difference in weight pre- and post-furnace treatment was divided by the original sample weight and multiplied by 100 to get loss on ignition (LOI). This was then converted to organic carbon by subtracting multiplying LOI by 0.476 and subtracting 1.87 (convert organic matter to organic carbon).

Soil texture was determined based on percent sand, silt, and clay and quantified using the suspended deposition method. Fifteen grams of soil was sifted using a 2 mm sieve. The sifted samples were mixed with 1 ml of 2% sodium pyrophosphate (dispersing agent, CAS # 13472-36-1) and then 1 ml of 0.008% polycrylamide (flocculent, CAS # 9003-05-8) to suspend the particles. The suspension was then placed in three test tubes: percent sand (tube A) was determined after 30 seconds, percent silt (tube B) after 30 minutes and percent clay (tube C) after 24 hours. The quantity of sand, silt, and clay in each tube was recorded in ml, multiplied by 100 and divided by the total volume to get percentage sand, silt, and clay of the sample.

Measurement of the concentration of hydrogen ions in a sample (pH) was measured following U.S. EPA method 9045D (Soil and Waste pH). Twenty grams of soil was placed in a 50 ml beaker to which 20 ml reagent grade water was added. The beaker was then covered and its contents were stirred for five minutes. The soil suspension stood for one hour to allow particles to settle and

the aqueous phase was centrifuged. The aqueous phase was used to measure pH.

Heavy metal concentrations were determined using quantitative and digestion methods following United States Environmental Protection Agency Test Methods (<http://www.epa.gov/epaoswer/hazwaste/test/index.htm>) and Milestone Microwave Laboratory Systems Test Methods (<http://www.milestonesci.com/digres-apps.php>). All chemicals used in digestions were reagent grade.

Heavy metals were digested from soil following the Milestone Soil Partial Digestion Method (Digestion Application Note DG-EN-13). A 0.2 g subsample of air dried soil was crushed and passed through a 1 mm sieve. The soil sample was placed into a vessel with 7 ml of HNO<sub>3</sub> 65%, 2 ml of HCL 37%, and 2 ml of HF 40% and run under a closed digestion system (Ethos EZ). The microwave program consisted of 10 minutes at 160 °C and 1500 W, followed by 20 minutes at 220 °C and 1500 W.

Milestone Dried Plant Tissue Method (Digestion Application Note DG-AG-02) was used to digest heavy metals from cotton (leaf, boll, stem, and root) and saxaul bush (stems and leaves). Cotton plants and saxaul bush were air dried for 3 days at room temperature. A 0.5 g subsample was crushed and placed in a vessel with 7 ml of HNO<sub>3</sub> 65% and 1 ml of H<sub>2</sub>O<sub>2</sub> 30% in a closed digestion system. The microwave program used was set at 10 minutes to reach 220 °C and was held at that temperature for 20 minutes. Power was at 1500 W throughout.

Heavy metals were digested from rodents using a method for animal tissue (Milestone, Digestion Application Report #05-011). Whole body rodent samples

were oven dried at 85 °C for 4 days. After being removed from the oven and cooled, entire rodents were independently ground in an industrial grade blender. A 0.5 g subsample of each rodent was placed in a vessel with 8 ml HNO<sub>3</sub> 65% and 4 ml H<sub>2</sub>O<sub>2</sub> 30% in a closed digestion system. The same microwave program used for cotton plants was also used for rodents.

Following digestions, concentrations of the heavy metals were quantified using a Thermoscientific inductively coupled plasma atomic emission spectrometer (ICP-AES) iCAP 6000 series. U.S. EPA method 6010C (Inductively Coupled Plasma-Atomic Emission Spectrometry) was the quantitative method used for the eight heavy metals. All of the metals were expressed as parts per million (ppm or mg/kg). Following digestion of samples, each analyte was placed in a 50 ml volumetric flask and diluted to 50 ml with distilled water. The following standards and concentrations were used: As (0.05 ppm, 0.1 ppm), Cd (0.05 ppm, 0.1 ppm), Cr (0.05 ppm, 0.1 ppm), Cu (0.05 ppm, 0.1 ppm), Se (0.05 ppm, 0.1 ppm), Ni (0.05 ppm, 0.1 ppm), Pb (0.05 ppm, 0.1 ppm), and Zn (0.05 ppm, 0.1 ppm). Wavelengths were chosen to optimize detection limits and minimize interference. The following wavelengths were used for each element: As 1890, Cd 2288, Cr 2677, Cu 3273, Ni 2316, Pb 2203, Se 1960, and Zn 2062. A calibration blank was run for each metal and at each wavelength after every 10th sample was analyzed. Correlation coefficients varied between 0.9990 and 0.9999. Samples were analyzed in triplicate with a 30 second delay between samples. The samples were corrected for background values. Concentrations were corrected for the volume of the sample.

*Statistical Analyses.*— The triplicate soil samples were nested within each capture. The boll, leaf, stem and root of the cotton plant were also nested. The leaves and stems of the saxaul bush were nested. Because of heterogeneity in captures, rodent species were pooled. Accumulation ratios were calculated for soil-cotton, soil-rodent and cotton-rodent. MANOVAs were used to analyze concentrations of the eight heavy metals (response variables) among the four regions. This was done for soil, cotton and rodents. MANOVAs were also used to analyze accumulation ratios of the eight heavy metals among the four regions. If a MANOVA was significant, an ANOVA was performed on each response variable. If an ANOVA was significant, a post-hoc Student-Newman-Keuls was used for multiple comparisons. Because fields are the experimental unit, individual rodents were nested (hierarchical) in each field to avoid pseudoreplication (Hurlbert, 1984). All inferences were based on type III sum-of-squares with  $\alpha = 0.05$ .

## RESULTS

*Soil properties.*— A total of 28 sites were sampled and categorized into 4 different soil types representing different soil texture, soil pH, and organic carbon content. The MANOVA was significant for clay content, sand content, silt content, pH and organic carbon among all four regions ( $df$  9, 645.09;  $f$ -value 30.48;  $wilks'$  0.42). There were significant differences in clay content among different soil types, specifically Towns 145 and 160; there were no significant

differences between Towns 147 and 150 (Tables 1 and 2, Fig. 3). There were no significant differences in sand and silt content between Towns 145, 147, and 150 (Tables 1 and 2). However, there was a significant difference in sand and silt content between Towns 145, 147, 150 and the desert (Figs. 4 and 5). There were significant differences in soil pH between Towns 145, 147, 150 and the desert with means of 7.9, 8.3, 8.1, and 8.7, respectively (Tables 1 and 2, Fig. 6). There were no significant differences in soil organic carbon content between Towns 147 and 150, however significant differences were found between Town 145 and the desert (Tables 1 and 2, Fig. 7). Organic carbon content means were 8.7 (Town 145), 4.0 (Town 147), 3.9 (Town 150), and 1.2 (desert).

*Soil metal.*— The MANOVA for soil heavy metals was significant among all four regions ( $df$  27, 640.24;  $f$ -value 20.13; *wilks'* 0.16). As soil concentrations differed significantly between Towns 145 and 147, whereas Town 150 and the desert were not significantly different (Tables 3 and 4, Fig. 8). Cd soil concentrations were not significantly different between Town 150 and the desert and Towns 147 and 145 (Tables 3 and 4, Fig. 9). Cr soil concentrations were significantly different, specifically between Towns 145 and 147. There were no significant differences in Cr concentrations between Town 150 and the desert (Tables 3 and 4, Fig. 10). Cu soil concentrations were significantly different between Town 150 and the desert. Towns 145 and 147 did not have significant differences in Cu soil concentrations (Tables 3 and 4, Fig. 11). There were no significant differences in Ni concentrations between Towns 145 and 147. Soil Ni concentrations were significantly different between the desert and Town 150

(Tables 3 and 4, Fig. 13). Soil Pb concentrations were not significantly different, specifically between Town 150 and the desert and between Towns 147 and 145 (Tables 3 and 4, Fig. 14). Se soil concentrations were significantly different between Towns 145 and 150. However, Se concentrations were not significantly different between Town 147 and the desert (Tables 3 and 4, Fig. 14). Soil Zn concentrations were not significantly different between Town 150 and the desert. Significant differences were found in soil Zn concentrations between Towns 145 and 147 (Tables 3 and 4, Fig. 15). More specifically, the MANOVA was significant for differences within fields ( $df$  441, 1964.7;  $f$ -value 3.01;  $wilks'$  0.01).

*Plant.*— The MANOVA was significant for plant heavy metals among all four regions ( $df$  27, 856.35;  $f$ -value 4.8;  $wilks'$  0.66). Plant As concentrations were not significantly different between Towns 150, 147 and the desert. Although, Town 145 plant As concentrations were significantly higher than Towns 150, 147 and the desert (Tables 5 and 6, Fig. 8). There were no significant differences in plant Cd concentrations across all towns (Tables 5 and 6, Fig. 9). Plant Cr concentrations were not significantly different between Town 147 and the desert and between Towns 147, 150, and 145 (Tables 5 and 6, Fig. 10). Plant Cu concentrations were not significantly different between Towns 145, 150 and 147. However the desert had significantly lower plant Cu concentrations (Tables 5 and 6, Fig. 11). Plant Ni concentrations were not significantly different across all regions (Tables 5 and 6, Fig. 12). Plant Pb concentrations were not significantly different between Towns 147, 145 and the desert and between Towns 147, 145, and 150 (Tables 5 and 6, Fig. 13). Plant Se concentrations were

not significantly different between Towns 150, 147, and the desert. Se concentrations were significantly higher in Town 145 (Tables 5 and 6, Fig. 14). Plant Zn concentrations were not significantly different in Towns 150, 145, and 147. Zn concentrations were significantly lower in the desert (Tables 5 and 6, Fig. 15).

*Rodents.*— Eight rodent species were sampled. However, three species were not included in statistical analyses due to low capture rates and diet (Table 7). MANOVA for As rodent tissue concentrations was not significantly different ( $df$  24, 107.91;  $f$ -value 2.3;  $wilks'$  0.30). As concentrations in rodents were not significantly different in Towns 147, 150, and the desert, however Town 145 had significantly higher As concentrations (Tables 8 and 9, Fig. 8). Cd concentrations were different between Town 147 and the desert and between Towns 145 and the desert (Tables 8 and 9, Fig. 10). There were no significant differences across all four towns in rodent Cu concentrations (Tables 8 and 9, Fig. 11). Ni concentrations were significantly higher in Town 145 (Tables 8 and 9, Fig. 12). There were no significant differences in rodent Pb concentrations among regions (Tables 8 and 9, Fig. 13). There were no significant differences in rodent Se concentrations, specifically between Towns 147, 150, the desert and between towns 150, 145 and the desert (Tables 8 and 9, Fig. 14). There were no significant differences in Zn concentrations between Towns 145, 150, and 147. However, the desert had significantly higher Zn concentrations in rodents (Tables 8 and 9, Fig. 15).

*Accumulation ratios.*— There were no significant differences in As, Cu,

and Pb soil-plant accumulation ratios across all towns (Tables 10 and 11). Cd soil-plant ratios were significantly higher in the desert compared to Towns 145, 147 and 150 (Tables 10 and 11). In Town 150, Cr ratios were significantly higher than Towns 145, 147, and the desert (Tables 10 and 11). Ni ratios were significantly higher in the desert and Towns 145, 147 and 150 were not significantly different (Tables 10 and 11). Se accumulation ratios were significantly different; they were higher in Town 145. Towns 145 and 150 were not significantly different and Towns 147, 150 and the desert were not significantly different (Tables 10 and 11). Zn ratios were significantly higher in the desert compared to Towns 145, 147 and 150 (Tables 10 and 11).

There were no significant differences in As, Cd, Cu, and Pb soil-rodent accumulation ratios across all towns (Tables 10 and 11). Cr ratios were significantly higher in the desert (Tables 10 and 11). Ni ratios were also significantly higher in the desert. However, Ni soil-rodent accumulation ratios in Towns 145, 147 and 150 were not significantly different (Tables 10 and 11). Se accumulation ratios were significantly higher in Town 150 compared to all other towns. Se accumulation ratios were not significantly different among Towns 145, 147 and the desert (Tables 10 and 11). There were significant differences in Zn ratios across towns; specifically the desert had the highest Zn ratios. Towns 145 and 150 were not significantly different, along with Towns 145 and 147 (Tables 10 and 11).

There were no significant differences in As and Se plant-rodent accumulation ratios across all towns (Tables 10 and 11). Cd ratios were

significantly higher in Town 147. Plant-rodent accumulation ratios were not significantly different between Towns 145, 150 and the desert (Tables 10 and 11). Cr, Cu, Ni, Pb, and Zn ratios were significantly higher in the desert. Cr, Cu, Ni, Pb and Zn plant-rodent accumulation ratios were not significantly different among between Towns 145, 147 and 150 (Tables 10 and 11).

## DISCUSSION

*Soil.*— With the exception of Se, trace metal concentrations of As, Cd, Cr, Cu, Ni, Pb, and Zn were highest in soils of Towns 145 and 147. The majority of industrial and anthropogenic activities occur adjacent to Shihezi city, Town 145, and decline with increasing distance from the urban area. Therefore, trace metal concentrations are higher in more urban, populated areas compared to agricultural regions. However, the agricultural areas generally had higher concentrations of heavy metals than the desert. Cu and Pb are highest in soils surrounding Town 145, suggesting their common source in automobiles. This suggests that agricultural inputs may not be of as great importance as industrial or anthropogenic sources. Town 145, adjacent to the city, has a higher density of automobiles compared to the other three towns. Cu is commonly found in brake pads and vehicle exhaust. Pb was an additive in lead based gasoline and has been found to persist for decades after its discontinuation (Mielke et al., 2000; Davis et al., 2001). Leaded gasoline was still used in China until at least 2000. The high concentrations of Zn can primarily be explained by its use in brake pads, exhaust,

oil, and tires (Hewitt and Rashed, 1990; Mielke et al., 2000; Imperato et al., 2003; Davis et al., 2001). Highest Cr and Ni concentrations were found in Town 147, most likely as a result of production of metal alloys. Town 147 had the highest concentrations of Zn most likely due to the combination of anthropogenic activities and the large area of agricultural land. The high concentrations of As in Town 147 and 145 can be explained by proximity to coal powered plants. Each coal powered facility contained 8 large cooling towers. The fields sampled in Town 145 are within 0.8 to 5 km of coal plants. Cd was also highest in Town 145 which can be explained by its emission into the atmosphere from coal powered plants. However, Cd does not persist in the atmosphere for long (Fishbein, 1981). Cr and Ni are also released as a by-product of burning coal and may help explain why concentrations are high in Town 145. In addition to coal powered plants, high As concentrations in fields surrounding Towns 147 and 145 could be due to the use of As based insecticides and fungicides (Cao et al., 2009). Cd is also used as a component in cadmium phosphate fertilizers (Li et al., 2001). Zn is also a component in fertilizer in all regions including areas adjacent to the city (Imperato et al., 2003). Ni and Cr are usually found in combination and both occur naturally in rock (Alemayehu, 2006). The highest concentrations of Se were found in the desert suggesting a non-anthropogenic source.

*Plant.*— Coal powered plants surround Town 145 where As, Cr, and Se concentrations in cotton are the highest. This can be explained by atmospheric deposition where these metals deposit on cotton leaves, in some cases with very little reaching the soil. Angelova et al. (2004) concluded that cotton leaves

accumulate more metals than any other part of the plant. Furthermore, As resides in the atmosphere for about nine days before soil deposition occurs, allowing the particles to travel longer distances (EPA, 1998). Since Cd does not have a long residence time in the atmosphere, high plant concentrations in the desert can only be explained by soil properties (Fishbein, 1981). The desert has low clay content and low organic carbon content allowing for maximum uptake of Cd to the saxaul bush.

*Rodent.*— Concentrations of As and Se in rodent species were highest in Town 145. As and Se particles are deposited onto soil particles as by-products of coal burning. Rodents are primarily exposed to trace metals by ingestion of contaminated soil particles. In addition, all of the rodent species sampled are burrowing rodents. Zn concentrations were highest in rodents trapped in the desert. Small mammals maintain a homeostatic regulation of Zn in their bones and soft tissue. The saxaul bush accumulated very low concentrations of Zn, allowing for soil to retain high Zn concentrations, which can be ingested by the rodents.

*Accumulation ratios.*— The high Cd and Ni soil-plant accumulation ratios in the desert can be explained by the low clay content of the desert soil, low organic carbon, and high pH compared to towns 145, 147, and 150, which are more proximal to the city. Furthermore, Ni is a naturally occurring element in rock. Cr and Zn ratios were highest in town 150 where transfer from soil to cotton cannot be easily explained by soil properties. However, Cr has been found to be most bioavailable under neutral pH (Fuller, 1977). Soil properties such as

low pH can explain the high Se accumulation ratio in town 145. The abundance of coal plants surrounding town 145 also explains the high ratios of both As and Se in town 145. Furthermore, the particle size of Se is very fine allowing Se to become volatilized into the atmosphere (Chlou and Manuel, 1986).

The transfer of Cr, Ni, and Zn from soil to rodent was highest in the desert. The plant species sampled in the desert, the saxaul bush, most likely does not have the same uptake mechanisms as cotton. Due to the small leaves on the saxaul bush, atmospheric deposition is probably not a significant source of trace metal contamination. Furthermore, consumption of the leaves is not likely since the majority of the rodents sampled prefer to eat leafy vegetation or simply the fruit from desert plants (Naumov and Lobachev, 1975). Therefore, the concentrations of these metals would be higher in the soil and more available for uptake by the rodents. Cr and Ni are both naturally occurring and are found jointly in nature. The high Zn ratio can be explained by the high Zn concentrations in rodents. Small mammals maintain a homeostatic regulation of Zn. Se and Zn are both elements that are primarily released into the atmosphere.

Although not all metals examined had significantly high accumulation ratios, plant-rodent ratios were higher than other trophic level ratios measured. Most of the ratios were over one, indicating the rodents had higher concentrations of the metal than the plant. Accumulation ratios were highest for Cr, Cu, Ni, Pb, and Zn in the desert due to the low concentrations in the saxaul bush. Furthermore, Cd ratios were highest in town 147 due to low concentrations in cotton. Significant differences in accumulation ratios from plant to rodent are

most likely due to different uptake mechanisms between cotton and saxaul bush.

Table 1

ANOVA table for soil properties of towns 145, 147, 150 and the desert.

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Soil clay content					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	10045.64411	3348.54804	42.24	<0.0001
Number(Field)	29	4349.12524	149.96984	1.89	0.0051
Sub(Number)	29	1156.44934	39.87756	0.50	0.9856
Error	258	20453.80789	79.27833		

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Soil sand content					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	71292.91666	23764.30555	108.62	<0.0001
Number(Field)	29	14127.54614	487.15676	2.23	0.0005
Sub(Number)	29	8221.31523	283.49363	1.30	0.1494
Error	258	56448.1674	218.7913		

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Soil silt content					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	28289.58328	9429.86109	73.43	<0.0001
Number(Field)	29	14909.61378	514.02116	4.00	<0.0001
Sub(Number)	29	6342.60509	218.71052	1.70	0.0166
Error	258	33134.50717	128.42832		

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Table 1 continued

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Soil pH					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	8.24721949	2.74907316	30.07	<0.0001
Number(Field)	29	10.36982208	0.35758007	3.91	<0.0001
Sub(Number)	29	4.03886821	0.13927132	1.52	0.0476
Error	242	22.12463233	0.09142410		

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Soil organic carbon					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	1135.008909	378.336303	386.84	<0.0001
Number(Field)	29	221.273122	7.630108	7.8	<0.0001
Sub(Number)	29	66.418109	2.290280	2.34	0.0002
Error	258	252.329255	0.978020		

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Table 2

Multiple comparison tables for soil properties.

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Clay

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desert 145 150 147

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Sand

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150 147 145 desert

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Silt

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desert 145 147 150

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pH

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145 150 147 desert

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desert 150 147 145

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Table 3

ANOVA table for heavy metals in soils of towns 145, 147, 150 and the desert.

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As

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	658.085624	219.361875	26.72	<0.0001
Number(Field)	65	2294.825509	35.305008	4.30	<0.0001
Sub(Number)	50	789.815312	15.796306	1.92	0.0008
Error	211	1732.223800	8.209591		

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Cd

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	2.50648806	0.83549602	57.39	<0.0001
Number(Field)	65	2.56496746	0.03946104	2.71	<0.0001
Sub(Number)	50	0.81586569	0.01631731	1.12	0.2866
Error	211	3.07171940	0.01455791		

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Cr

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	20907.56164	6969.18721	187.95	<0.0001
Number(Field)	65	30072.73150	462.65741	12.48	<0.0001
Sub(Number)	50	7932.82130	158.65643	4.28	<0.0001
Error	211	7824.03636	37.08074		

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Table 3 continued

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Cu					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	11036.57500	3678.85833	86.82	<0.0001
Number(Field)	65	13729.47418	211.22268	4.98	<0.0001
Sub(Number)	50	4604.36173	92.08723	2.17	<0.0001
Error	211	8941.08905	42.37483		

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Ni					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	2309.326110	769.775370	54.16	<0.0001
Number(Field)	65	3389.626932	52.148107	3.67	<0.0001
Sub(Number)	50	1216.661386	24.333228	1.71	0.0048
Error	211	4709.59724	22.32037		

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Pb					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	7406.469217	2468.823072	110.61	<0.0001
Number(Field)	65	9135.476218	140.545788	6.30	<0.0001
Sub(Number)	50	2995.472534	59.909451	2.68	<0.0001
Error	211	2998.877661	14.212690		

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Table 3 continued

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Se					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	63.1267247	21.0422416	45.18	<0.0001
Number(Field)	65	207.7520153	3.1961849	6.86	<0.0001
Sub(Number)	50	74.8418923	1.4968378	3.21	<0.0001
Error	211	98.2802782	0.4657833		

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Zn					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	38041.57160	12680.52387	44.04	<0.0001
Number(Field)	65	48913.63445	752.51745	2.61	<0.0001
Sub(Number)	50	21600.60659	432.01213	1.50	0.0262
Error	211	60756.5711	287.9458		

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Table 4

Multiple comparison tables for heavy metal concentrations in soils.

As

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desert 150 145 147

Cd

##### \*\*\*\*\*

150 desert 147 145

Cr

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desert 150 145 147

Cu

!!!! ##### \*\*\*\*\*

150 desert 147 145

Ni

##### !!!! \*\*\*\*\*

desert 150 145 147

Pb

##### \*\*\*\*\*

150 desert 147 145

Se

!!!! ### \*\*\*\*\*

150 145 147 desert

Zn

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desert 150 145 147

Table 5

ANOVA table for heavy metal concentrations in plants of towns 145, 147, 150 and the desert.

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As					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	14.48682942	4.82894314	16.47	<0.0001
Number(field)	70	80.53640018	1.15052000	3.92	<0.0001
Sub(Number)	66	45.57848836	0.69058316	2.36	<0.0001
Error	285	83.5438455	0.2931363		

---

Cd					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.01600164	0.00533388	0.67	0.5727
Number(field)	70	0.71658122	0.01023687	1.28	0.0839
Sub(Number)	66	1.20794557	0.01830221	2.29	<0.0001
Error	285	2.27810546	0.00799335		

---

Cr					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	231.199863	77.066621	2.37	0.0704
Number(field)	70	1927.024367	27.528920	0.85	0.7935
Sub(Number)	66	2806.084986	42.516439	1.31	0.0702
Error	285	9250.29485	32.45717		

---

Table 5 continued

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Cu					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	8605.54290	2868.51430	4.31	0.0054
Number(field)	70	58676.31693	838.23310	1.26	0.0986
Sub(Number)	66	49611.58625	751.69070	1.13	0.2484
Error	285	189597.4092	665.2541		

---

Ni					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	13.6712874	4.5570958	1.15	0.3287
Number(field)	70	249.1429878	3.5591855	0.90	0.6975
Sub(Number)	66	222.4654276	3.3706883	0.85	0.7809
Error	285	1127.921593	3.957620		

---

Pb					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	50.9452440	16.9817480	3.26	0.0219
Number(field)	70	321.2875143	4.5898216	0.88	0.7321
Sub(Number)	66	400.7029907	6.0712574	1.17	0.1982
Error	285	1483.531426	5.205373		

---

Table 5 continued

---

Se					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	4.64265727	1.54755242	14.16	<0.0001
Number(field)	70	26.96438203	0.38520546	3.52	<0.0001
Sub(Number)	66	10.47374742	0.15869314	1.45	0.0206
Error	285	31.14589705	0.10928385		

---

Zn					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	5168.68507	1722.89502	8.46	<0.0001
Number(field)	70	29273.41256	418.19161	2.05	<0.0001
Sub(Number)	66	20415.71503	309.32902	1.52	0.0110
Error	285	58071.1186	203.7583		

---

Table 6

Multiple comparison tables for heavy metal concentrations in plants.

---

As

##### \*\*\*

150	desert	147	145
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Cd

\*\*\*\*\*

147	150	145	desert
-----	-----	-----	--------

---

Cr

#####

\*\*\*\*\*

desert	147	150	145
--------	-----	-----	-----

---

Cu

\*\*\*\* #####

desert	145	150	147
--------	-----	-----	-----

---

Ni

\*\*\*\*\*

desert	150	145	147
--------	-----	-----	-----

---

Table 6 continued

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Pb

\*\*\*\*\*

#####

desert 147 145 150

---

Se

\*\*\*\*\* ###

150 147 desert 145

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Zn

\*\*\*\* #####

desert 150 145 147

---

Table 7

Number of each species of rodent captured including diet.

Species	Number (n)	Diet
<i>Apodemus uralensis</i>	13	Herbivore
<i>Cricetulus migratorius</i>	41	Herbivore
<i>Cardiocranius paradoxus</i>	15	Herbivore
<i>Meriones libycus</i>	2	Herbivore
<i>Meriones meridianus</i>	24	Herbivore
<i>Meriones tamariscinus</i>	2	Omnivore
<i>Mus musculus</i>	17	Herbivore
<i>Rattus tanezumi</i>	1	Herbivore

Table 8

ANOVA tables for heavy metal concentrations in rodents of towns 145, 147, 150 and the desert.

---

As

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	7.30799614	2.43599871	12.98	<0.001
Number(field)	62	21.85866000	0.35255903	0.95	0.5598
Error	44	8.25610386	0.18763872		

---

Cd

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.17050767	0.05683589	2.92	0.0443
Number(field)	62	0.96086348	0.01549780	0.80	0.7968
Error	44	0.85560067	0.01944547		

---

Cr

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	548.194559	182.731520	5.81	0.0020
Number(field)	62	3397.940892	54.805498	1.74	0.0271
Error	44	1383.745641	31.448765		

---

Table 8 continued

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Cu					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	83.4411755	27.813752	3.29	0.0293
Number(field)	62	973.9232364	15.7084393	1.86	0.0161
Error	44	372.112374	8.457099		

---

Ni					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	50.4491554	16.8163851	5.19	0.0037
Number(field)	62	311.9726017	5.0318162	1.55	0.0629
Error	44	142.5529530	3.2398398		

---

Pb					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	36.5030529	12.1676843	2.36	0.0863
Number(field)	62	141.6875885	2.2852837	0.44	0.9981
Error	44	206.5765363	5.1644134		

---

Se					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	3.43857213	1.14619071	4.23	0.0103
Number(field)	62	15.65945061	0.25257178	0.93	0.6044
Error	44	11.91409453	0.27077488		

---

Table 8 continued

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Zn					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	2294.90281	764.96760	4.09	0.0099
Species	5	1579.82110	315.96422	1.69	0.1490
Number(field)	36	12148.95825	337.47106	1.81	0.0184
Error	67	12523.59207	186.91928		

---

Table 9

Multiple comparison tables for heavy metal concentrations in rodents.

---

As

##### \*\*\*

150	desert	147	145
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---

Cd

#####

150	145	desert	147
-----	-----	--------	-----

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Cr

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!!!!!!!!!!!!!! #####

147	145	150	desert
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Cu

\*\*\*\*\*

150	147	desert	145
-----	-----	--------	-----

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Ni

\*\*\*\*\* ###

150	147	desert	145
-----	-----	--------	-----

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Pb

\*\*\*\*\*

150	145	desert	147
-----	-----	--------	-----

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Se

\*\*\*\*\*

#####

147	150	desert	145
-----	-----	--------	-----

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Table 9 continued

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Zn			
#####			***
145	150	147	desert

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Table 10

ANOVA tables for accumulation ratios in Towns 145, 147, 150 and the desert.

## Soil-plant As

---

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.04210153	0.01403384	1.17	0.3236
Error	108	1.29246000	0.01196722		

---

## Soil-plant Cd

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	12.67839264	4.22613088	2.99	0.0343
Error	108	152.7675405	1.4145143		

---

## Soil-plant Cr

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.25846450	0.08615483	4.67	0.0041
Error	108	1.99057559	0.01843126		

---

## Soil-plant Cu

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	110.2772073	36.7590691	0.97	0.4109
Error	108	4103.029199	37.991011		

---

## Soil-plant Ni

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.36304376	0.12101459	3.59	0.0160
Error	108	3.63631394	0.03366957		

---

Table 10 continued

---

Soil-plant Pb					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.15347453	0.05115818	1.69	0.1737
Error	108	3.27133185	0.03029011		

---

Soil-plant Se					
Source	DF	ANOVA SS	Mean Square	F value	Pr > F
Region	3	0.12407838	0.04135946	2.73	0.0473
Error	108	1.63444878	0.01513378		

---

Soil-plant Zn					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	2.60194805	0.86731602	6.47	0.0005
Error	108	14.48355769	0.13410702		

---

Soil-rodent As					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.01341365	0.00447122	0.50	0.6842
Error	103	0.92395869	0.00897047		

---

Soil-rodent Cd					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	8.55945302	2.85315101	2.32	0.0798
Error	103	126.7164816	1.2302571		

---

Table 10 continued

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Soil-rodent Cr					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	2.17601229	0.72533743	3.25	0.0250
Error	103	23.01505028	0.22344709		

---

Soil-rodent Cu					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	8.74686103	2.91562034	1.25	0.2962
Error	103	240.5490657	2.3354278		

---

Soil-rodent Ni					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	1.25008701	0.41669567	3.48	0.0185
Error	103	12.31654761	0.11957813		

---

Soil-rodent Pb					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.25016664	0.08338888	0.62	0.6035
Error	103	13.84770917	0.13444378		

---

Soil-rodent Se					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	0.96517229	0.32172410	4.58	0.0047
Error	103	7.23397236	0.07023274		

---

Table 10 continued

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Soil-rodent Zn					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	42.50564453	14.16854818	8.66	<0.0001
Error	103	168.5509225	1.6364167		

---

Plant-rodent As					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	4.01265769	1.33755256	1.29	0.2820
Error	101	104.7353116	1.0369833		

---

Plant-rodent Cd					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	53.61082001	17.8727334	3.92	0.0107
Error	101	459.9506036	4.5539664		

---

Plant-rodent Cr					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	7434.134881	2478.044960	13.49	<0.0001
Error	101	18558.93036	183.75179		

---

Plant-rodent Cu					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	431.5466408	143.8488803	26.79	<0.0001
Error	101	542.3541126	5.3698427		

---

Table 10 continued

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Plant-rodent Ni					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	1072.244504	357.414835	6.70	0.0004
Error	101	5389.638696	53.362759		

---

Plant-rodent Pb					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	330.5142320	110.1714107	6.01	0.0008
Error	101	1851.685469	18.333519		

---

Plant-rodent Se					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	17.35643724	5.78547908	1.18	0.3220
Error	101	496.0681730	4.9115661		

---

Plant-rodent Zn					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Region	3	151980.3281	50660.1094	22.05	<0.0001
Error	101	232005.5159	2297.0843		

---

Table 11

Multiple comparison tables for accumulation ratios in Towns 145, 147, 150 and the desert.

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Soil-plant As

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147	desert	150	145
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---

Soil-plant Cd

\*\*\*\*\*

#####

147	145	150	desert
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---

Soil-plant Cr

\*\*\*\*\*

147	desert	145	150
-----	--------	-----	-----

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Soil-plant Cu

\*\*\*\*\*

Desert	145	147	150
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---

Soil-plant Ni

\*\*\*\*\*

#####

147	145	150	desert
-----	-----	-----	--------

---

Soil-plant Pb

\*\*\*\*\*

Desert	147	145	150
--------	-----	-----	-----

---

Soil-plant Se

\*\*\*\*\*

#####

147	desert	150	145
-----	--------	-----	-----

Table 11 continued

## Soil-plant Zn

\*\*\*\*\*

#####

Desert 147 145 150

## Soil-rodent As

\*\*\*\*\*

147 145 desert 150

## Soil-rodent Cd

\*\*\*\*\*

#####

145 147 150 desert

## Soil-rodent Cr

\*\*\*\*\*

147 145 150 desert

## Soil-rodent Cu

\*\*\*\*\*

145 147 desert 150

## Soil-rodent Ni

\*\*\*\*\*

#####

147 150 145 desert

## Soil-rodent Pb

\*\*\*\*\*

145 desert 147 150

Table 11 continued

## Soil-rodent Se

\*\*\*\*\*

#####

147	145	desert	150
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## Soil-rodent Zn

\*\*\*\*\* !!!!!!!

#####

147	145	150	desert
-----	-----	-----	--------

## Plant-rodent As

\*\*\*\*\*

147	150	145	desert
-----	-----	-----	--------

## Plant-rodent Cd

##### \*\*\*

Desert	145	150	147
--------	-----	-----	-----

## Plant-rodent Cr

##### \*\*\*\*\*

147	145	150	desert
-----	-----	-----	--------

## Plant-rodent Cu

##### \*\*\*\*\*

150	147	145	desert
-----	-----	-----	--------

## Plant-rodent Ni

##### \*\*\*\*\*

150	147	145	desert
-----	-----	-----	--------

Table 11 continued

---

Plant-rodent Pb

##### \*\*\*\*\*

150 145 147 desert

---

Plant-rodent Se

\*\*\*\*\*

147 145 150 desert

---

Plant-rodent Zn

##### \*\*\*\*\*

150 145 147 desert

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Fig. 1. Location of study site in North Central Xinjiang province.

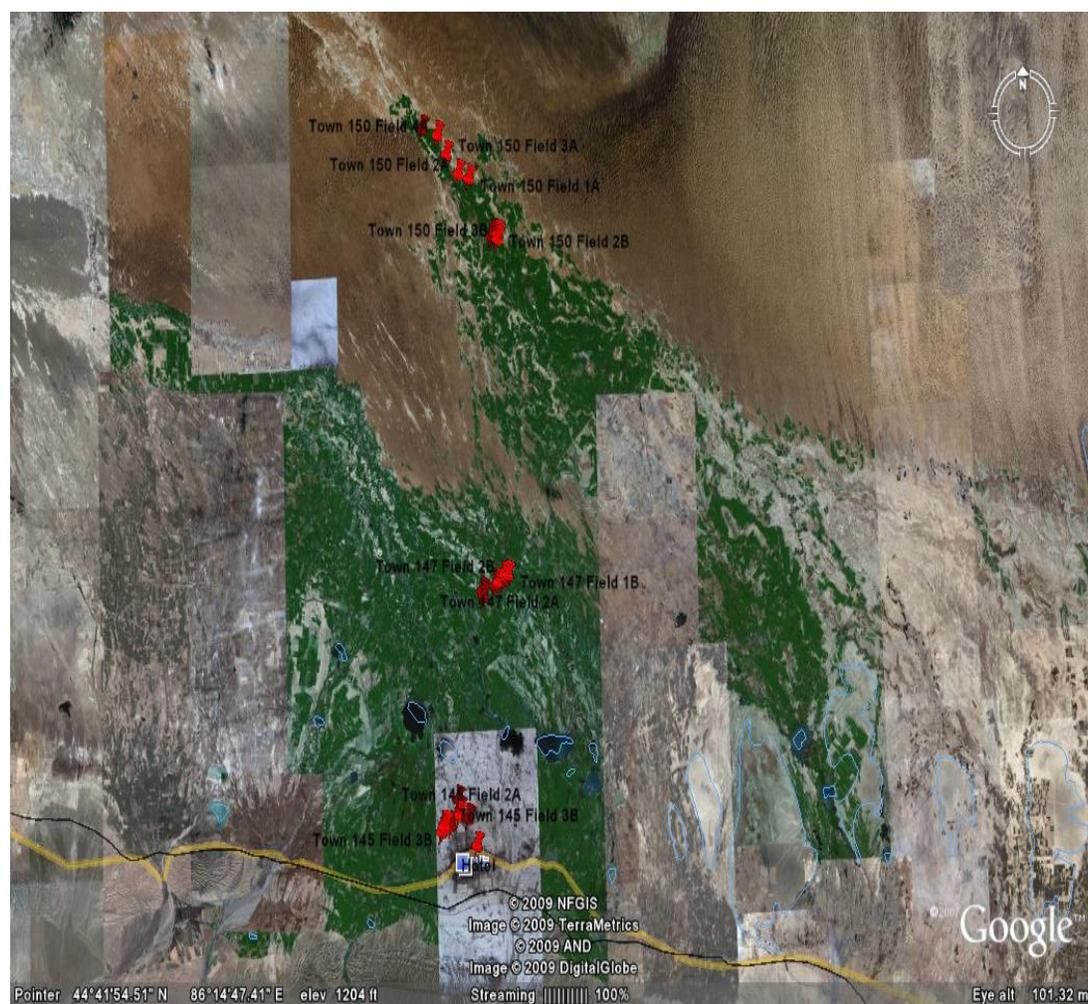


Fig. 2. Cotton fields sampled in July 2007 and July 2008.

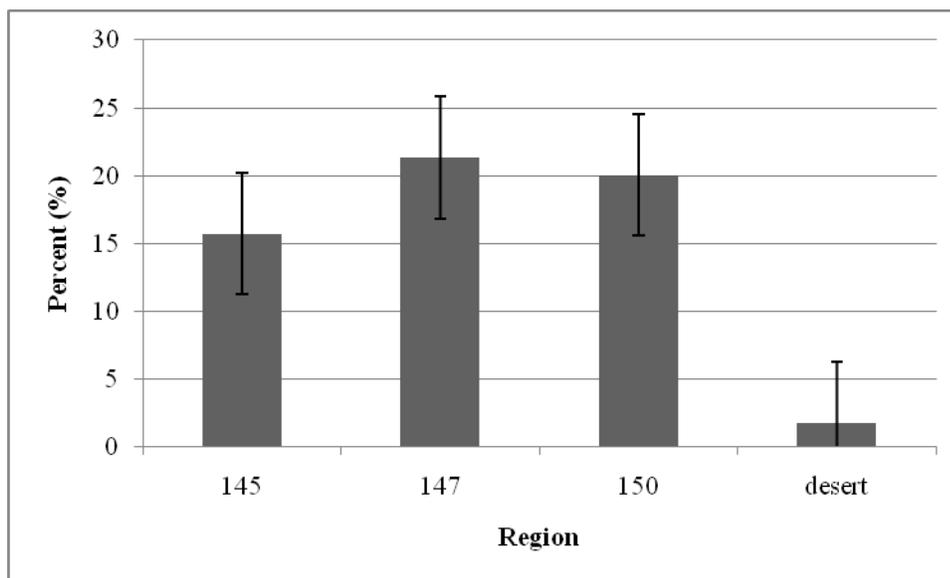


Fig. 3. Average percent clay in soils of each region  $\pm 1$  st. err..

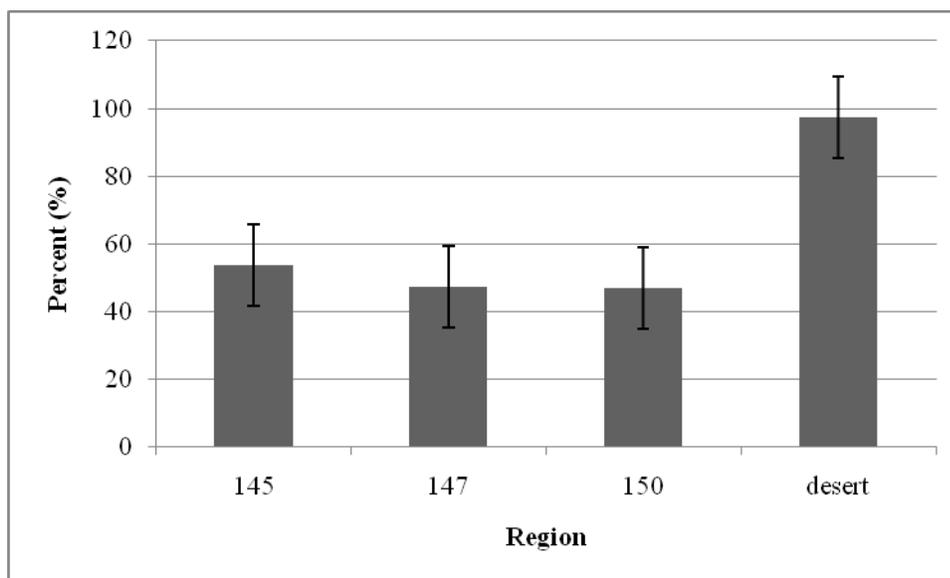


Fig. 4. Average percent sand in soils of each region  $\pm 1$  st. err..

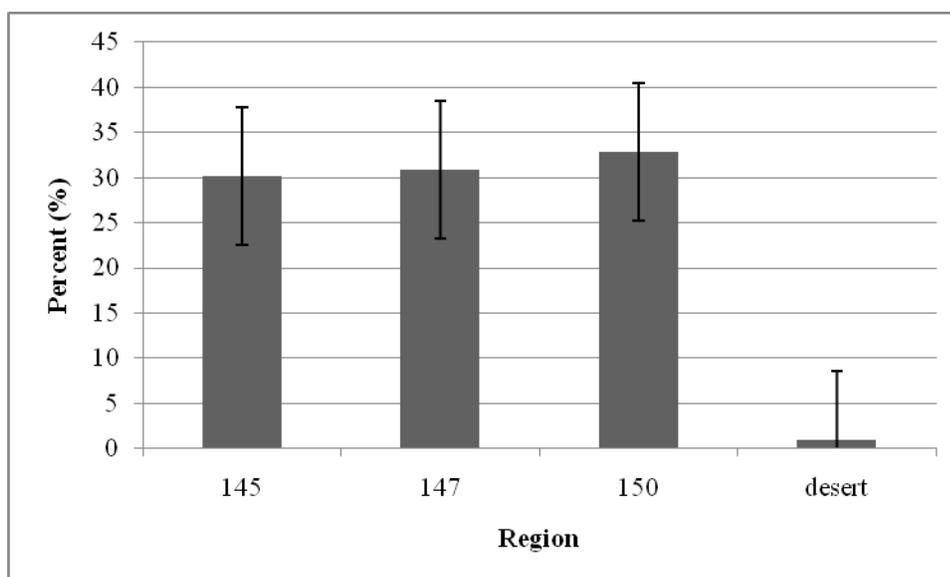


Fig. 5. Average percent silt in soils of each region  $\pm$  1 st. err..

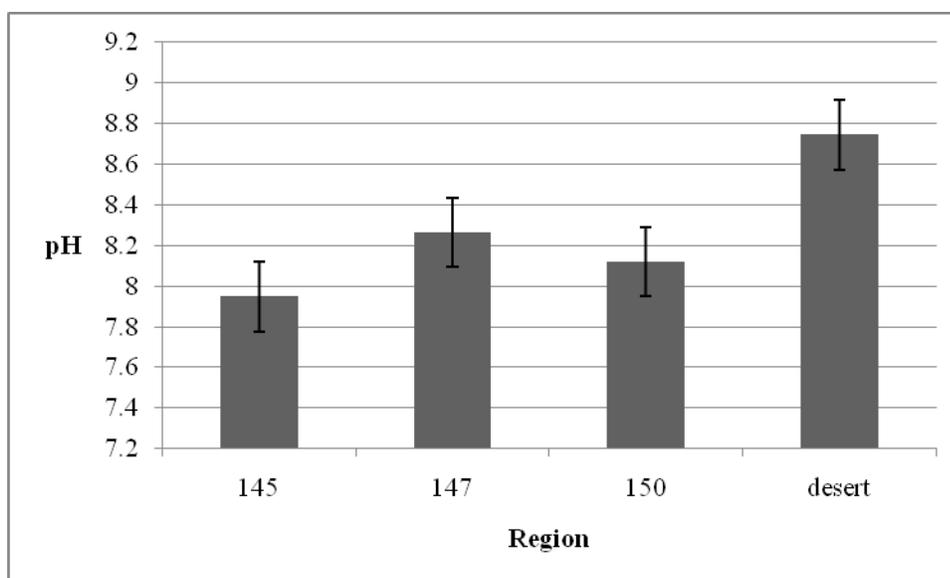


Fig. 6. Average soil pH in each region  $\pm$  1 st. err.

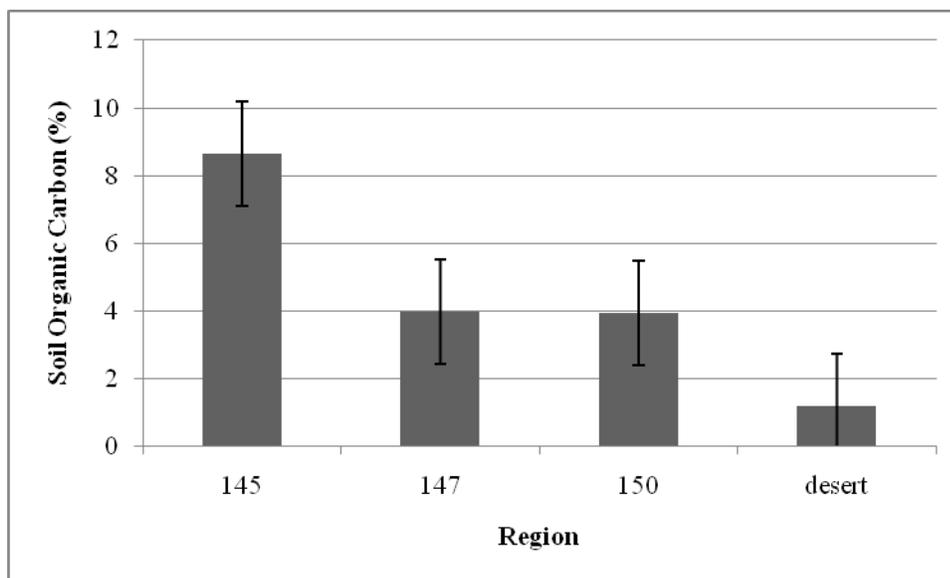


Fig. 7. Average soil organic carbon in each region (%)  $\pm$  1 st. err.

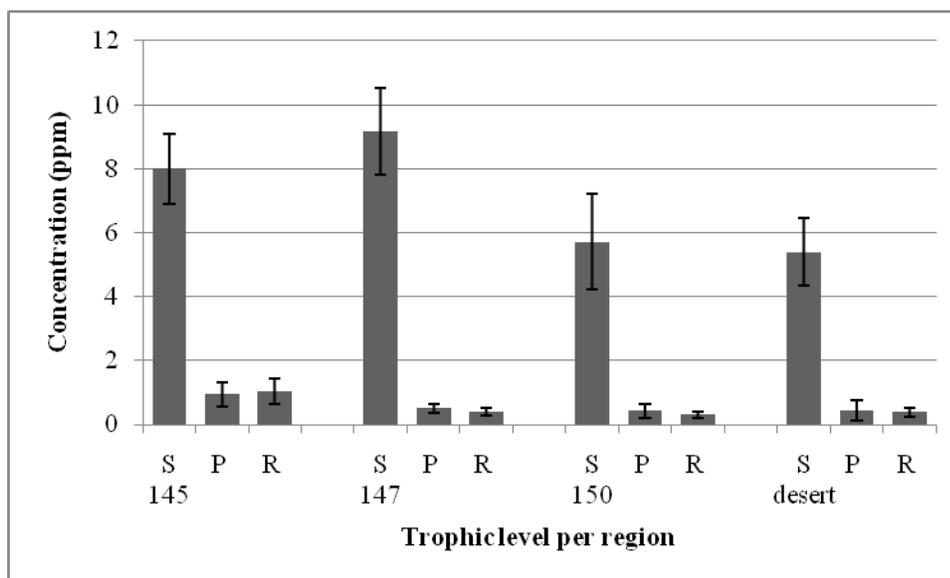


Fig. 8. Mean As concentrations  $\pm$  1 st. err.. Soil (S), plant (p) and rodent (r) concentrations are given for each region.

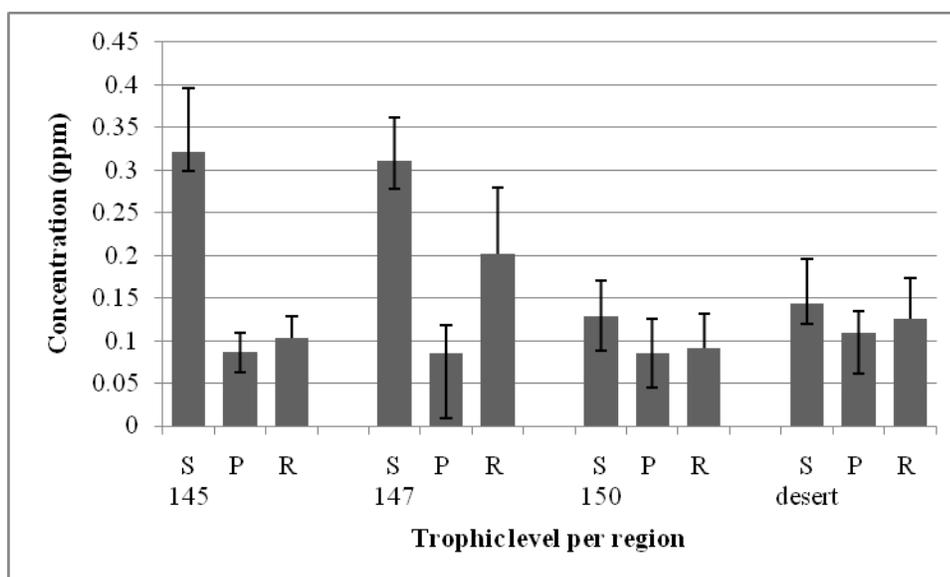


Fig. 9. Mean Cd concentrations  $\pm$  1 st. err.. Soil (S), plant (p) and rodent (r) concentrations are given for each region.

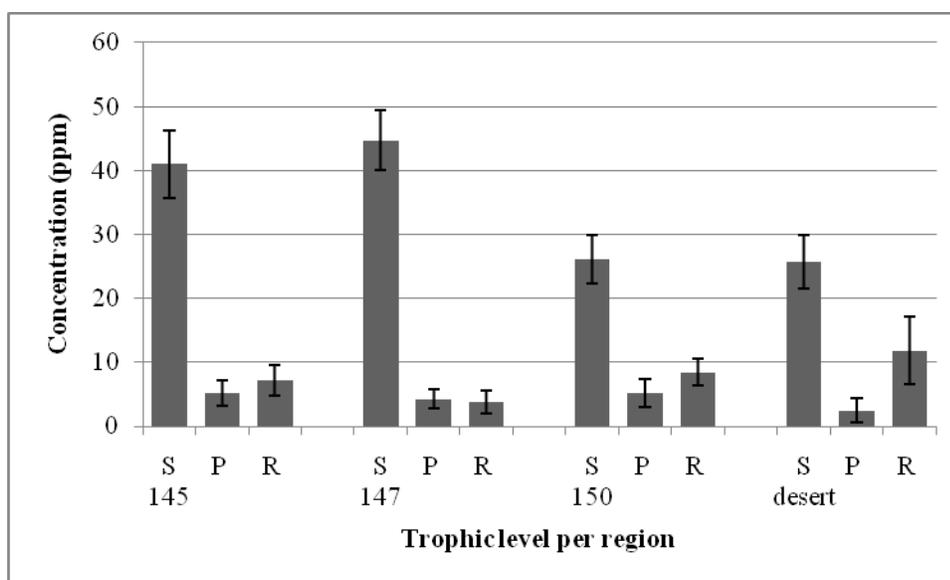


Fig. 10. Mean Cr concentrations  $\pm$  1 st. err.. Soil (S), plant (p) and rodent (r) concentrations are given for each region.

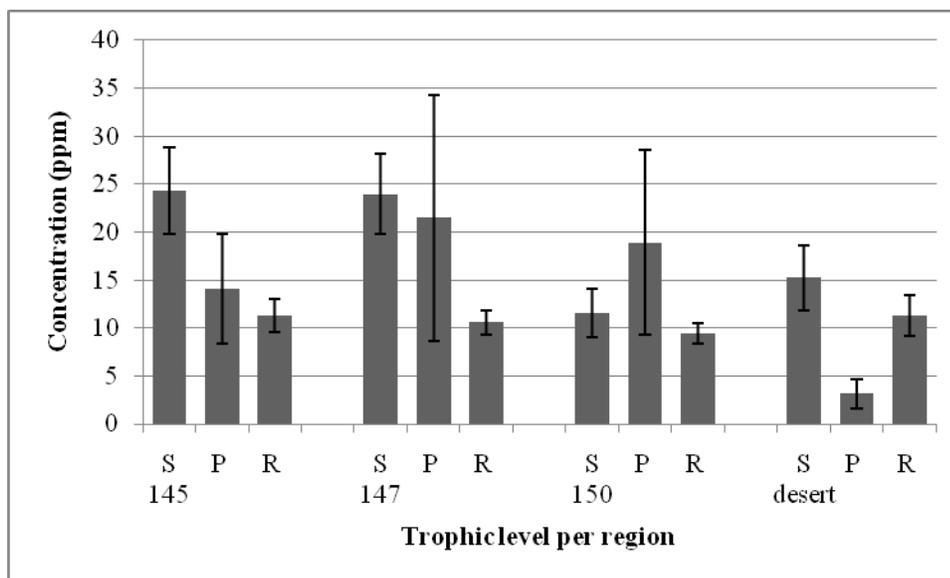


Fig. 11. Mean Cu concentrations  $\pm$  1 st. err.. Soil (S), plant (p) and rodent (r) concentrations are given for each region.

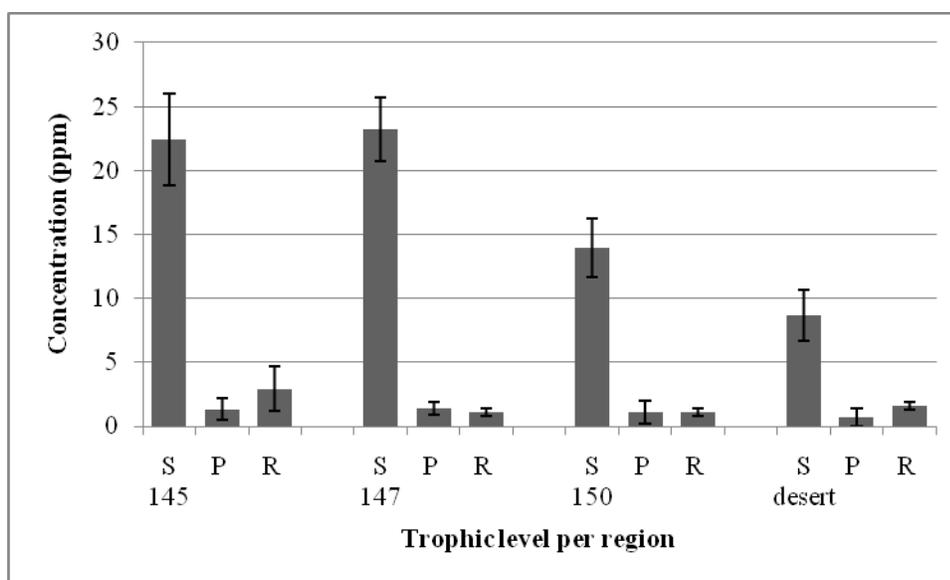


Fig. 12. Mean Ni concentrations  $\pm$  1 st. err.. Soil (S), plant (p) and rodent (r) concentrations are given for each region.

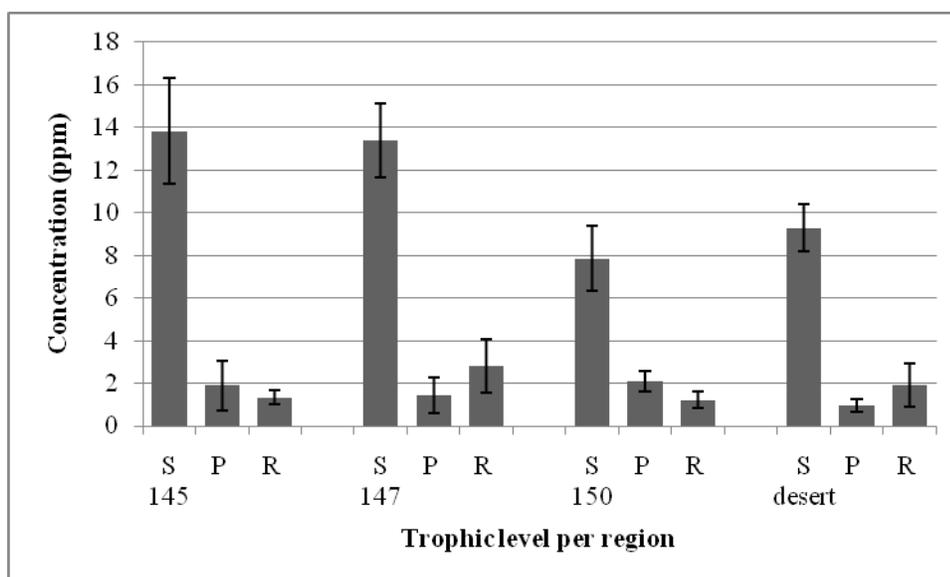


Fig. 13. Mean Pb concentrations  $\pm$  1 st. err.. Soil (S), plant (p) and rodent (r) concentrations are given for each region.

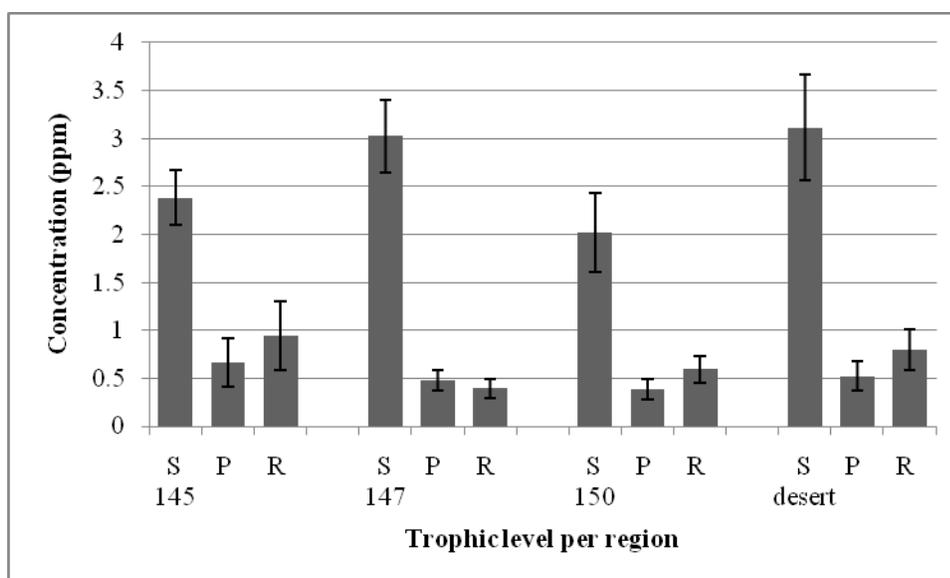


Fig. 14. Mean Se concentrations  $\pm$  1 st. err.. Soil (S), plant (p) and rodent (r) concentrations are given for each region.

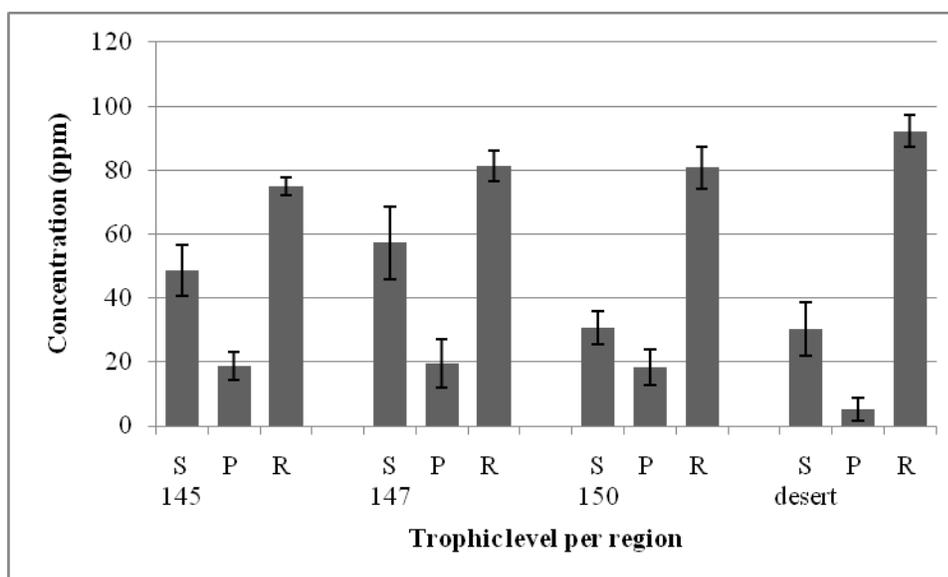


Fig. 15. Mean Zn concentrations  $\pm$  1 st. err.. Soil (S), plant (p) and rodent (r) concentrations are given for each region.

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