Diagnosing a Silent Epidemic:

The Historical Ecology of Metal Pollution in the Sonoran Desert

by

Cyrus M. Hester

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved March 2019 by the
Graduate Supervisory Committee:

Kelli L. Larson, Co-Chair
Manfred D. Laubichler, Co-Chair
Joshua MacFadyen

ARIZONA STATE UNIVERSITY

May 2019

ABSTRACT

This research investigates the biophysical and institutional mechanisms affecting the distribution of metals in the Sonoran Desert of Arizona. To date, a long-term, interdisciplinary perspective on metal pollution in the region has been lacking. To address this gap, I integrated approaches from environmental chemistry, historical geography, and institutional economics to study the history of metal pollution in the desert. First, by analyzing the chemistry embodied in the sequentially-grown spines of long-lived cacti, I created a record of metal pollution that details biogeochemical trends in the desert since the 1980s. These data suggest that metal pollution is not simply a legacy of early industrialization. Instead, I found evidence of recent metal pollution in both the heart of the city and a remote, rural location. To understand how changing land uses may have contributed to this, I next explored the historical geography of industrialization in the desert. After identifying cities and mining districts as hot spots for airborne metals, I used a mixture of historical reports, maps, and memoirs to reconstruct the industrial history of these polluted landscapes. In the process, I identified three key transitions in the energy-metal nexus that drove the redistribution of metals from mineral deposits to urban communities. These transitions coincided with the Columbian exchange, the arrival of the railroads, and the economic restructuring that accompanied World War II. Finally, to determine how legal and political forces may be influencing the fate of metals, I studied the evolution of the rights and duties affecting metals in their various forms. This allowed me to track changes in the institutions regulating metals from the mining laws of the 19th century through their treatment as occupational and public health hazards in the 20th century. In the process, I show how Arizona's environmental and resource institutions were often transformed by extra-territorial concerns. Ultimately, this created an institutional system that compartmentalizes metals and fails to appreciate their capacity to mobilize across legal and biophysical boundaries to accumulate in the environment. Long-term, interdisciplinary perspectives such as this are critical for untangling the complex web of elements and social relations transforming the modern world.

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INTRODUCTION

1.1 The Silent Epidemic

Over two millennia ago, Dioscorides, physician to the Roman emperor Nero, observed that "lead makes the mind give way" (Needleman 2009). His conclusion was not drawn from a robust medical literature or a comprehensive understanding of human physiology. It came from direct experience. Acute metal poisoning was prolific in his world. Epidemics of paralysis, epilepsy, and gastrointestinal pain swept repeatedly through Roman society—whose wine, aqueducts, and cookware were all amended with lead (Pb; Waldron 1973). Other, less obvious, symptoms of severe lead exposure include headache, restlessness, and behavioral abnormalities (Järup 2003). There can be little doubt that Rome's elites, who most often partook in lead-tainted amenities, as well as its miners, suffered from such hardships regularly. Some scholars have even suggested that lead poisoning contributed directly the decline of Roman culture, progressiveness, and intellectuality that precipitated the fall of the empire (Gilfillan 1965).

Metal poisoning is not just a hazard relegated to ancient times (Figure 1). By one estimate, millions of people in the modern world suffer from the effects of chronic metal exposure (Nriagu 1988). These effects often go undiagnosed, in part because their symptoms are typically generic and sub-clinical (i.e., undiagnosable through observation). The delayed onset of symptoms is also problematic. Typically, it takes years for the effects of sub-acute metal poisoning to manifest. Children are particu-

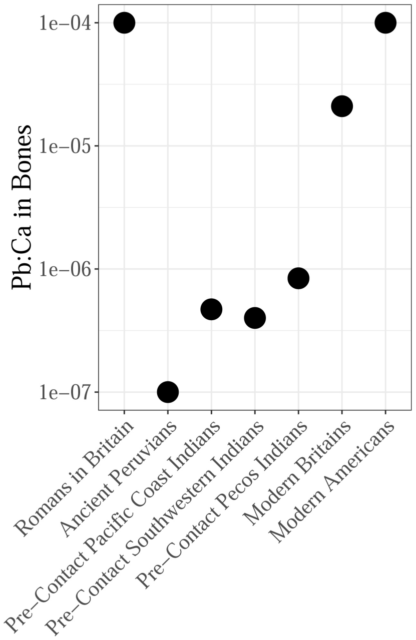

Figure 1: Concentrations of lead relative to calcium in bones from ancient-to-modern humans. Prior to European contact, peoples of the Americas experienced bodily Pb burdens several orders of magnitude less than the citizens of imperial Rome and modern, industrialized nations.

larly at risk due to frequent hand-to-mouth contact, which increases the likelihood of gastrointestinal exposure (Järup 2003). Lead poisoning during childhood can have profound implications for the well-being of individuals and society. Several studies have linked childhood Pb exposure to a propensity for violence and delinquency as an adult (Nevin 2007; Needleman 2009; Mielke and Zahran 2012). Errant behavior, in this case, is encouraged by lead-induced cerebral impairments which undermine one's ability to manage impulses or even learn. And Pb poisoning is not the only metal-borne hazard we face today.

Transition metals—such as copper (Cu), cadmium (Cd), chromium (Cr), and nickel (Ni)—can modify or damage DNA and promote cell death (Gaetke et al. 2014).

This in turn can lead to cancer, cardiovascular diseases, diabetes, chronic inflammation, and the accumulation of arterial plaques. Poisoning from arsenic (As), antimony (Sb), Ni, Cd, or Pb can also impair the reproductive systems of both men and women (Langston 2010). This results in impaired sperm count and function, reduced birth weight and postnatal growth, and an increased risk of spontaneous abortion or perinatal mortality (Nriagu 1988). Iron (Fe), zinc (Zn), and Cu can also induce oxidative stress and protein misfolding, precursors to neurological diseases like Alzheimer's or Parkinson's (Kozlowski et al. 2012, Gaetke et al. 2014). Such maladies not only represent social burdens, but financial ones. The annual cost of health care for neurodegenerative diseases alone is estimated at $200 billion and is expected to surpass a trillion by 2050 (Tejada-Vera 2013).

The cumulative toxicity of all metals released annually into the environment may well exceed the risk posed by all radioactive and organic pollutants combined (Nriagu 1988). The chronic and widespread effects of metal pollution are severe enough for some scholars to refer to the problem as a "silent epidemic" plaguing the modern world (p. 139; Nriagu 1988). Urbanites appear to be particularly at risk, with multiple studies identifying cities as hot-spots for metal pollution (Nriagu 1988, McClain et al. 2003, Grimm et al. 2008). This is all the more concerning given the explosive growth underway in cities worldwide (UNDESA 2015).

Metal pollution is also a local issue with relevance to the health and well-being of Phoenicians. Research on the environmental chemistry of the Phoenix metropolitan area suggests the soils, air, and biota of the region are all burdened by elevated metal concentrations. Prabhakar and colleagues observed that Phoenix's air hosts the highest levels of Cu, Pb, and Zn in southern Arizona (2014). Metals in this case are likely adsorbed onto fine soil particles (e.g., $PM_{2.5}$), whose size increases the likelihood that contaminants will bypass the natural defenses of the bronchi. Given that wind-blown dust in the city hosts elevated concentrations of metals, it should not come as a surprise that the soils and flora tend to as well. By comparing the concentrations of metals in surficial soils to those deeper below, Zhuo concluded that silver (Ag), As, Cd, Cu, Pb, and Zn are all likely to have been anthropogenically-enriched in Phoenix (2010). Meanwhile, Zschau and colleagues compared contemporary lichen with samples taken from botanical archives to determine that conditions appear to be improving for some elements (i.e., Pb is down 71% since the 1970s), but worsening for others (Zn has risen 245% in some places; 2003).

On the matter of metal contamination, Phoenix is not alone. Cities from as varied economic and cultural backgrounds as New York (United States), Delhi (India), Baoji (China), Naples (Italy), Christchurch (New Zealand), Kingston (Jamaica), and London (United Kingdom) all host elevated metal concentrations (Fergusson and Ryan 1984b; Banerjee 2003; Imperato et al. 2003; Lu et al. 2009). Elements commonly found to be enriched by these studies included antimony (Sb), Cd, Cr, Cu, Ni, Pb, and Zn. This dissertation will refer to this characteristic suite of metallic elements simply as "urban metals." But metal contamination is not constrained to the urban environment. In this case, cities are a microcosm of a global phenomenon.

1.2 Sustainability in the Anthropocene

Our understanding of long-term, global trends in the metallic elements owes much to the field of Earth System Science. By investigating the geochemical proxy-records embodied in natural archives (e.g., peat or ice cores), earth scientists have demonstrated that background concentrations of Cd, Cu, Pb, and Zn rose between

3- and 400-fold during the twentieth century (Cole et al. 1990, Headley 1996, Candelone et al. 1995, Shotyk et al. 2002). Even remote environments like Greenland and Antarctica that are far removed from urban and industrial activities have become enriched with metals (Hong et al. 1994, Planchon et al. 2002). The timing, extent, and anthropogenic origins of this global challenge sets the issue of metal pollution squarely within the discursive bounds of the Anthropocene.

The concept of the Anthropocene gained widespread scholarly and public attention after being reintroduced to the Western world by climatologist Paul Crutzen (2002). It refers to a novel, contemporary period in Earth's history epitomized by the substantial anthropogenic perturbation of global biogeochemical processes (Crutzen and Steffen 2003, Steffen et al. 2007, Lewis and Maslin 2015). Prior to the Anthropocene, the cycling of metals operated more or less at a steady state limited by natural rates of weathering (Nriagu 1988). Today, human industry disrupts and transports roughly the same mass of mineralogical materials as all of the Earth's rivers combined (Haff 2010). In the process, the movement of somewhere between a quarter and a half of all the chemical elements has become dominated by anthropogenic influences (Sen and Peucker-Ehrenbrink 2012).

Many of these changes in the Earth System have come about relatively recently. At the beginning of the 20th Century, the average American consumed around two metric tons of resources annually. One hundred years later, that quantity has risen fivefold (Matos and Wagner 1998). Industrial activities, such as mining and metal manufacturing, have transformed as well by focusing increasingly on throughput (Chandler 1990, LeCain 2009). The extraction of Zn, Cu, and Ni rose 4-, 5-, and 35-fold, respectively over the last century (Nriagu 1988). To achieve this rate of extraction, most mines shifted from extracting rich, well-defined ores to diffuse, low-grade deposits that generate significantly more waste (McNeill 2001, LeCain 2009). In one form or another, all of these materials will ultimately end up in the biosphere.

To understand industrial society's demand for the metallic elements, one must be aware of the ubiquity of their uses. A typical, modern building has a galvanized frame (a Zn-Fe alloy), is wired with Cu, and is adorned with stainless steel (Fe, Ni, Cr; Graedel and Cao 2010). If some portion of the building's power supply comes from thin-film photovoltaics, it would demand copper-indium-gallium diselenide solar cells or cadmium telluride cells (Harper et al. 2015). And the devices within that building will also contain a number of metals or their alloys. Modern electronics rely heavily upon Cu for its conductivity (Nassar et al. 2012). Lead-acid batteries are widely used in vehicles and for auxiliary power, while nickel-cadmium batteries are employed in cordless devices and industrial applications (Harper et al. 2015).

Only a handful of metals (i.e., Ag, Cu, Cr, Fe, Ni, Pb, Zn) make up 85% of global annual demand (Graedel and Cao 2010). The intrinsic beneficial attributes of these elements—e.g., their durability, conductivity, and high melting point—are difficult or impossible to reproduce with other materials (Graedel and Cao 2010). This makes simple substitution with less hazardous materials a dubious prescription. The diversity of end uses also means that demand is resilient and that a multitude of different sources can emit metal pollution to the environment. Given the critical role that metals play in modern society, their nonrenewable nature, and the inherent risks posed by their (mis)use, metal pollution must be recognized as among the foremost sustainability challenges of our time.

Sustainability in this context refers to an inclusive philosophy that believes in the inter-dependence of humans with their environment and aspires to remedy maladaptive facets of that relationship (Holling 2001, Kates et al. 2001, Caradonna 2014). It is defined by a core set of grand and persistent problems which demand an integrative approach to understand the complex dynamics of socioecological systems (Kates et al. 2001, Clark 2007). Many of the problems that feature prominently in the sustainability community are at their core a conflict between the biosphere's tendency toward homeostasis and modern society's goal of maximum production (Odum 1969). Take these examples: over-harvesting consumes resources faster than they can regenerate, nutrient loading alters the carrying capacity of algae (producing harmful blooms), and fossil fuel emissions introduce carbon faster than the oceans can absorb it.

Metal pollution—and toxins, in general—are a different type of problem. They result from an inherent conflict between the chemistry of the ancient world, to which our genome is adapted, and that of the modern, which we have created (Eaton et al. 2002, Fox 2018). Metal-induced diseases are predominately epigenetic, resulting from environmental signals that trigger changes in genomic expression (Arita and Costa 2009, Zawia et al. 2009, Bakulski et al. 2012, Smeester et al. 2014). Moreover, some genes function differently in developing versus industrialized contexts, where allele expression confers disease risk only in populations experiencing the latter setting. For instance, the $\varepsilon 4$ allele is associated with a significantly increased risk for contracting Alzheimer's disease in Americans across a wide spectrum of ethnic and racial backgrounds. Yet this same allele shows no association with neurodegeneration among elders from numerous Bantu, Nilotic, and Arabic populations living in preindustrial settings (Fox 2018). In other words, metal-incited diseases are an emergent phenomenon that result from the interaction of a geochemical environment with a complex genetic inheritance of the exposed population. It is a function of the coevolution of our biology and the planet. A process where the interactions between individuals, our immediate surroundings, and planetary phenomena redefine the nature of each. Such features are characteristic of complex systems, suggesting that the growing field of complexity science should inform our approach to the issue.

1.3 Complexity and the Study of Industrial Metabolism

Complex systems often resist solutions that have proven to be effective in simpler situations. In large part, this is due to the interconnected and responsive nature of a complex system's components. For instance, societies can craft institutions that alter the organization of individuals within that society and how they generally respond to their environment (North 1990, Renn and Laubichler 2017). Such regulatory networks can promote stability or even intransigence in a system (Laubichler and Renn 2015). Yet these same systems are also capable of unexpected and relatively swift change. This includes transitioning to alternative stable states which resist efforts to restore them (i.e., hysteresis; Scheffer 2009). Case in point, early life exposure to metals can alter the expression of genes which, in turn, can lead to maladaptive protein synthesis and eventually late stage neurodegeneration (Zawia et al. 2009). Because of their evolutionary character, research on complex systems requires observations across time and of sufficient duration to permit the expression of slow- and fast-reacting components (Eidelson 1997, Fisher et al. 2009). For this reason, history and scale matter a great deal in complex systems.

The sustainability of complex systems depends on their ability to anticipate and adapt to changes in the environment. This is a significant undertaking for co-evolving systems—like those shaping our physiology, behaviors, and environment (Eidelson 1997). This task is made all the more challenging by rapid rates of change. And by all indications we are transforming the world around us faster than we can understand the implications (Vitousek et al. 1997, Steffen et al. 2004). Hence, the need for urgent research on the drivers of change in the Earth System and particularly for cases like metal pollution, which not only undermine our well-being but also our adaptive capacity. Given the scale and duration of such problems, a comprehensive investigation is implausible. Nevertheless, significant insights can be gleaned by studying representative cases using a well-crafted research approach. Here we can make use of the observation that cities appear to be acting as a microcosm of global change and focus on the urbanization of a symptomatic landscape (Grimm et al. 2008). Given the evidence previously discussed from Phoenix, the northern Sonoran Desert exhibits all indications of a fruitful study area. And the study of its long-term evolution may be made tractable through the use of a socioecological framework: industrial metabolism.

As an intellectual paradigm, industrial metabolism rose in prominence following the Enlightenment's celebration of logic and reductionism. The widespread and effective use of metabolic paradigms today owes much to the work of renowned biochemist, Justus von Liebig. Liebig viewed organisms and their environments as the emergent properties of chemical processes which circulate, transform, and exchange matter (Smith 2006, Swyngedouw 2006). From this perspective, the atmosphere, lithosphere, hydrosphere, and biosphere are all historically-contingent, dynamic, and co-evolving processes. And all living organisms depend upon material and energetic exchanges with those biogeochemical systems to resist the tendency of all physical systems toward maximum entropy (i.e., death; Williams and Da Silva 2006).

Recently, the circulatory facets of metabolism have been adopted as a framework for the analysis of sociotechnical systems, including cities. Haberl and colleagues succinctly define this "functionalist" approach to metabolism: "socioeconomic metabolism refers to the material, substance or energy throughput of socioeconomic systems, i.e. all the biophysical resources required for production, consumption, trade and transportation" (p. 29; 2013). The functionalist view likens cities to organisms that consume organic and mineral resources and release wastes back into the biosphere. This approach has offered profound insights particularly with respect to longitudinal and international trends in consumption and waste (Grimm et al. 2008, Graedel and Cao 2010, Fischer-Kowalski et al. 2014). As systems grow in complexity—be they ecosystems, economies, or nation-states—they require greater quantities of information, energy, and materials just to maintain their current functions (Mill 1885, Odum 1969, Tainter 1988). Infrastructure requires regular maintenance, institutions must be enforced, laborers need to be trained, and capital must be serviced. A functionalist account helps us to understand why the developed world uses ten times the global average of metals, but also why nations that use an excess of any one metal are likely to demand more of all metals (Graedel and Cao 2010).

In practice, functionalist views on industrial metabolism tend to emphasize the natural history of cities, with much of the agency in the system attributed to society. But there is another conceptualization of metabolism that warrants attention. The "dialectical" view follows Karl Marx's assertion that social and ecological processes are mutually constitutive and, hence, co-evolving phenomenon (Smith 2006). That is, changing the environment changes who we are and how we relate to one another. The nexus of this co-evolution, from Marx's perspective, is the socially- and politically-structured act of labor. The dialectical school of metabolism thus focuses on the social and political disparities inherent in the division of labor, rather than emphasizing the movement of matter or energy (Gandy 2004). It is concerned foremost with observing the historical, geographical, and experiential epiphenomena that lead to social, spatial, and cultural disparities (Braun 2005, Heynen et al. 2006). At the landscape scale, this approach emphasizes how cities and their rural surroundings shape one another (e.g., Cronon 1991). This intuition extends to more distant, telecoupled systems, as well (Liu et al. 2013).

1.4 The Path Ahead

Despite the utility of both the functionalist and dialectical views on industrial metabolism, the two have rarely, if ever, been integrated. This has fostered a number of gaps in the research on long-term socioecological change and the Anthropocene. Foremost, the co-dependence of the social, biological, and physical worlds as they have developed over time is rarely made explicit (Palsson et al. 2013). New technologies, for instance, not only change the way we interact with the world, but how we understand it (Dyson 2012, Renn 2015). And changes to our built and natural environments often create challenges for the next generation to solve—sometimes with new technologies, other times with new institutions (Norgaard 2006).

Secondly, we must connect individual experiences with the dynamics of the broader world (Palsson et al. 2013). The Anthropocene is not, after all, a product of human biology or consensus among nations. Epistemological and ideological divides have been integral to the resulting ecological crises, including prolific metal contamination (Malm and Hornborg 2014). The institutions and markets that structure the dynamics of metal pollution are not separate from the politics that have crafted them. Since we inherit much of our material and cultural world, their political nature is often shrouded by time. This is yet another justification for a long-term perspective on the historical ecology of industrial metabolism in the region.

Historical ecology studies the co-evolution of social and natural processes as they manifest in the landscape (Crumley 1994). Put another way, landscapes are the material expression of that co-evolution. Central to the work of historical ecology is a diversity of perspectives. Changes in socioecological systems are rarely driven solely by the natural forces. Rather, they are more often a patchwork manifested from generations of human agency, biophysical phenomena, and the unexpected (Fisher et al. 2009). Here the synthesis of observations from widely varying sources (e.g., ice cores, personal testimonies, maps) is often fruitful (Crumley 1994). Hence, this study will integrate findings from paleoecological, geographical, and institutional approaches to understand how temporal, spatial, and political forces have shaped the modern, metal-laden landscape. I will now briefly summarize each of these approaches, which are detailed in the chapters to follow.

The first objective is to understand how metal concentrations in the Sonoran Desert have changed over time. Chapter 2 addresses this matter by analyzing the chemistry incorporated into the spines of long-lived cacti, which are indicative of changes in the landscapes they inhabit. This novel paleoecological approach reveals that urban metal pollution is not simply a product of early industrialization in the Desert. Contemporary sources, and fossil fuel combustion in particular, continue to enrich both urban and rural landscapes despite a host of environmental regulations limiting the release of metals.

The second task is to not only investigate the distribution of potential sources, but to understand how they got there. Chapter 3 takes up this matter, dealing specifically with the "energy-economy-environment dilemma" (p. 424; Holdren 2008).

This refers to the seemingly paradoxical proposition that cheap, reliable energy is critical for human well-being, while the system that develops and provisions that energy is one of the main culprits inducing social and environmental harm. To research this matter, a functionalist view is taken and the material evolution of the northern Sonoran Desert is discussed using a historical geographic approach. Archival research and geospatial methods support a historical narrative around the social and material construction of urban space. In particular, it focuses on the causes of metal-dependent urban land uses and how this shaped and was affected by exchanges with other locales.

The final objective of this research is to assess the role of institutions and State politics in the industrialization of the Desert. Chapter 4 integrates a discursive study of legal consciousness (Merry 1992) with a categorical analysis of property rights (e.g., Libecap 1978). It focusses specifically on the sectors of mining, manufacturing, and public health. To understand how these issues have been institutionalized over time, I conducted a content analysis of State legislative records. Specific attention is given to the years when the most legislative effort was directed toward industrial development and pollution control, as indicated by a text mining analysis. In my analysis and the historical narrative it inspired, the dialectical view is privileged. Institutions are understood to have a significant effect on our identities, practices, and landscapes. Moreover, these same factors reciprocate and influence how rules and customs are implemented. This informs our understanding of how and when the Sonoran Desert industrialized and why metal pollution remains a modern hazard.

As this introductory chapter has served to illustrate, metals are persistent and potentially-toxic compounds that can undermine the health and well-being of our communities and the biosphere. Hence, research on the social and biogeochemical factors driving urban metal pollution is a critical prerequisite for sustainability in the Anthropocene. If we aspire to leave healthy, prosperous, and just environments for future generations, we first must address the toxins—and the sources of those toxins—burdening the present. The following chapters provide the elements for a historical ecology of metal pollution in the Sonoran Desert. Throughout, this research aspires to learn from the past in order to set a course toward a safer, healthier future. It represents an important, albeit small, step toward that end.

Chapter 2

LONG-TERM TRENDS IN URBAN AND RURAL METAL CONCENTRATIONS AS INDICATED BY THE SPINES OF LONG-LIVED CACTI (*CARNEGIEA GIGANTEA*)

2.1 Introduction

Research on long-term socionatural change often relies upon insights gleaned from natural archives—environmental processes which incorporate ambient biogeochemical conditions into temporally-stratified, natural features (Shotyk 1996). Several decades of such research has demonstrated the insights that can be provided by analyzing snow and ice deposits (e.g., Hong et al. 1994, 2004; Eichler et al. 2012, 2014), peat formations (e.g., Lee and Tallis 1973, Shotyk 1996, Marx et al. 2010, Bao et al. 2015), lake sediments (e.g., Goldberg et al. 1981, Thomas et al. 1984, Di Leonardo et al. 2006, Mahler et al. 2006, Zaborska et al. 2017), and in some cases tree rings (e.g., Sheppard et al. 2007, MacDonald et al. 2011, Cui et al. 2013). A common finding of such studies is that a significant global rise (between a 3- and 400-fold) in Cd, Cu, Pb, and Zn concentrations accompanied industrialization and peaked around the 1960s (e.g., Cole et al. 1990, Headley 1996, Boutron et al. 1991, Candelone et al. 1995, Shotyk et al. 2002, Mahler et al. 2006, Eichler et al. 2014). This trend is consistent with estimates of metal emissions in the northern hemisphere, which reached their zenith in the decades following World War II (McNeill 2001).

Yet global trends can obscur spatial heterogeneities which can facilitate source attribution. Case in point, sediment cores collected across the United States showed that urban lakes were enriched in Cr, Cu, and Zn by two orders of magnitude over rural waterbodies (Mahler et al. 2006). While the researchers concluded that metal pollution rates in America have generally been declining since the 1970s, urban-industrial activities have clearly had a mitigating effect on this trend. And American cities are not unique in this regard. Urban-industrial settings across the globe have been found to host elevated levels of Cd, Cr, Cu, Pb, Sb, and Zn (Fergusson and Ryan 1984, Banerjee 2003, Charlesworth et al. 2003, Imperato et al. 2003, Lu et al. 2009). Such findings have inspired urban ecologists and epidemiologists to characterize cities as "hot spots" of trace metal pollution (Nriagu 1988, McClain et al. 2003, Grimm et al. 2008). Yet, we know remarkably little about the timing of urban metal pollution or what past events could explain the geochemical similarities observed between such disparate locales as London, Delhi, Christchurch, New York, and Phoenix (Fergusson and Ryan 1984, Banerjee 2003, Zhuo 2010). In part this is because suitable natural archives are rarely found in highly-modified environments, like cities, or are lacking altogether from certain regions (e.g., arid deserts).

The sequentially-grown spines of columnar cacti have previously been shown to be capable of providing a detailed record of seasonal-to-annual precipitation patterns (English et al. 2007; 2010a, b). Meanwhile, other research suggests long-lived saguaro cacti (*Carnegiea gigantea*) grown on metal-enriched soils tend to exhibit higher metal concentrations in their parenchyma and chlorenchyma tissue (Kolberg and Lajtha 1997). This indicates that saguaro accumulate metals from the soil and may incorporate them into external structures (i.e., spines) which can be temporally-sequenced. Yet, to my knowledge, no study to date has evaluated the potential for saguaro to act as natural archives of metal pollution, which is the principal focus here. If this approach is demonstrated to be effective, it could offer valuable insights on human-environment interactions in the Sonoran Desert—a region known for its rich biodiversity, industrial history, and fervent urbanization.

2.2 Study Area and History

The Sonoran Desert spans 260,000 km^2 of the Lower Colorado River Valley and is typified by extreme heat, drought, and a subtle basin topography interrupted by steep ranges of exposed bedrock. Summer air temperatures here can exceed 49 °C and some locations have experienced upwards of 36 months without rain (Phillips and Comus 2000). Rainfall is typically biannual with widespread, mild showers common from December-March and sudden deluges accompanying the summer monsoon between July-September. The ecology of the region is well-adapted to such extremes. Botanically, it is dominated by drought-tolerant shrubs, leguminous trees, and columnar cacti.

Metallic mining and agriculture were the principle economic activities of the region following the arrival of the Spanish, and later Americans (Sheridan 2012). Silver ores dominated early mining concerns, but by 1907 Arizona had become the leading producer of copper (Sheridan 2012). World War II then encouraged further industrialization. Defense, electronics, and aerospace manufacturing became integral parts of the state economy (Nash 1990). Wartime manufacturing relied upon the metallic elements heavily—principally Al, Cu, Fe, Mg, Ni, and Zn (Nash 1990, McNeill 2001). Several military bases and bombing ranges were also established in remote areas of the desert during this era.

After the War, Arizona became a hub for hi-tech manufacturing, predominately located in the Phoenix metropolitan area (Sheridan 2012). But, by the 1970s, manu-

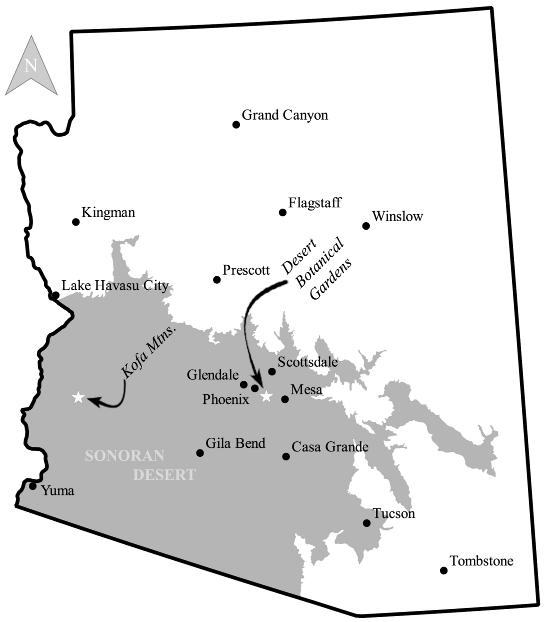

Figure 2: Sample locations within the Sonoran Desert of Arizona, USA. Prominent cities and towns have been included for orientation purposes.

facturing began to move abroad. Economically, it was compensated for by growth in the professional services and construction sectors (Shermer 2013). With the exception of the Great Recession (c.a., 2007-9), Arizona's urban population and footprint has grown steadily ever since. Much of this growth has also been concentrated in the Phoenix metropolitan area.

This project focused on two sites in the northern Sonoran Desert, which are part of several long-term monitoring initiatives by the Desert Botanical Gardens, the University of Arizona, and Arizona State University (Figure 2). The first site is located in the heart of the Phoenix metropolitan area on an unirrigated parcel of the Desert Botanical Gardens (henceforth, the urban or "URB" site). Geologically, the site is characterized by porphyritic granite of Precambrian origin (Péwé et al. 1986, AGS 2000). It is also the wetter of the two study locations, frequently receiving around

2.39 mm during the winter rainy season and 6.41 mm with the summer monsoon (Arizona Meteorological Network 2018). Saguaro inhabiting this environment grow relatively faster here as a result of the additional precipitation.

The second study site is located on the remote, western-side of the Kofa Mountains National Wildlife Refuge (henceforth, the rural or "RUR" site). The sampled cactus is established on a Quaternary deposit of sand and gravel directly downhill from outcroppings of Late Jurassic Conglomerate (AGS 2000). Median total rainfall between December-March is 1.41 mm, while the summer monsoons tend to bring around twice that amount (i.e., 2.86 mm; Arizona Meteorological Network 2018). Air temperatures are comparable between the Kofa Mountains and Desert Botanical Garden, with annual averages of 21.9 °C and 22.4 °C at the urban and rural sites, respectively.

2.3 Methods

2.3.1 Sample Collection and Preparation

In December 2017, a sequentially-grown (i.e., height-ordered) series of spines were collected from saguaro of similar heights (approximately 4 m tall) at each study site. Both cacti were established atop loose pediment sloping off adjacent bedrock outcroppings with a generally southern exposure. At each location, the uppermost 2.7 m of spines grown along a single pleat (i.e., rib) were sampled from one individual. Spine clusters produced from individual areoles were collected from the upper- and lower-most 25 rows of each cactus. For those rows occurring in-between, spines were composite sampled in groups of ten. This permitted an analysis of the entire vertical profile of each cactus, albeit at different temporal resolutions. Samples were collected with ceramic shears and stored in 15 mL "metal free" polypropylene centrifuge tubes, to limit the risk of contamination. Depositional materials were later removed from all samples via two rounds of sonicated rinsing in ultrapure (18.2MΩ) water. Samples were dried at 70 °C for three days and ground to a powder-like texture in a liquid nitrogen ball mill to ensure homogeneity. Ground samples were then split for inorganic and light isotope analyses.

2.3.2 Determining Spine Ages

Unlike tree rings or fish otoliths, saguaro spines do not produce visually-detectable chronological markers. Fortunately, acanthochronologists have shown that isotopic measurements offer an effective substitute for tracking the passage of time (English et al. 2007; 2010a, b). In our study, post-bomb, carbon-14 dating ($F^{14}C$) of the oldest spine collected at each site was used to approximate the start date of each series (Reimer et al. 2004). We also measured carbon isotope values ($\delta^{13}C$) for each of the 100 individually-sampled spines. Because $\delta^{13}C$ values oscillate with physiological changes in the cacti coinciding with precipitation events, this periodicity enabled us to approximately delineate annual time-steps (English et al. 2007).

Isotopic measurements were performed at the University of Arizona Accelerator Mass Spectrometry Laboratory and followed the methods described by English and colleagues (2010a). Spine $\delta^{13}C$ values were determined using a Thermal Combustion Elemental Analyzer and CHN elemental analyzer, integrated with continuous flow isotope mass spectrometers. Materials from the oldest spines (n = 2) were dried overnight at 70 °C and subjected to three rounds of ultrasonic rinsing (in 0.1 M

HCl) and soaking (in Milli-Q water). Rinsed samples were dried and reduced to graphite, then measured for $F^{14}C$ (Slota et al. 1987). Using line blank and carbon-13 corrected radiocarbon values, we estimated the probable start date of each series with the program Calibomb (Reimer et al. 2004).

2.3.3 Measuring Elemental Concentrations

The remaining powdered materials underwent microwave digestion (EPA Method 3052X-XPRESS) in a multi-acid mixture of 9 mL trace metal grade HNO_3, 1 mL trace metal grade HCl, and 1mL Optima grade HF acids. Digested samples were taken to near-dryness on hot plates in a Class 10 laminar air-flow exhaust hood and diluted in a weakly-acidic solution (2% HNO_3) for analysis by inductively-coupled plasma mass spectrometry (ICP-MS). All sample preparation occurred in a dedicated trace metal clean environment.

Blanks and certified reference standards (NIST 1575, pine needles) were randomly distributed among each batch of samples. Samples were analyzed on a Thermo Finnegan iCAP Q with KED mode for a suite of 65 trace elements. Here I focus specifically on those metals traditionally associated with urban and industrial activities (i.e., Ag, As, Cd, Cr, Cu, Ni, Pb, Sb, V, Zn). With the exception of Ag, As, and Pb, all concentrations fell between the limit of detection and the maximum concentration measured in our standards. For Ag (1%), As (3%), and Pb (6%), only a small minority of observations fell outside these limits.

2.4 Results and Discussion

2.4.1 Chronology

The results of the $F^{14}C$ analyses indicated a start date between September 1983 and February 1986 for the rural series and between September 1994 and March 1997 for the urban series. These dates were used as a benchmark for approximating the age of the oldest samples in each series, which was further informed by regional precipitation patterns. By matching the $\delta^{13}C$ values of our samples with shifts in precipitation, I was able to delineate annual breaks patterns in the data (Fig. 3). However, it's important to note that $\delta^{13}C$ oscillations were less pronounced here than in previous studies (e.g., English et al. 2007), thus making the effort more challenging. While the sequence of the samples is not in question and the start date of each series is reasonably established by our radiocarbon analyses, the date of any one sample should be considered a best approximation.

2.4.2 Metal Concentrations and Enrichment Factors

For every metal analyzed, with the exception of Ag, average concentrations in the urban environment were consistently greater than in the rural setting. In the case of As, Cd, Cu, Ni, Pb, Sb, and Zn, this difference was statistically significant (Table 1, Fig. Such a finding is consistent with a number of other biogeochemical assessments conducted in the Phoenix area, as well as in other cities (e.g., Fergusson and Ryan 1984, Charlesworth et al. 2003, Zschau et al. 2003, Zhuo 2010, Prabhakar

Table 1: Metal concentrations measured in urban and rural saguaro spines dated from 1985 to 2016. Distance (cm) refers to the length from the apical meristem to the row sampled.

Site	Dist. (cm)	Year	Concentration (ppb)										
			Al	V	Ag	As	Cd	Cr	Cu	Ni	Pb	Sb	Zn
RUR	284-277	1985-1986	1126852 (±581691.6)	2130.4 (±1099.3)	59.5 (±30.6)	42.3 (±32.2)	48.0 (±15.0)	12476.9 (±7250.9)	3647.6 (±1334.8)	1142.8 (±581.6)	2025.7 (±881.4)	90.6 (±52.2)	4933.4 (±1704.2)
	275-263	1987-1989	1595506 (±345763.9)	2648.7 (±502.6)	73.7 (±15.8)	52.6 (±21.6)	48.04 (±11.6)	10056.4 (±4285.8)	3788.8 (±663.1)	1260.6 (±320.7)	2371.5 (±522.8)	103.4 (±24.0)	5697.9 (±947.2)
	261-243	1990-1992	1159565 (±476368.3)	1890.3 (±700.6)	53.8 (±18.1)	51.5 (±28.2)	52.8 (±38.7)	8834.3 (±4478.4)	3213.4 (±1079.3)	1037.7 (±386.6)	1781.0 (±467.0)	84.8 (±29.1)	5548.4 (±2958.3)
	242-235	1993-1995	1113341 (±436422.4)	1804.8 (±677.0)	55 (±19.6)	39.8 (±20.0)	42.6 (±10.7)	7210.6 (±3401.2)	3125.0 (±748.4)	993.0 (±278.4)	1668.0 (±371.4)	85.2 (±22.3)	4582.4 (±1348.9)
	198-177	1996-1998	840668.3 (±294513.5)	1344.8 (±395.1)	42.7 (±17.0)	17.7 (±9.6)	35.6 (±3.7)	4440.7 (±969.7)	2300.3 (±701.3)	742.5 (±177.6)	1294.4 (±183.3)	79.3 (±34.5)	3864.3 (±809.1)
	175-137	1999-2001	190723.3	405.5	11	88	27.6	1606.8	1166.5	310.888	862.2	22.2	2112.4
	134-98	2002-2004	216445.9 (±54789.78)	448.7 (±72.4)	49.5 (±23.3)	93.5 (±4.9)	34.8 (±1.6)	3050.4 (±30.8)	1282.4 (±29.6)	416.7(±15.8)	1072.1 (±111.6)	54.7 (±22.3)	2863.2 (±18.4)
	82-67	2005-2007	224358.7 (±49537.26)	453.8 (±188.8)	47 (±35.4)	103 (±12.7)	32.6 (±9.8)	7154.7 (±5225.8)	1588.4 (±362.8)	572.4 (±245.1)	1323.3 (±495.7)	100.9 (±0.31)	3470.5 (±1844.8)
	65-41	2008-2010	95151.75 (±98159.25)	185.4 (±97.9)	91.7 (±38.1)	62.5 (±25.7)	27.0 (±6.0)	3732.4 (±1999.3)	5501.1 (±10874.5)	583.6 (±593.6)	638.9 (±249.4)	73.0 (±34.7)	2893.2 (±1342.2)
	40-28	2011-2013	27375.82 (±16382.73)	98.3 (±35.2)	90.9 (±31.7)	56.1 (±33.2)	44.5 (±60.0)	3626.7 (±1612.8)	1138.7 (±673.1)	565.9 (±379.8)	647.3 (±369.2)	42.4 (±26.2)	5515.6 (±7798.4)
	26-7	2014-2016	22595.44 (±16625.22)	88.9 (±39.1)	55.3 (±37.1)	51.5 (±27.9)	25.5 (±24.4)	3321.7 (±2464.4)	645.5 (±341.7)	802.4 (±1002.3)	243.0 (±162.2)	30.6 (±23.2)	2734.3 (±3148.4)
URB	278-250	1992-1994	1887977 (±2402658)	3378.0 (±4311.0)	63.4 (±32.3)	42.8 (±33.4)	229.8 (±280.4)	12588.5 (±15729.5)	27103.3 (±34194.2)	3501.186 (±4506.7)	9292.6 (±11963.2)	656.2 (±776.2)	54547.3 (±68333.4)
	249-222	1995-1997	2326562 (±5503124)	3801.446 (±8383.7)	63 (±34.0)	56.9 (±46.0)	240.3 (±454.2)	20208.6 (±44670.9)	27244.6 (±44425.6)	6934.0 (±11555.8)	9404.7 (±17471.2)	799.4 (±1631.5)	61379.31(±118294.6)
	221-165	1998-2000	2159877 (±3073665)	3562.398 (±5046.2)	39.3 (±20.1)	46.3 (±59.9)	316.3 (±415.5)	17583.1 (±24456.0)	26537.2 (±36112.4)	4292.0 (±6065.0)	11203.1 (±15229.5)	668.0 (±890.3)	79801.6(±106508.2)
	163-118	2001-2003	183543.9 (±81359.48)	521.217 (±106.6)	56 (±7)	70.7 (±59.0)	91.4 (±6.1)	2953.2 (±242.1)	9768.0 (±1887.4)	2396.2 (±2580.8)	3015.8 (±126.0)	386.5 (±140.8)	22444.6 (±3543.5)
	116-68	2004-2006	96886.44 (±48262.31)	348.8752 (±113.2)	16.3 (±5.9)	93.7 (±8.0)	66.3 (±15.0)	2773.6 (±505.7)	6642.2 (±1541.4)	716.7 (±245.4)	1780.6 (±500.8)	183.9 (±26.8)	15481.5 (±3438.7)
	66-38	2007-2009	67717.24 (±30437.63)	262.4673 (±103.4)	59.1 (±47.7)	88.4 (±17.8)	39.6 (±10.7)	6474.8 (±3489.7)	3873.2 (±1162.1)	766.5 (±398.5)	1178.8 (±453.8)	197.6 (±131.9)	9814.3 (±2158.6)
	37-22	2010-2012	37946.55 (±53382.02)	127.9203 (±132.7)	57.1 (±52.5)	83.9 (±30.3)	30.8 (±34.3)	4313.4 (±5680.3)	2241.6 (±2265.3)	1352.5 (±2444.6)	478.2 (±405.1)	71.8 (±60.6)	6480.6 (±7435.8)
	19-6	2013-2015	40615.17 (±44717.74)	226.3652 (±161.7)	74.3 (±43.1)	103.1 (±14.2)	25.7 (±27.6)	5634.1 (±5444.9)	2081.6 (±1249.0)	906.7 (±846.0)	589.5 (±918.5)	123.8 (±78.8)	3791.0 (±2758.1)
RUR		1984-2016	6.25e5 (±6.7e5)	1829.14 (± 4242.594)	64..0 (±31.7)	53.8 (±29.1)	39.4 (±30.2)	6 188.0 (±4 521.3)	2 542.4 (±3584.4)	848.5 (±598.9)	1 205.3 (±830.5)	67.95 (±37.5)	4 311.4 (±3 550.7)
URB		1992-2015	1.02e6 (±2.6e6)	1070.0 (± 1082.905)	59.1 (±38.7)	68.8 (±39.1)	138.0 (±256.3)	9 953.0 (±19 867.5)	15 034.1 (±27 752.7)	2 822.6 (±5 476.9)	5 140.7 (±10 313.8)	418.67 (±793.1)	33 286.9 (±64798.9)
t			1.1576	1.3638	-0.76421	2.4124	3.0094	1.4536	3.514	2.8207	2.9945	3.478	3.5155
p			0.251	0.177	0.446	0.017	0.004	0.151	0.0008	0.006	0.004	0.001	0.001

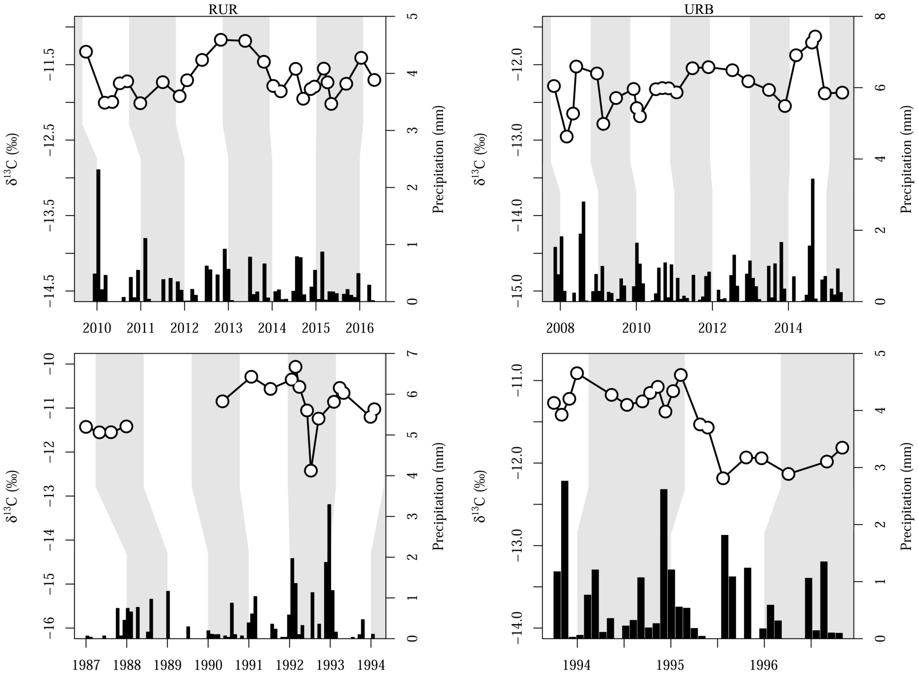

Figure 3: Trends in precipitation and δ^{13}C used to approximate the age of individual saguaro spines collected for the rural (left column) and urban sites (right column).

et al. 2014). For the remaining discussion, I will concentrate on the analysis of this suite of significantly-enriched, urban metals.

In an effort to mitigate for the natural variability that exists between sites (e.g., lithospheric age, bedrock mineralogy), researchers have traditionally calculated crustal enrichment factors (e.g., Hong et al. 1994, Shotyk 1996, Espi et al. 1997, Shotyk et al. 2002, Cortizas et al. 2002, Planchon et al. 2002, Monna et al. 2004). Crustal enrichment factors attempt to control for such variability by using observations of a conservative element whose fate can be reasonably expected to be the product of non-anthropogenic forces (e.g., Al, Sc; Shotyk 1996, Shotyk et al. 1996, Planchon et al. 2002, Sen and Peucker-Ehrenbrink 2012). I follow several other studies in normalizing the concentrations of metals observed in saguaro spines to the

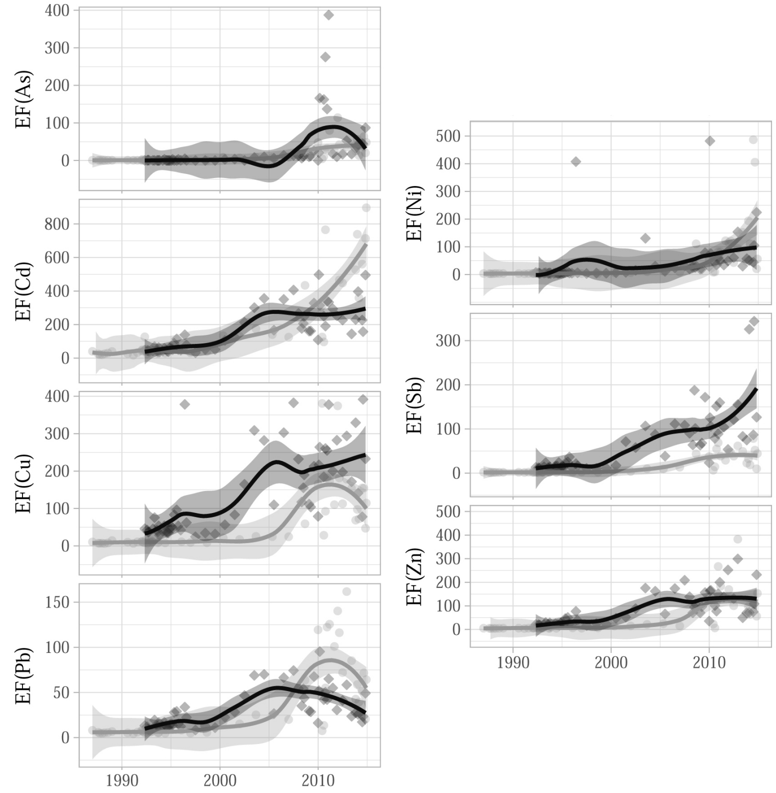

Figure 4: Trends in crustal enrichment factors for selected metals as measured in the spines of saguaro cacti inhabiting urban (dark gray) and rural (light gray) environments.

ratio of metals and Al measured in bedrock (Planchon et al. 2002, Shotyk 1996, Espi et al. 1997). Specifically, enrichment factors (EF) are calculated here as:

$$\frac{M_s/Al_s}{M_c/Al_c}$$

Where, M is the metal of interest, s refers to the concentration observed in saguaro spines, and c denotes the average concentration in local bedrock, as determined by Zhuo (2010). Figure 4 illustrates the trends in urban and rural enrichment factors as indicated by my samples.

Baseline enrichment factors (i.e., those prior to 2000 in the urban samples and 2005 in the rural) indicate that both sites host greater concentrations of some metals than one might expect based on local bedrock chemistry (Table 2). With the exception of As and possibly rural Sb, mean enrichment factors for the earliest records are all significantly greater than one, which may be evidence of past pollution. In the case of Cu, Pb, Sb, and Zn—where older urban samples host higher concentrations than their rural counterparts—it seems quite likely that legacy contamination is a factor. Given the industrial history of the Phoenix metropolitan area, such a finding is to be expected. Yet, clearly, whatever legacy effects are being observed in the saguaro chemistry, they pale in comparison to contemporary enrichment trends. Most metals studied here increase by an order-of-magnitude over the course of recent time (Table 2). Several of these metals (i.e., As, Cd, Ni) are classified as hazardous air pollutants by the U.S. Environmental Protection Agency.

In hopes of understanding the drivers behind recent trends, I turn now to the patterns of enrichment at both sites. At the urban site, saguaro spines exhibit remarkably similar temporal patterns for Cd, Cu, Pb, and Zn (Fig 4). Concentrations of all four metals rose between 2000-2005, at which time levels stabilized or, in the case of Pb, began to decline. On average, metal enrichment factors after this period are 3-5 times greater than previously observed. The timing and logistic appearance of this multi-element trend also bears a striking resemblance to Arizona's real GDP, which rose steadily from the late 1990s until the global financial crisis c.a. 2008 (USBEA 2018). While not conclusive, it suggests that urban emissions of Cd, Cu, Pb, and Zn may be externalities which are more tightly coupled to economic activity than is the case for other metals.

Shifting focus to Sb, urban enrichment levels also began to rise around the turn of the century, but show no evidence of stabilizing by the end of the record. In the end, Sb levels are 7-fold greater on average than previously observed. This pattern is quite different than the case of urban As. Arsenic enrichment factors remained low for most of the record, spiking only once for what appears to be a prolonged episode around 2005. While evidently a temporary phenomenon, average As levels during this episode were a staggering 83-times greater than baseline observations.

Meanwhile, aside from a few extreme episodes, Ni levels remained more-or-less stable for most of the recent past. But, somewhere between 2005-2010, Ni concentrations began to climb at both sites. By the end, urban Ni concentrations are 3-times those initially observed; while at the rural site Ni concentrations increase 27-fold over a relatively short period at the end of the record. A remarkably similar pattern is observed for rural Cd which increases by two-orders of magnitude over the course of a decade (Fig 4). This finding is generally consistent with an analysis of sediment geochemistry from Sonora (Mexico), which determined that Cd enrichment factors were several orders of magnitude greater than could be expected under natural circumstances (Eliseo Ochoa-Valenzuela et al. 2009). Although noteworthy because both studies were conducted in the western Sonoran Desert, the distance between sites (650km) makes a common source seem unlikely. Rather, these findings merely suggest that Cd trends in the region deserve additional attention.

While the rural enrichment factors of other metals exhibit a concurrent increase, none are as extreme as Cd. As a result, I will remark only briefly on them here. Between 2005-2016, the Pb (9x), Cu (13x), Sb (18x), Zn (35x) and As (38x) rural enrichment factors all rose. But, only in the case of Cd, Pb, and Ni do rural enrichment factors exceed those of the urban environment. It is interesting to note the lack of differences between urban and rural enrichment factors for the other metals in the most recent years. At the end of the record, only Cu, Sb, and Zn levels differ markedly between sites. Despite a history of urban enrichment for As, Pb, and Ni, recent enrichment levels are quite similar to those at the rural site. Critically, my findings indicate that this is the product of pollution at the rural site, not an improvement in the urban environment. Spatially-distributed sampling across an urban-to-rural gradient, a common design for urban geochemical studies, would have been unable to make such as distinction. This illustrates the merits of spatiotemporal research designs in general, whether they rely upon natural archives or active, long-term monitoring.

2.4.3 Agreement with Observations at Active Monitoring Sites

Because of the novelty of this approach and the uncertainty inherent in our dating results, it was essential that I evaluate the resulting trends in light of independent observations of metal concentrations in the region. To do so, I compared the enrichment factors of Cu, Pb, and Zn derived from saguaro spines with metal concentrations measured at regional air monitoring sites. Aerosol chemistry data were acquired from the Interagency Monitoring of Protected Visual Environments network (IMPROVE; Malm et al. 1994). The aerosol monitoring stations used for reference here are located in the Phoenix metropolitan area and Organ Pipe Cactus National Monument. These stations collect 24-hr ambient air samples every third day and use a combination of X-ray fluorescence (XRF) and particle-induced X-ray emission (PIXE) to determine the constituents of each sample (Prabhakar et al. 2014).

I calculated the monthly averages for metals in aerosol samples since 2007 and compared them to the enrichment factors determined from saguaro spines using a first-differenced linear regression with mean-normalized variables. A positive, linear

Table 2: Crustal enrichment factors for metals in urban and rural settings of the Sonoran Desert. The enrichment factors from several studies analyzing peat cores in various other locations are included for reference.

Source	Location	Year	Enrichment Factors						
			As	Cd	Cu	Ni	Pb	Sb	Zn
This Study	RUR	1984-1989	0.6(±0.3)	34.6(±13.2)	10.1(±3.7)	3.9(±1.1)	6.5(±1.5)	1.8(±0.5)	5.4(±1.2)
		1990-1994	0.8(±0.6)	42.5(±25.5)	10.1(±2.3)	4.0(±1.0)	6.3(±1.5)	1.9(±0.4)	6.3(±2.5)
		1995-1999	0.4(±0.1)	41.5(±11.5)	9.7(±1.2)	3.9(±0.4)	6.3(±1.7)	2.3(±0.3)	6.3(±0.9)
		2000-2004	8.0(±1.1)	145.8(±24.9)	21.3(±4.1)	8.0(±2.0)	19.3(±5.2)	5.5(±3.8)	17.0(±3.7)
		2005-2009	11.0(±4.7)	232.9(±174.0)	36.1(±19.9)	44.1(±57.9)	36.2(±23.8)	22.2(±18.7)	40.8(±36.6)
		2010-2016	52.4(±69.0)	1,501.8(±2,072.0)	146.9(±86.6)	114.7(±112.2)	68.4(±42.7)	39.7(±17.8)	248.5(±385.9)
	URB	1992-1994	0.5(±0.7)	47.8(±9.7)	43.1(±10.5)	5.0(±1.0)	12.8(±2.8)	13.6(±4.1)	21.2(±3.9)
		1995-1999	0.9(±1.7)	66.6(±38.5)	95.5(±139.1)	72.0(±164.3)	16.8(±9.6)	13.9(±4.2)	33.3(±22.8)
		2000-2004	4.8(±3.8)	220.0(±108.7)	179.0(±113.7)	38.0(±52.6)	47.3(±22.1)	68.1(±33.8)	68.1(±60.5)
		2005-2009	12.6(±5.6)	247.1(±88.6)	191.8(±93.4)	29.4(±48.1)	48.1(±17.8)	100.3(±47.8)	118.4(±48.9)
		2010-2015	84.6(±105.3)	376.6(±439.6)	224.1(±94.3)	91.0(±109.2)	42.4(±19.8)	126.2(±84.1)	131.9(±75.6)
Shotyk et al. (2002)	Jura Mtns., Switzerland	10,000BC- 2002AD	14.9(±3.2)	357.4(±53.8)	8.8(±1.3)	—	4.0	4.8(±1.4)	4.1(±1.4)
Cole et al. (1990)	Indiana Dunes, USA	1400-1978	—	23.1	78.3	20.8	94.4	—	262.3
Kamenov et al. (2009)	Florida marsh, USA	1989-2009	—	191	80	6.2	145	109	77

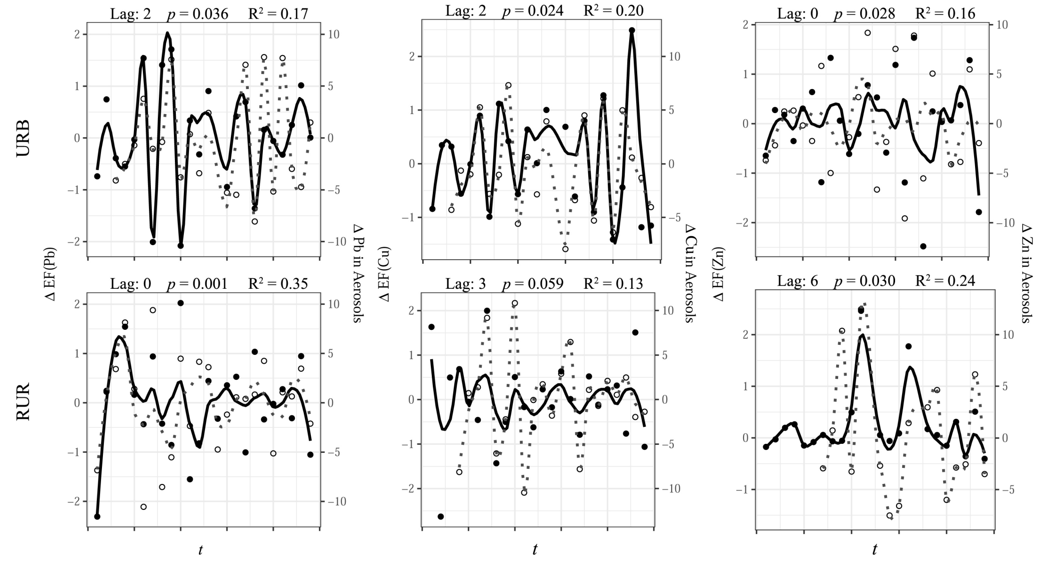

Figure 5: Changes in metal concentrations in aerosols measured at regional air quality monitoring sites compared to changes in metal enrichment factors estimated from saguaro spines. Regression summary statistics are provided in the margin above each plot.

relationship ($0.32 \leq \beta \leq 0.62$) was estimated for each case (Fig. 5; Tbl. S3.). That is to say, changes in the concentration of metals in particulate matter were largely reflected by changes in saguaro spine chemistry, albeit with varying periods of delay (i.e., lags from 0-6 time steps; Fig. 5).

However, a note of caution is warranted. The relatively small sample size (n = 24) available in this case meant that regression performance was occasionally susceptible to the influence of outliers. Two observations at each site exhibited such extreme values in either the air or saguaro chemistry that they compromised the assumption of normality underlying the regression. Removing these outliers improved results and, most importantly, resulted in models that met the assumptions of linear regression. Table cludes additional details on this process.

2.4.4 Source Categorization

Historically, inventories of metal emissions have concluded that certain elements or combinations can be indicative of a specific category of sources. For instance, fossil fuel emissions, specifically oil combustion, account for nearly all anthropogenic Ni (90%) and V (100%) emissions (Pringle and Jervis 1987, Pacyna and Pacyna 2001). Comparing the trends in concentrations of my focal metals and V suggests that fuel oils may be a major source for urban Cu, Cd, Pb, Sb, and Zn (Fig. 6). This is consistent with previous research in Phoenix which attributed a significant share of fine particulate emissions to local combustion sources (Upadhyay et al. 2011). It also appears that oil combustion could explain some of the changes in urban Ni concentrations. But, clearly there are observations of Ni which do not follow changes in V and presumably indicate additional sources, be they anthropogenic or otherwise (Fig. 6).

In contrast, there appears to be no direct relationship between metals and V in the rural ecosystem. Similarly, though not depicted here, trends in urban As and V show no obvious relationship. The source of these metals remains unclear. But, there are a number of military bombing ranges within 100km of the rural site. Despite its remote location, it is possible that emissions from munitions could be contributing to the metal enrichment trends seen at this locale. Unfortunately, my data are unable to distinguish munitions-based emissions from other potential sources. So, the cause of metal pollution at the rural site remains for future investigations to evaluate.

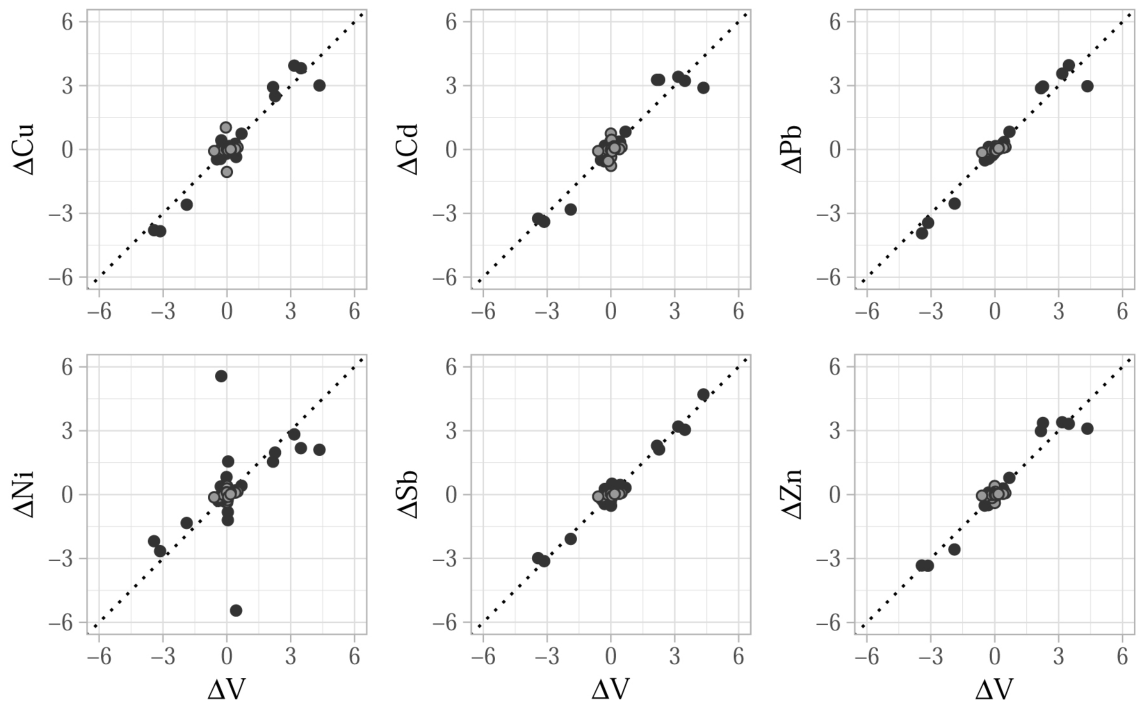

Figure 6: Changes in metal concentrations relative to changes in vanadium for saguaro spines from urban (black) and rural (gray) cacti. In both cases, first-differenced observations have been mean-normalized to focus on relative degrees of change.

2.5 Conclusion

My findings suggest that urban-industrial activities have contributed significantly to the enrichment of metals in the Sonoran Desert, a conclusion similar to those reached in studies leveraging natural archives to understand other environments (e.g., Shotyk 1996, Espi et al. 1997, Olid et al. 2010, Pratte et al. 2013). For a number of metals, observed concentrations reached upwards of 200-times above what would be expected from natural processes (Tbl. 2). But, more surprising is the evidence that remote, undeveloped environments are also being enriched with potentially-toxic metals. In both cases, it appears that this is predominately a contemporary phenomenon, not simply a legacy of unregulated industrialization in Arizona's past.

Of course, there are a number of important limitations to this work which should be addressed by future studies. First and foremost, the conclusions presented here are based upon long-term proxy records derived from only two cacti. While it demonstrates the potential for saguaro to act as natural archives of biogeochemical change, additional sites and individuals should be incorporated into future research. Here it would be wise to include observations from co-located cacti to determine within site and individual-level variability. Adding other sample locations, meanwhile, may assist with source attribution efforts, while also indicating how generalizable these findings may be (e.g., if other rural settings are experiencing similar enrichment patterns). A second area warranting research involves the relationship between atmospheric deposition and spine chemistry. Specifically, it remains unclear how quickly or consistently changes in local geochemistry are incorporated into saguaro spines. Tracer studies subject to various soil and weather conditions could go a long way toward addressing such uncertainty. Such research could also help justify, or reconsider, the lags used in this study (Fig. 4).

Clearly more work is needed before these findings should be considered generalizable or actionable. Yet, the magnitude of changes implied herein, which may be reshaping the biogeochemical conditions of both cities and far more remote parts of the Sonoran Desert, suggests that such research should proceed directly.

Chapter 3

METALS AND THE HISTORICAL GEOGRAPHY OF INDUSTRIALIZATION IN THE SONORAN DESERT

3.1 Introduction

This chapter addresses the role of conflict and consumerism in producing the modern, metal-laden spaces of the Sonoran Desert. Adopting the concept of the "hazardscape," I explore how material geographies of risk—manifested in the potential for exposure to potentially-toxic metals—were produced and transformed over generations through social and biogeochemical processes (Mustafa 2005, Collins 2009, Bolin et al. 2013). The notion of hazardscapes follows an established line of inquiry in geography and political ecology concerned with the mechanisms that link social transformation to changes in the structure, function, and meaning of place (e.g., Smith 1990, Heynen et al. 2006).

The physical disposition of place, combined with its capacity to shape our sense of belonging and identity, ascribes to it both social and natural characteristics (Harner 2001). Place is where supranational and hyperlocal movements intersect with personal agency, where biogeochemical processes are mediated by social histories and vice versa. As a culturally-delineated matrix of places, landscapes play a leading role in advancing our understanding of how such spaces are produced and transformed. They are assemblages defined by physical, ecological, infrastructural, and institutional forces—all of which shape their productivity or potential to harm (e.g., Cronon 1983). In an era of widespread concern over the social and environmental changes unfolding around us, we might benefit from a critical examination of the socioecological transitions that shaped the landscapes of the present.

Historical geography has demonstrated an ability to advance our understanding of landscape change by integrating abstract, philosophical critiques of culture (e.g., capitalist production of space) with grounded, empirical investigations into specific cases. For example, Winiwarter and colleagues have shown how the maximization of usable energy under industrialization reshaped the structure and function of the Danube River Basin (2013). As a result, the modern Danube is home to a network of energy-dense arrangements that subject local communities to the persistent threat of flooding. In the same vein, Güldner and others demonstrated that highly-disruptive industries (e.g., gunpowder manufacturing) can alter the biogeochemical foundations of a landscape, thereby limiting the land use opportunities for future generations (2016). Similar findings have been found by disturbance ecologists, who have shown that landscapes often retain the biophysical figerprints of extreme events (e.g., Thompson et al. 2002). The tendency of certain landscape features to persist or evolve depends upon how the socionatural forces at play structure the circulation of matter, energy, and information (Heynen et al. 2006). Put succinctly, metabolic processes reflect the socioecological production of landscapes at work.

In this context, metabolism refers to the throughput of "all the biophysical resources required for [the] production, consumption, trade, and transportation" supporting (or impairing) the growth and maintenance of land uses over time (pg. 29; Haberl et al. 2013). Under the modern development paradigm, much of the collective political and economic will has been directed toward maximizing the metabolic potential of landscapes by manipulating their biophysical properties (Haberl et al. 2013). The same political economy that promotes this intensification of land uses has also linked disparate landscapes through trade, price signals, and technology (e.g., infrastructure; Liu et al. 2013). This telecoupling of land uses means that landscape histories must be situated within a broader context of regional-to-global trends. For instance, the evolution of American agriculture cannot be adequately understood without an appreciation for the parallel changes that took place in the Nation's cities and the transportation technologies that coupled their fates (e.g., Cronon 1991). So too I argue is the case for the Sonoran Desert, where landscapes of extraction, conflict, and reincorporation can only be integrated into a broader understanding of space by appreciation how each generation responded to the material and energetic constraints of their time.

One of the foremost social dilemmas facing the modern world emerges from the implications of two widely-held but incongruous beliefs about the energy system at the heart of industrial metabolism. First, that providing for basic human needs and economic prosperity depends upon access to reliable and affordable sources of energy. Second, the physical means by which this energy is acquired and provisioned is often at the heart of the worst socio-ecological problems. Collectively, this dilemma is referred to as the "energy-economy-environment" or *3E* dilemma (Holdren 2008). The modern world has tended to address such problems with technological and managerial innovations that emphasize efficiency and control (Chandler 1990, Norgaard 2006). To the extent that these imply new material and organizational demands, we might ask whether we are treating the symptoms of the 3E dilemma with the same logic that produced it (Malm 2016)? More specifically, have the material arrangements (i.e., uses of metals) adopted to maximize the productivity of industrial landscapes produced modern hazards that undermine the well-being of these same spaces?

The metallic elements provide us with the means to explore the geographic implications of the 3E dilemma. Their intimate link to modern energy regimes allows for a study of changing and competing land uses. Meanwhile their non-degradable nature presents an extreme case for understanding inter-generational effects on the landscape. This persistence means that their present distribution is a product of both natural processes and the decisions made by previous generations. Metals are symptomatic of each generation's socio-technical development and offer an alternative biogeochemical frame by which to view the production of space. In that spirit, this chapter considers how social, physical, and organic phenomenon shaped the movement of metals across the landscapes of the Sonoran Desert. Specifically, I ask: how has the industrial use of metals affected our demand for energy and how has our demand for energy affected our use of metals? And most importantly, how has this co-evolution constructed and transformed the landscapes of the Sonoran Desert to shape the modern distribution of risk for metal exposure?

The Desert is an opportune setting for the study of the energy-metal nexus. Thanks to its geological history it is endowed with numerous metals, which enables one to track the implications of society's demand for a greater quantity and diversity of resources. Moreover, the region industrialized in a relatively short and recent period of time. As a result, much of the process has been documented in newspapers, memoirs, and maps over the past two centuries.

The analysis that follows relied upon a mixed methods approach. The mapping and modeling of geospatial resources provided a quantitative perspective. This permitted the identification of contemporary hot-spots for metal pollution, which corresponded to the region's centers for mining, manufacturing, and urbanization. To understand how these landscapes were experienced and transformed by each generation, I also explored numerous historical accounts. This included the memoirs and oral histories of tribal members, early miners, explorers, and public health inspectors. The result of this line of inquiry is presented in the following section as a historical narrative. Methodological details can be found in the notes appended to the end of this document.

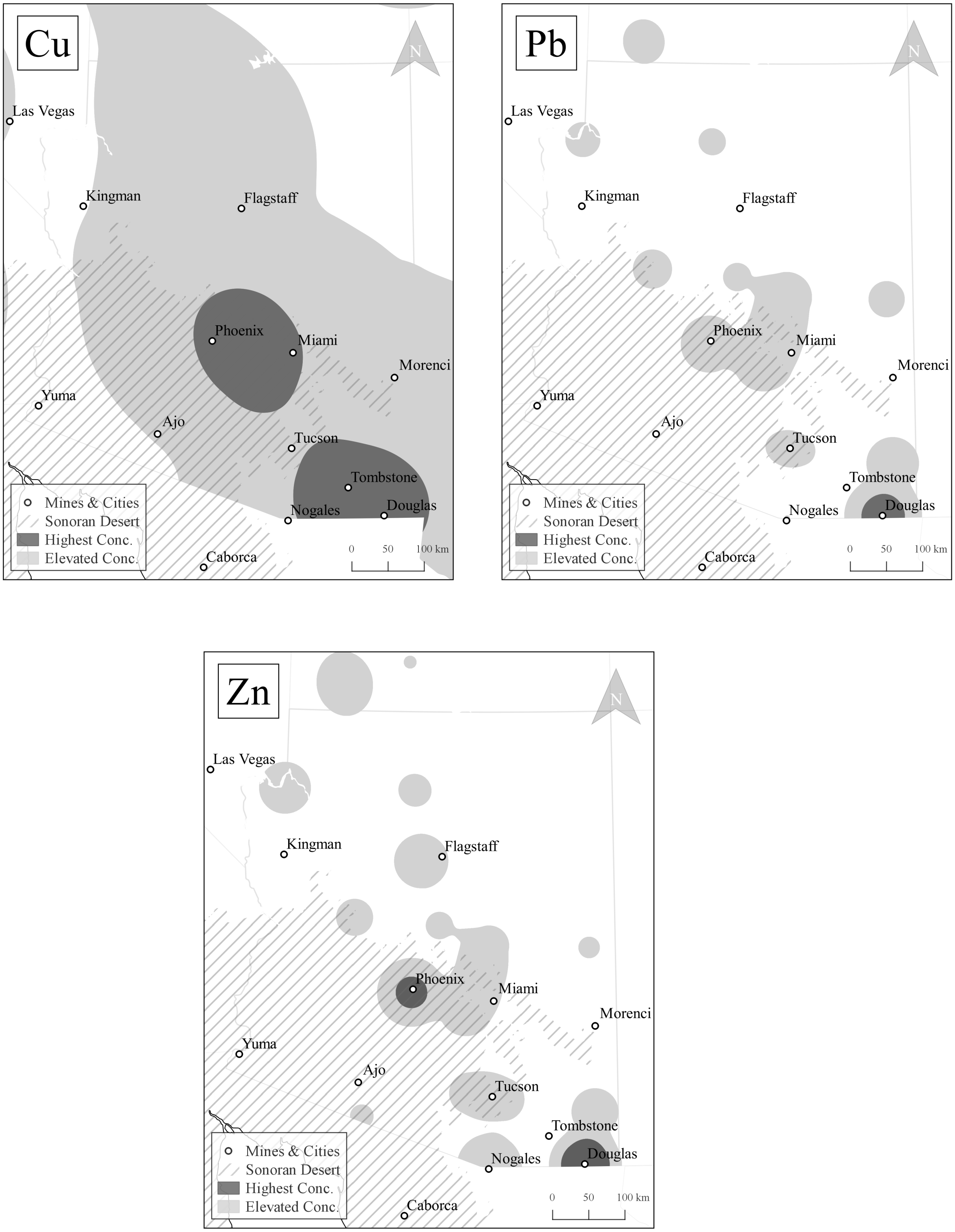

Figure 7: The contemporary distribution of elevated concentrations of copper, lead, and zinc in aerosols of the Sonoran Desert. These hot-spots overlap with the major mining districts and cities in the region, suggesting a need to explore the urban-industrial history of these places.[1]

3.2 The Historical Geography of Industrialization

3.2.1 Precious Metals and the Territorialization of the Desert

Prior to European settlement, the energy and mineral regimes of the Sonoran Desert were weakly coupled at best. Energy was provided by manual labor and the combustion of botanical matter. Both were constrained by the primary productivity of arid landscapes. The use of the metallic elements, meanwhile, was limited to ornamental purposes (e.g., copper bells, body painting; Sheridan 2012, Briggs 2016). Among some native peoples there were even taboos against mining. The Apache, for instance, went so far as to name gold the "forbidden ore" since they were customarily barred from digging it up (Ball 1980). Even when a community did not hold a stigma against what the European's called the "precious" metals (e.g., silver, gold), the elements were generally too soft for most practical uses. This lack of interest did not imply a lack of insight. Tribes showed remarkable ingenuity when a material was useful. For instance, Apache warriors were known to craft bullets from the partially oxidized wastes of mine furnaces. These bullets contained copper and lead mixed with sulfur and arsenic, resulting in horrific wounds (Pumpelly 1870). What distinguished Native Nations' valuation of metals from that of Europeans was the latter's decision to construct a political and economic empire from an exchange economy underwritten by silver and gold. The economic activity of Europe relied upon access to metals defined by, and valued for, their scarcity.

In 1583, driven by their hunger for precious metals, the Spanish Espejo expedition ventured north into the Sonoran Desert and discovered silver and copper deposits near present-day Jerome (Sheridan 2012). One of the first European ex-

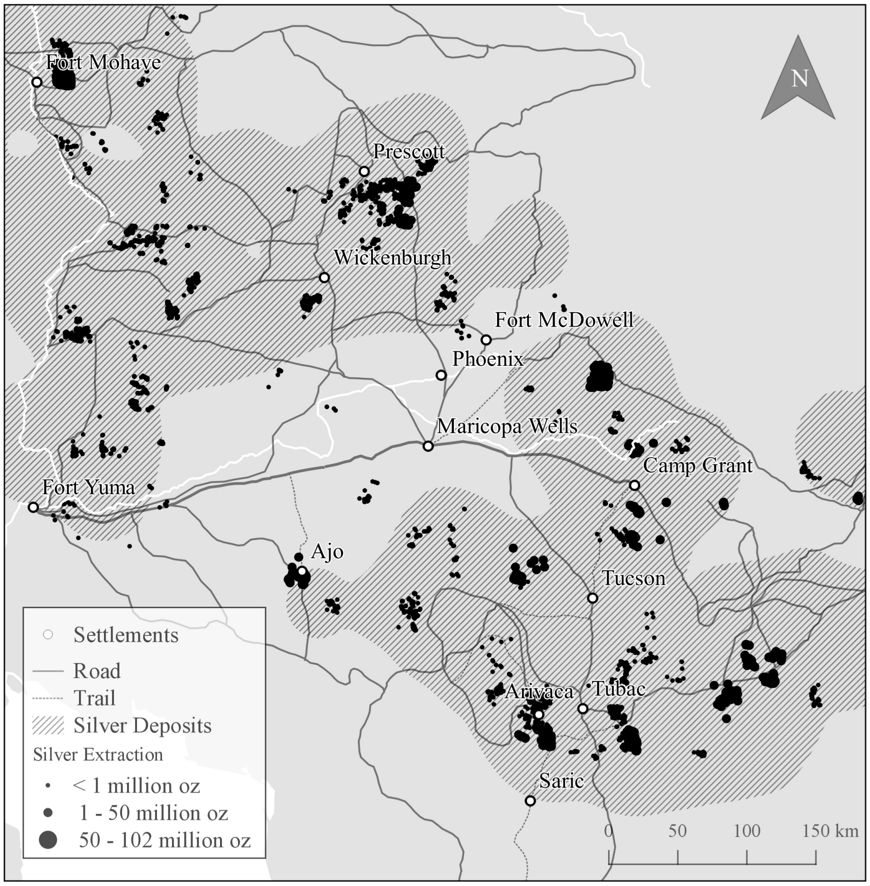

Figure 8: Transportation routes, silver mining districts, and settlements of the Sonoran Desert established by the territorial period (c.a. 1854-1870). Natural characteristics, namely the accessibility of water and precious metal deposits, heavily influenced the colonization of the Desert and had a far greater influence on the movement of goods and people than the geopolitical boundaries of the period (e.g., the U.S.-Mexico Border). While the rush for precious metals was relatively short-lived, the transportation network depicted here provided a foundation for the route of the railroads and public highways to follow.[2]

peditions in the region, it combined many of the ingredients that would re-emerge throughout the industrial experience: metals, the military, and the capacity of infrastructure to concentrate development. The earliest infrastructure came in the form of religious establishments, such as the missions at Sonoyta and Tucson. These missions served as bases of operation for Spanish prospectors who made many of the discoveries that would later inspire American explorers (Poston 1894, Briggs 2016). New Spain produced half of all precious metals mined in the Americas during the sixteenth to eighteenth centuries and forty-percent of the global supply of silver, although much of this bounty appears to have come from the mining districts of central Mexico (Studnicki-Gizbert and Schecter 2010). There is little evidence of widespread mineral extraction in the Sonoran Desert before 1736, when a Yaqui Indian found silver near the ranch of a local Basque elite. The name of the ranch was Arizona, or "the good oak tree" in Basque (Sheridan 2012). This discovery incited the first Sonoran mineral rush.

The Spanish military was quickly dispatched to assert the Crown's claim to metal deposits (Sheridan 2012). Tithing precious metals to the royal treasury was a common expectation of New Spain's government (Studnicki-Gizbert and Schecter 2010). Spanish authorities constructed *presidios* (i.e., military settlements) near rich mineral deposits throughout the Desert in order to suppress violence and enforce their authority (Sheridan 2012). This police action came to a close, however, when the Mexican Revolution ignited in 1810. The Spanish abandoned their fortifications in the Desert, implicitly returning authority to its original inhabitants. Mexico won its independence from Spanish rule only after eleven long years of conflict. The costs of war left the country bankrupt and devastated the silver industry (Sheridan 2012). Its military and economy were in no shape to fight another war when tensions ignited with the United States over the annexation of Texas.

A year after the cessation of hostilities with the U.S., and mere weeks before the peace treaty was signed between the two nations, gold was discovered in California. As prospectors and capitalists flocked to the Pacific state, the northern Sonoran Desert transferred into American control under the Treaty of Guadalupe Hidalgo (Briggs 2016). The American government was principally concerned with charting the route for a transcontinental railroad, while many of its citizens were keenly aware of the Spanish accounts of mineral wealth in the territory (Poston 1894, Sheridan 2012). As it happened the two interests became one in the desert north of the Sonoran mission at Sonoyta. In 1853, American railroad surveyors were led to a rich mineral deposit by their Native guide (Briggs 2016). When these surveyors reached San Francisco, they incorporated the Arizona Mining and Trading Company and shortly thereafter returned to the parched landscape of Ajo to lay their claim. Three years later, a party led by the future Arizonan statesman, Charles D. Poston, arrived at the old presidio of Tubac and began to develop the silver deposits of the Santa Rita and Arivaca Mountains (Fig. 8; Browne 1864).

Despite their productivity, transportation and energy resources severely limited early Spanish and American mining ventures. Coal deposits were not known to exist within 200-300 miles of the mine sites, forcing miners to rely on fuel-wood for power (Pumpelly 1870). Local timber, especially mesquite and oak, were used to make charcoal that powered the stamp mills and smelters (Pumpelly 1870, Taylor 2008). Unable to acquire or maintain sufficient livestock to power six-horse wagons, silver miners were forced to haul wood by hand. This, plus the time needed to burn charcoal, meant that it could take three weeks of fuel preparation before smelting could get underway. Smelting, meanwhile, required an additional six weeks and separating the silver out of the resulting lead slabs took another fifty-sixty hours (Pumpelly 1870). All told, it took upwards to two and a half months to produce a marketable product from mined ore—which then had to be transported to a purchaser.

Shipping challenges represented a second major constraint on precious metal extraction. There were four principle means by which to reach the Sonoran Desert during this era (Fig. 8; Pumpelly 1870). The first followed the overland mail route west from the terminus of the railroad in Missouri for twenty-plus days by horse (Browne 1864). In emergencies (e.g., for carrying a presidential message) riding through the night could reduce the trip to sixteen days. Thus, information concerning circumstances beyond the local area (e.g., commodity prices) could be received once or twice a month, at best. The second option, was traversing the 1,000+ miles from ports on the Texas coast. Some of the first mining equipment, including boilers and heavy engines weighing upwards of 6,000 pounds, had to be carried by wagons along this route (Browne 1864, Pumpelly 1870). The third route was westward to Fort Yuma on the Colorado River. As steam travel along the river became more common later in the century, this route saw more traffic (Sheridan 2012). But initially the best roads were south through Sonora, the fourth and final option. Guaymas, a port town on the Gulf of California, was 400 miles southwest of the main silver mines. Between three and four million dollars in precious metals were shipped each year to Europe from the Sonoran Desert through Guaymas (*Daily Alta California* 1857). For base metal operations, like the copper mines at Ajo, it only made sense to ship the richest samples of high-grade cuprite and native copper (Briggs 2016). This inspired slow and selective approaches to early extraction.

Transportation and energy constraints were too great for many early mining ventures in the Desert to persist. Ajo operations ceased by 1859 due to insufficient flux, coke, or charcoal to permit smelting (Briggs 2016). Settlements also struggled to find sustainable sources of fuel. They relied heavily on local vegetation for home heating and cooking. And, like the mines, they quickly denuded the landscapes around them (Studnicki-Gizbert and Schecter 2010). This inspired one of the earliest cases of international shipping: the mesquite trade between Sonora, Mexico and the settlements around Tucson (Taylor 2008).

As if these logistical challenges were not enough, there was also an ever-present security concern in the region. Hostilities between the Americans and Apache presented a third barrier to early industrialization (Browne 1864). Mining settlements and ranches were common targets for raids and miners were particularly vulnerable because the light of smelters revealed their presence at night (Pumpelly 1870, Robinson and Altshuler 1984). While political tensions and harassment by the U.S. forces certainly inflamed the issue, some early observers speculated that incompatible uses of the land put the Apache and Americans on a collision course (e.g., Pumpelly 1870). Energy-intensive land uses (e.g., grazing, mining) displaced game, and those who relied upon it, from the most productive habitats. Mobile, hunter-gathers were forced to subsist in poorer habitats where resources were more-readily exhausted. Apache often turned to raiding as a means to secure valuable goods, including weapons and horses (Ball 1980). Each nation appear to have found the resource practices of the other abhorrent.

Yet a purely ecological explanation for the wars between America and Native America falls short of the empirical reality. Political as much as environmental forces drove efforts to conquer the Sonoran Desert. Among the most insidious drivers was the myth circulating among the Americans that the richest ores were found in the immediate vicinity of Native settlements. Some even believed that massive columns of pure silver were hidden within the Apache's strongholds (Pumpelly 1870). Between 1865-1891, there were over 1,000 violent engagements between the United States military and the Native Nations of the West. Native Americans fell at twice the rate of American soldiers (Wyckoff 2014). Much as the Spanish *presidios* that preceded them, American military installations secured transportation routes and critical resources while serving as a beacon for colonization (Fig. 8).

Mineral exploration, conflict, and resource exhaustion characterized America's entrance into the region. In the process, the young nation gained control of the vast metal deposits of the Sonoran Desert. With the territory secured militarily, all that remained was to remove the last shackles on industrial development: the Desert's constraints on fuel and freight.

3.2.2 Base Metals and the Industrial Metabolism of War

In 1867, miners from the small camp of Wickenburg, south of Prescott, relocated to the Salt River Valley and established Phoenix (Luckingham 1981). For the better part of a century, Phoenix was an agricultural center thanks to its proximity to the Salt and Verde Rivers. Unlike the hills that surround it, the Salt River Valley was not naturally endowed with metals (Figs. 8, 9). For Phoenix to become a hot-spot for metals, industry had to mobilize and incorporate them into the area. This process began a decade after Phoenix's founding with the arrival of the Southern Pacific Railroad. The railroad establishing a rapid overland connection to global markets and became the taproot of industrialization in the Sonoran Desert. (Sheridan 2012)

In 1882, the Longfellow copper mine near Morenci constructed a narrow-gauge

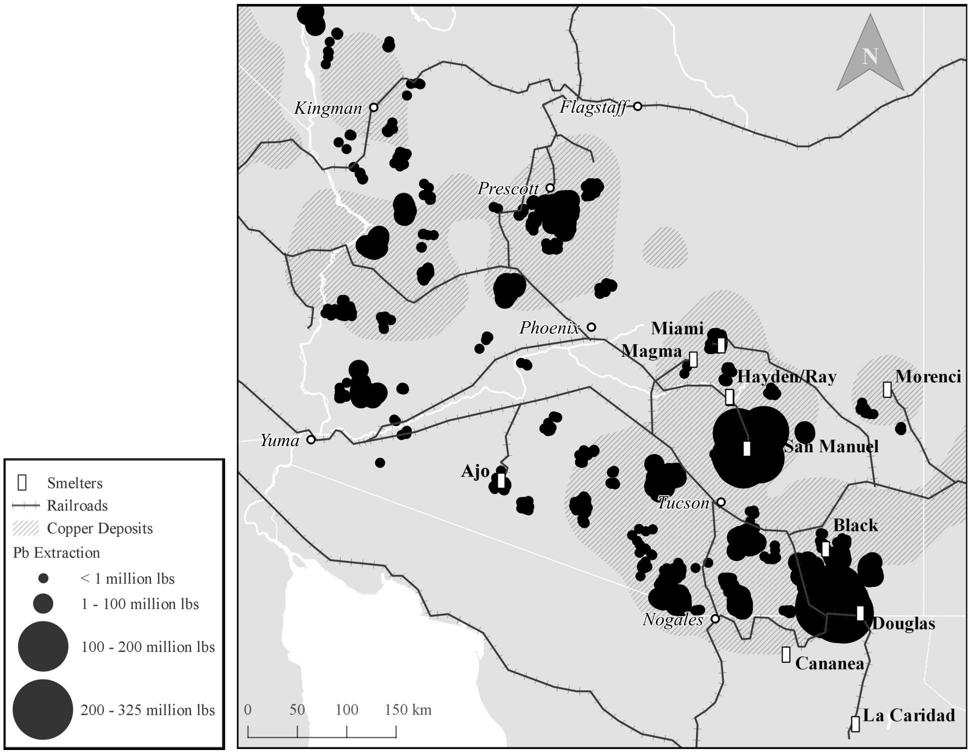

Figure 9: Copper deposits, smelter locations, lead production statistics, and railroad infrastructure in the Sonoran Desert (1858-1981). High-capacity, high-throughput mining and smelting depended on the railroads to bring in fossil fuels, while also hauling the smelted metals to eastern markets. Metal pollution was particularly severe in the vicinity of smelters, the capital- and energy-intensive means by which metals are liberated from their mineral matrix (i.e., ore). Mine and smelter wastes would have contained copper and lead alongside other co-occurring metals (e.g., zinc, arsenic). [3]

railline to New Mexico. The dedicated rail service enabled the miners to export twenty tons of copper and import thirty-two tons of coke each day (Sheridan 2012). It also allowed them to abandon charcoal, a move that nearly doubled the productivity of their smelters (from 8,000 to 15,000 lbs/day; Rickard 1987). The days of being rate-limited by fuel were over for the Longfellow operation and other mines quickly followed.

Phelps Dodge began to acquire the mines around Douglas in the mid-1880s. The Company invested heavily in railroad acquisition and development, as well. In 1889, it financed a rail-line from Douglas to meet the Southern Pacific spur west of Tombstone (Fig. 9; Sheridan 2012. Five years later it built another line to undercut price hikes by the Santa Fe line. Later, it built yet another route from its smelter in Douglas directly to El Paso. This close connection with the railroad allowed the mines and smelters around Douglas to be one of the leading producers of copper and lead in the history of the Desert (Fig. 9). It remains a hot-spot for lead over a century later (Fig. 7).

Between 1880-1920, no fewer than forty-six railroads snaked out from the two transcontinental lines that crossed Arizona (Sheridan 2012). By the time Arizona achieved statehood, it was home to 1,678 miles of track—much of which led to and from the state's mining districts (Fig. 9). The mines, railroads, and workforce grew to depend on one another in system defined foremost by its parasitism. The mines needed the rails to ship and receive freight and fuel, while the railroad needed the mines to earn money hauling ore. When the mines lost money shipping ore, they made up for it by extracting wealth from their own workforce in the company store (Sheridan 2012).

With the mineral-powered railroad, metal extraction rates were less often constrained by energy supplies. Underground mines were instead limited by the rate at which they could bring ore to the surface for processing, dictated foremost by their hoisting capacity (Park Jr. 1968). The solution they found was to bring the surface to the ore. In 1910, John Greenway came to the abandoned mine at Ajo hoping to adapt the open-pit methods of Daniel Jackling to the Sonoran Desert (LeCain 2009, Briggs 2016). The first miners at Ajo had sorted the richest copper by hand, now a mere two percent copper distributed over forty million tons of rock could fetch a profit (Briggs 2016). Open pit methods succeeded by expending massive amounts of energy in the blasting, hauling, grinding, and concentration of earth. Industrial mines could deal with ninety-eight percent of a deposit being waste because the high rate of throughput allowed them to capture and concentrate marketable quantities of metal. Half a century later, a meager half a percent of copper defined an economically-viable deposit, if it happened to be located near the surface (Park Jr. 1968).

Metal prices rarely reflect the falling grade of deposits. Rather, their cost is driven by the energy spent in their extraction and production (Park Jr. 1968). With the high throughput potential of open-pit mines serviced by dedicated railroads, metal production shifted from being supply-constrained to demand-limited. During the twentieth century, a price fluctuation of one to two cents in the value of lead or copper determined whether a business was profitable or not (Park Jr. 1968).

Electrification ensured that this demand remained high. Power stations employed heavy copper wires to transmit energy across vast distances (LeCain 2009). As power lines, telephone lines, and electric streetcars connected an urbanizing America, Arizona's copper industry boomed. Electrification also transformed how mining and metal-manufacturing was conducted. Electrolytic refining produced cheaper and higher-grade products. Between 1880-1914, electricity demand for metal production rose from nearly nothing to upwards of nine million horsepower (LeCain 2009).

At its peak in 1929, Arizona copper mines were generating $155 million in sales and employing 16,000 people (Sheridan 2012). Arizona alone met half the copper demand of the Nation that year. Most of this metal came from the "Big Four" districts near Douglas, Miami, Morenci, and Jerome (Fig. 9; Sheridan 2012). Then, when the global economy slowed in the fall of 1929, copper prices plummeted to a third of their former worth. The mines at Ray, Inspiration, Miami, and Ajo all closed. Mining employment in Arizona fell below 3,000 workers.

By 1933, over a quarter of Arizonans relied on federal income relief. The Depression hit minority workers the hardest. Half of all Mexican- and African-Americans were on relief, compared to eleven percent of white Americans (Luckingham 1981). Financial hardship was not the only experience delineated by race in Arizona during that era. Urban spaces, like Phoenix, were notoriously segregated. And the same railroads that fed the mines, separated kind. A quarter of Phoenix's population—Latino-, Native-, African-, and Asian-Americans—lived south of the tracks in shacks lining unpaved streets (Konig 1982). Iron works, metal manufacturers, electric power stations, and transformer yards clustered in the same areas (Fig. 4b; York et al. 2003). White Americans, meanwhile, lived to the north on higher ground that was less prone to hazards (Luckingham 1981).

In an effort to relieve the hardships brought on by the Depression, the federal government began to invest in infrastructure development that would redefine the nature of metals in the Sonoran Desert. Federal authorities spent three-times the national average in western states, much of it invested in road and hightway construction (Sheridan 2012). The Bureau of Public Roads built 1,218 miles of state highways and ancillary roads, employing between 1,200-3,000 people annually in the process (Sheridan 2012). Investments like this quite literally paved the way for the automobile culture and the metal-laden emissions it would produce.

As was the case across the Nation, automobiles had started to replace public modes of transportation in Arizona during the decades leading up to the Depression. The number of automobiles in the Phoenix metropolitan area rose from 646 in 1913, to 11,539 by 1920 and reached 53,654 by 1929 (Luckingham 1981). By time the Depression hit, there was one car for every three people in Phoenix. What set Arizona's cities apart from urban spaces elsewhere in the U.S. was that it was still in the early stages of development when the new mode of travel was adopted. This fundamentally altered the structure of the urban landscape and the distribution of energy infrastructure (Fig. 10). Resources remained clustered near the railroad, while also beginning to diffuse out into the urbanizing landscape. More importantly, the automobile represented a new vector through which metals would be redistributed into the city.

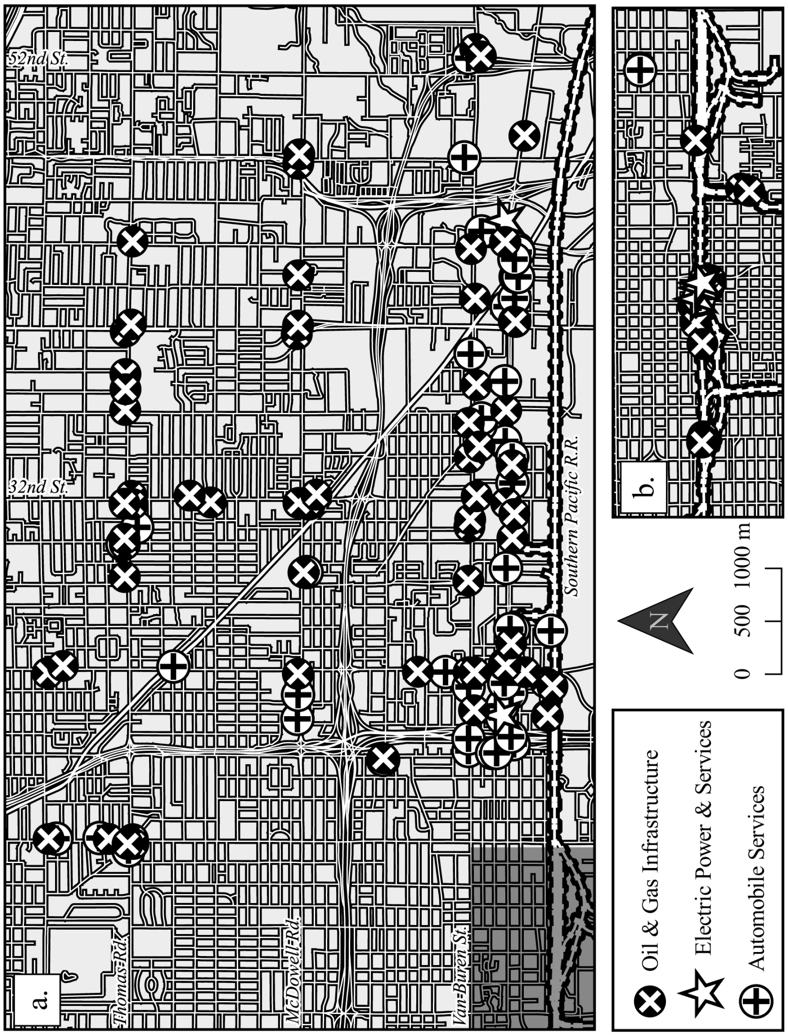

Figure 10: Metal-dependent enterprises in neighborhoods of Phoenix established by a) 1958 and b) 1915. Overlap between the maps is denoted by the lightly shaded area in sub-figure a. Sites hosting oil and gas were initially located in corridors adjacent to railroad yards. As the automobile became the dominant means of transportation, such activities started to disperse across the city.[4]

General Motors came to dominate the car market beginning in 1920. It overshadowed its competitors (e.g., Ford) through two innovations: consumerism and leaded gasoline. Alfred Sloan, the president of GM, developed a business model that inspired demand for constant advances in style, comfort, and power among consumers (Rosner and Markowitz 1985). To deliver this constant material progress, GM needed a highly-structured source of energy. They found that in leaded gasoline.

In 1922, researchers at General Motors discovered that tetraethyl lead prevented secondary combustion in four-cycle engines, thereby increasing their fuel efficiency (Cumming 1925, Rosner and Markowitz 1985). Leaded fuels added fifty times the horsepower of the Boulder Dam annually to America's energy profile, while also helping to maintain engine performance (Nriagu 1990). In the three years after its invention, 300 million gallons of ethyl (leaded) gasoline had already been sold by distributors across the country (Cumming 1925). Industry and military representatives advocated zealously for the fuel (Cumming 1925). At a conference on the public health implications of the fuel additive, a commander from the Bureau of Aeronautics staunchly defended the energy source:

"Aviation gasoline with tetraethyl lead, is the only satisfactory fuel that we have at the present time… It is of great military importance that nothing be done to preclude our getting it." (Cumming 1925).

Military aviation could burn through 750 gallons of leaded gas in a single endurance flight (Cumming 1925). Power and resource efficiency would be critical in the decades that followed as the world experienced its second industrial war, a conflict that radically transformed the Desert's landscapes.

Eight-hundred pounds of copper went into each tank shipped overseas in the Twentieth Century, another ton went into every bomber, and thousand more tons in each battleship (LeCain 2009). The Big Four mining firms produced over eighty percent of the metals demanded with America's entry in World War II (Nash 1990). Three of these firms—Anaconda, Kennecott, and Phelps Dodge—came to dominate the industry. In 1930, they controlled less than half of Arizona's copper production. Ten years later, they controlled nearly all of it (Sheridan 2012). During the War, western America also provided the vast majority of the Nation's petroleum, fueling engines of war and commerce with the raw materials for leaded gasoline (Nash 1990). Meanwhile, the federal government restricted the mining of precious metals, hoping to push gold and silver producers to shift toward extracting base metals (e.g., Cu; Nash 1990).

The federal government also expanded its control of landholdings in the West, part of a strategy to decentralize and limit their vulnerability to a targeted strike (Nash 1990). The wars over the Pacific (i.e., Korea, Vietnam) solidified the strategic value of these western military installations. To this day the vast majority of military lands remain in the West (Wyckoff 2014). These are landscapes, such as bombing and shooting ranges, defined by the anthropogenic bombardments of lead and other metallic alloys implicit in their land use.

During the territorial era, the military had worked to secure landscapes rich in metals, with industrialization and global war it transitioned into the role of a consumer. The military did more than just demand metals for combat, however. It expanded and diversified the use of metals (e.g., leaded gasoline) through financial investment and political will.

3.2.3 Urbanization and the Reincorporation of Metals into Desert Communities

Arguably the greatest impact of domestic defense spending in Arizona was on the structure of the Desert economy. Wartime production created over 12,000 defense jobs and moved thousands of pilots and soldiers through Arizona's cities (Sheridan 2012). It also created a massive demand for resources and labor south of the border. The U.S. and Mexico created the First International Migrant Labor Agreement (i.e., the *Bracero* Program; Hansen 2003). This permitted Mexican laborers to fill in for American workers entering the military. The Bracero Program also inspired marked development along the border, surpassing even that of the Prohibition days (Hansen 2003). These borderland settlements would later become key manufacturing hubs when American industrialists began to outsource production.

The influx of people and capital to Arizona also inspired a growing demand for new construction. Three Army cantonments and six air bases were established near Phoenix (Luckingham 1981). Defense installations came on line at this time, as well. Organizations like the Aluminum Corporation of America (Alcoa), AiResearch, and Goodyear Aircraft relocated assets to the Desert (Luckingham 1981). Alcoa built an aluminum extrusion plant in the Valley, while Goodyear began constructing aircraft parts near Litchfield Park (Konig 1982). These industries contributed millions to the Phoenix economy over the years and their operations were fundamentally tied to the expanding demand for metals.

As geopolitics shifted from hot to cold wars, wartime production plants expanded into civilian markets. In Phoenix, this attracted other industries—especially light- and high-tech manufacturing firms. Electronics manufacturers benefited from the low humidity climate, the availability of cheap electrical power, and the proximity of the

Army's Electronic Proving Grounds at Fort Huachuca (Luckingham 1981, Konig 1982). Between 1948-1960, 300 new manufacturing enterprises were located in the City. In 1949, around 8.5 thousand Phoenicians were employed in manufacturing. The number leapt to 16,000 by 1953 and doubled again by 1960 (Konig 1982). Motorola, for instance, established a research and development facility in Phoenix in 1948, in part because the city was strategically positioned between defense supply sites in Albuquergue and southern California. By 1960, the Company had three electronics plants in Phoenix and five thousand employees (Luckingham 1981).

Meanwhile, federal programs like the 1944 G.I. Bill and the home loan bank promoted the purchase of individual family homes, particularly by veterans returning from the War (Konig 1982). And workers drawn to the growing industries, many of them affluent scientists and engineers, created additional demand for housing (Konig 1982). In the years leading up to the War, around half of the state's population lived in either Phoenix or Tucson. A decade later, two out of every three Arizonans were urbanites (Sheridan 2012).

This new demand for urban housing dwarfed existing supply. Developers, like California-native Dell Webb, reaped the windfall of the construction boom that followed. Webb built every major military installation in the state, apart from the Davis-Monthan Air Base near Tucson (Sheridan 2012). His company went on to build many of the most high-profile residential developments, as well. More construction was completed in Phoenix during 1959 than in all the years from 1914-1946 combined (Luckingham 1981).

To ensure that residences and schools remained hygienic, the paint industry encouraged the use of washable, lead-based pigments (Markowitz and Rosner 2000). Nationally, forty-four percent of buildings constructed prior to 1950 contained leaded paint, while over a quarter to those built in the 1950s did. Because so much of the growth in the Phoenix metropolitan area occurred during this time, a sizable share of the urban landscape contains this high-risk housing stock (Fig. 11). Over 42,000 structures built before 1950 remain in use today and another 70,000 plus are from the decade that followed (MCAO 2011). As lead was extracted from Arizona's mines, it was at some level being reincorporated into domestic spaces. And, as implied above, it was also being dispersed into the air through the combustion of leaded fuels. The automobile not only emitted metals through combustion and friction, it also inspired a urban form that only made the matter worse.

During the construction boom, Phoenix became notorious for its "leapfrog" model of urban growth. Developers sought to maximize profits by purchasing cheap land away from developed areas. This allowed them to avoid contaminated sites and the stigma associated with the inner city (Heim 2001). Ironically, these barriers to domestic land uses were themselves the product of earlier development models (e.g., railroad industrialization and segregation). Of the sixteen major developments proposed in 1972, only four were within five miles of the Phoenix metropolitan area (Heim 2001). Residents of these ex-urban communities would have to rely on heavy automobile use to meet their needs. Beginning in the 1950s, wealthier and more mobile residents began to vacate the commercial areas of the city for the new suburbs (Kane et al. 2013). In the decades the followed, a distinct clustered geography emerged. Industry was concentrated around the railroad, professional services downtown, retail and entertainment near the transition to the suburban periphery (Konig 1982, Leslie and Ó hUallacháin 2006). It is an urban form that is manageable only with support of the personal automobile.

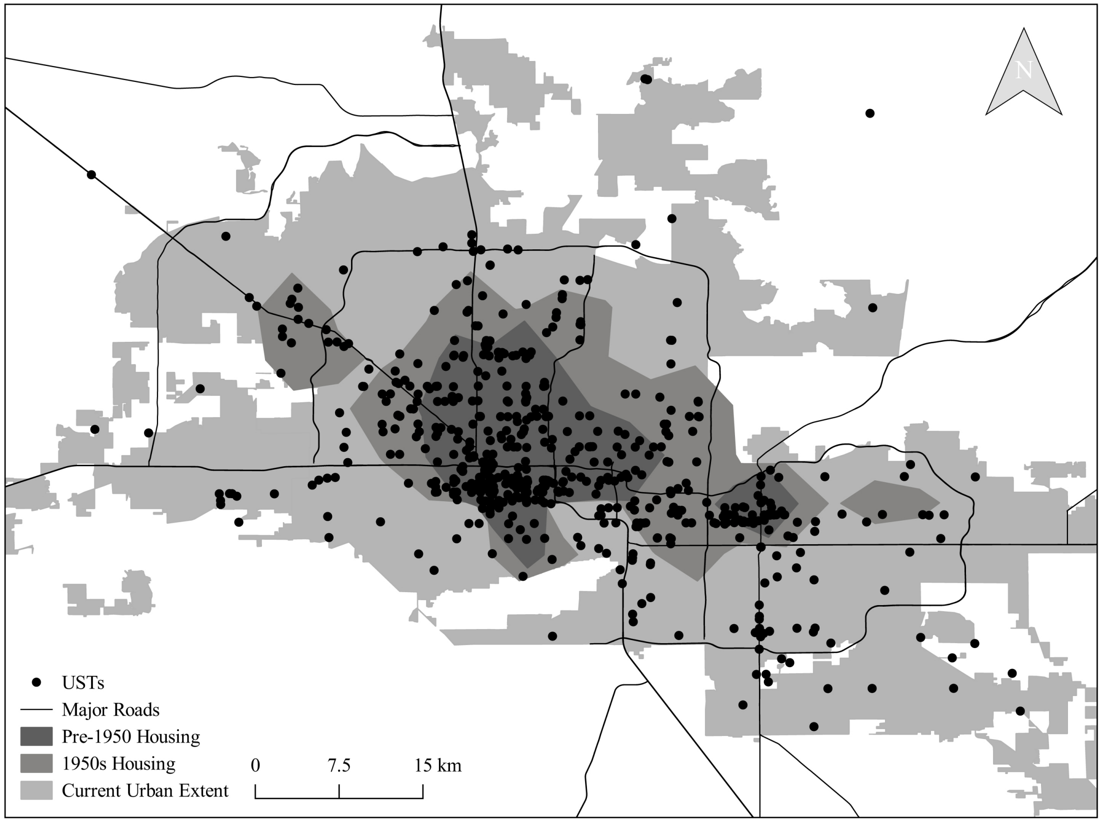

Figure 11: The distribution of underground storage tanks installed between 1920-1970, when leaded gas was in production, and housing districts built before 1960, when lead-based paints were most commonly used.

At its zenith in the 1970s, 270,000 tons of leaded gas was being consumed, nearly all of it in the United States (Nriagu 1990). Several factors conspired to drive American's insatiable demand for lead-doped energy. First, since lead improved the efficiency and power of engines, it saw wider use. Second, the 1940s witnessed the introduction of the fuel-hungry V-8 engine that powered American muscle cars and trucks. Finally, in the 1960s, aircraft began to rely on tetramethyllead fuel additives, coupling yet another mode of transportation to the use of metals (Nriagu 1990).

While environmental data are lacking for the Sonoran Desert, simply examining the distribution of underground storage tanks installed between 1920-1970 can give one a sense of the picture (Fig. 11). Over two-thousand fuel containers are known to have been interred beneath the metropolitan landscape during this period. In all likelihood, the vast majority of them once contained leaded fuels which were subsequently released into the dry, desert air or leaked into the earth. Of course, lead is not the only metal dispersed by automobiles. Brake wear alone can emit 8000lbs of copper, 2200lbs of Zn, and 70lbs of Pb annually (Hjortenkrans et al. 2007). Tire wear adds another 9200lbs of Zn annually to the environment (Hjortenkrans et al. 2007). All of these metals are concentrated in Arizona's urban air (Fig. 7).

As the case of lead illustrates, there is also a risk of these metals being incorporated into the bodies of those who call the Desert's urban and extractive landscapes home (Fig. 12). The distribution of communities burdened by the highest risk of infant lead exposure live in those places where mining and the railroad redefined the biogeochemical foundations of the Desert. These hazardscapes are the product of decades of pursuing wealth through the metals demanded by consumerism and war.

As industrialization and war were metabolizing metals from the Desert and distributing them across the high-energy land uses of urban sprawl and defense, our

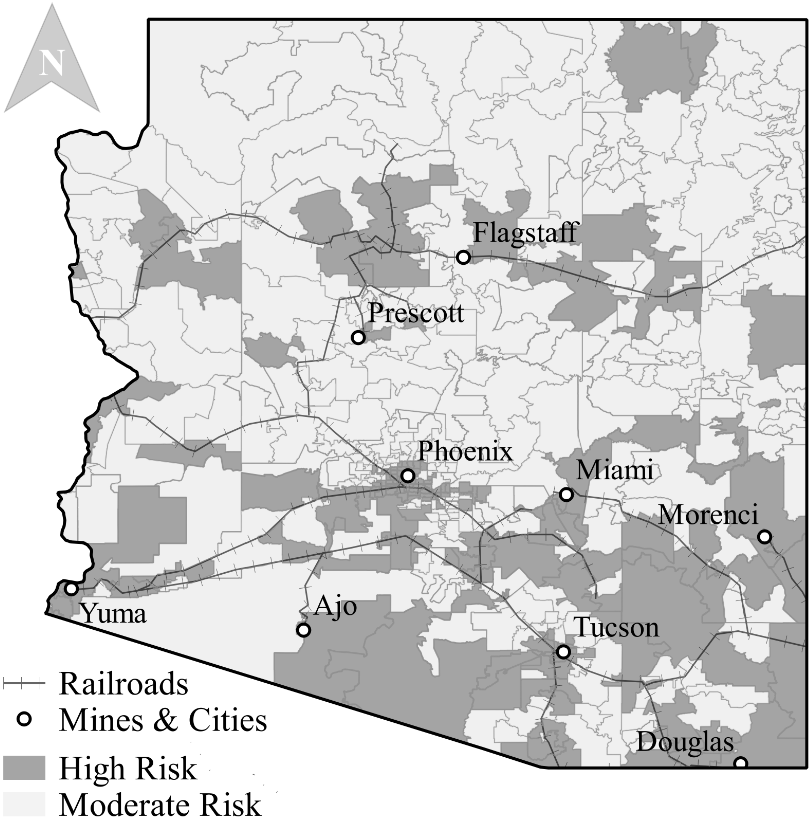

Figure 12: The spatial distribution of risk for elevated blood-lead concentrations in infants living in Arizona. Note that the high-risk areas correlate spatially with historically-productive mining districts, smelter locations, and railroad routes.

access to domestic resources was growing slim. In the mid-20th Century, Americans consumed six-times the global average for copper and 8-times that for lead (Park Jr. 1968). As early as 1945 there were signs that the West could no longer meet the Nation's demand for either metals or petrol. Reserves for twenty-two critical minerals had dwindled and only nine of the most important ones remained in America's domestic inventory (Nash 1990). This led to a dependence on foreign imports that only increased annually thereafter (Nash 1990). Industrialists and decision-makers increasingly looked abroad for the matter and energy to fuel economic growth.

American industry began to outsource production first from those places where unions had successfully fought for higher earnings for workers. Wages on the Sonoran side of the US-Mexico border were between a quarter to a third of that in America—making it an ideal wage haven for industrialists. By 1970 there were 147 manufacturing plants employing 17,000 employees—mostly women—along the border (Hansen 2003). Agua Prieta, Nogales, Ciudad Juarez, Matmoros, Mexcali, and Tijuana were among the first towns to host these new *maquiladoras* (Hansen 2003). These manufacturing centers became integral to the international production and trade of electronics—an industry reliant of lead, copper, aluminum, and a host of other metals (Smil 2014).

In 1985, a short drive north of the border in an arid expanse where railroad surveyors had once been led to a sacred copper deposit, the owners of the Ajo mine learned that it would cost $45 million to bring their smelter into compliance with the Clean Air Act. A decade later Phelps Dodge felled the stack with a controlled detonation rather than pay for the upgrade (Briggs 2016). Today, the new owners routinely evaluate the potential to bring the site back into production. The property is estimated to contain 482 million tons of rock, less than a half of a percent of which is copper (Briggs 2016). Time and the markets will tell if this landscape will be brought back into production, and how future generations will respond to the risks inherent in the process.

3.3 Discussion

Drawing on the concept of the hazardscape, I investigate here the biogeochemical transformation of the Sonoran Desert by industrialists, mass-consumers, and the military. What is perhaps novel is this history is the effort to understand how these interests relate to fundamental transitions in the coupled dynamics of energy and material demand in the region. Four phases of the energy-mineral regime emerged from this pursuit.

First, indigenous metal use was restricted by social customs, as well as a lack of the tools and energy sources which facilitate extraction (e.g., metal tools, domestic livestock, large-scale slavery; Nikiforuk 2012). More importantly, they did not labor under an economic system predicated on scarce metals (e.g., Au, Ag). The second phase follows the quest for precious metals, especially silver, by European entrants to Desert. Extraction was intended for international markets, foremost in Spain and later England. Energy was provided by manual labor and local timber, the latter of which was quickly exhausted in service of smelting, cooking, and heating. Beyond energy sources, extraction during this period was limited by the time it took to move resources and information between locations, as well as persistent land use conflicts.

With the arrival of the railroad, the third phase of the energy-mineral regime began. Fossil fuels (e.g., coke) could be readily supplied to mines located near a rail-line. These operations could also move their product to eastern markets more quickly. Electrification and wartime production created an insatiable domestic demand that miners met only by shifting to more energy- and land-intense open-pit methods of extraction. Electric power was also incorporated into metal production to increase the value of their products. This phase was less concerned with the wealth afforded by scarce, precious metals and more focused on the extraction of the base metals (e.g., Cu) whose intrinsic properties (e.g., conductivity) supported urban-industrialization.

The final analysis considers the incorporation of lead and other metals into the booming metropolitan landscapes that followed industrialization and the rise of consumerism. The metallic elements' capacity to resist degradation promoted their use in fuels, paints, propellants, and more. This led to marked efficiency gains and power output from the engines of automobiles and aircraft. It also led to the gradual and widespread accumulation of potentially-toxic metals in industrial and residential spaces, prompting one of the greatest public health crises of the last century. Many urban settings continue to host elevated concentrations of these same elements (e.g., Fergusson and Ryan 1984, Wong et al. 2006, Zhuo et al. 2012).

What does the evolving biogeochemistry of the Sonoran Desert indicate about each generations perception of the environment and how does this relate to the mineral-energy regime they participated in? Much as European conceptions of value shaped how settlers perceived the landscapes of New England (Cronon 1983), the same influences colored their approach to the Sonoran Desert. The Spanish defined the Desert's landscapes by the presence of arable land and precious metals. So too did the first Americans. They pursued scarce metals by consuming massive quantities of biomass for energy. These pursuits were disrupted repeatedly by geopolitical instability. Had they not, we might expect a constant struggle with the energetic constraints of renewable fuels, similar to how extraction progressed in other pre-industrial settings (e.g., Schmidt 1994). The railroad's capacity to bring fuel seems to have kept this scenario from playing out in the Desert during the nineteenth and twentieth centuries.

Mining and metal-dependent land uses, including war, inspired an economic restructuring that led to persistent and profound growth in the Desert's cities. By 1960, four federal highways connected Phoenix with the rest of the Nation. Two transcontinental railroads allowed it to send and receive freight with the rest of the southwest. Thirty trucking companies hauled goods through the City (Konig 1982). The industrial modes of travel did not so much compete as compound, differentiating into provisioning niches that helped fuel an ever-growing urban metabolism.

As has been stated elsewhere, mass consumption, mass production, and mass extraction are inherently coupled processes. The former provides the demand and the latter the means (LeCain 2009). This appears to be true in the history of the Sonoran Desert, as well. What was unseen, at least by most, was that these same activities were gradually redistributing metals into the industrial parks, roadsides, and residences of the city. Today, the legacy of industrialization remains thanks to the non-degradable nature of metals. What were once places of extraction and production are now hazardscapes where metals are incorporated into future generations (Fig. 12).

The 3E dilemma suggests that the inherent tension we should observed in the evolution of the mineral-energy regime(s) of the Desert is between affordable access to energy for human well-being and the hazards resulting from the means of acquiring that energy. In part, this appears to hold true for the history of the Desert. To the extent that electrification democratized access to light and heat, while the material basis for it resulted in the massive alteration of mined landscapes, the 3E premise holds. Likewise, if we presume the automobile has mobilized the masses at the cost of prolific emissions of greenhouse gases and metals, the logic of the 3E dilemma stands.

But this case also reveals some nagging flaws to the logic. True mobility was reserved for the affluent and predominately white urbanites who relocated away from the industrial hazards brought with prior land uses. And the energy savings afforded by leaded gas did not go toward the conservation or distribution of energy. It was spent in pursuit of more powerful and energy-intensive engines by those who could afford them. Lastly and most blatantly, electrification was only one of several drivers behind the demand for metals. Another was widespread, industrial warfare—a catalyst for change, though not in collective well-being.

As a sustainability challenge, the 3E dilemma warrants careful consideration in large part because there are circumstances where its logic holds and represents a significant challenge of socio-ecological well-being. Scholars should also attend to the points where its premise falls short. As this study suggests, at that juncture we may wish to more closely interrogate the political forces structuring the means by which energy and matter are begin acquired or provisioned. In the process we might critically evaluate whether the resulting maladies are the product of predominately natural or social forces and to what extent our decisions are shaping the hazards of tomorrow.

Chapter 4

MINE AND THINE: PROPERTY RIGHTS, INTER-SCALAR POLITICS, AND THE EVOLVING GOVERNANCE OF METALS IN THE AMERICAN SOUTHWEST

4.1 Introduction

An estimated 8,000-16,000km of rural streams and rivers in the American West have been seriously impacted by metals released into the environment by mining on public lands (USFS 1993). Meanwhile, the quality of the soil and air in many major metropolitan areas has been undermined by elevated concentrations of the same elements (Nriagu 1988, Wong et al. 2006, Grimm et al. 2008). Given its non-degradable and potentially-toxic nature, metal pollution can undermine the long-term safety and sustainability of the environments in which we live (Wong et al. 2006). Yet, despite a half-century of legislative efforts to curb their release (e.g., environmental regulations), these studies suggest that metals continue to be a persistent and pervasive concern.

Physical, biological, and social processes all affect the fate and flux of elements in the environment.[5] Among the most prolific metal-releasing activities are hard rock mining, fossil fuel development, and metal manufacturing (Pacyna and Pacyna 2001, Wong et al. 2006). Not surprisingly, these same activities were central to the economic development of the American West. And while market forces played a role, these economies did not emerge simply from the collective aspirations of westerners.

Economies are shaped by the system of rights and duties governing them (Cole 2002, Cole and Grossman 2002).

Traditionally, institutional scholars have tended to frame natural resource issues in terms of ownership or property rights (Coase 1960, Hardin 1968). This approach emphasizes how rights incentivize behaviors and allocate authority, thereby defining the key stakeholders in an economy (Libecap 1993). Such rights are an explicit form of power, an ability to affect the use and disposition of resources (Cole 2002). Beyond individual needs and preferences, economies are shaped by those who hold the rights to decide what a market offers. This line of thought indicates that the system of rights and duties affecting metals in the economies and environments of the American west deserves critical evaluation.

How the property rights governing resources, such as metals, have changed over time is an empirical question. Previous work employing these concepts has offered separate insights into the rationale behind mineral rights and pollution regulations (e.g., Libecap 1993, Cole 2002). However, most—if not all—studies in this field have stopped short of a systematic study of the rights to extract, emit, and be protected from the same elements. It is, after all, the same copper or lead that some have a right to mine, others a duty to clean-up, and still more a right not to be poisoned by in the process. As such, this analysis differs from previous policy studies in that it does not bound the problem within a single category of law (e.g., mineral rights or air pollution).

Instead, it is inspired by biogeochemical processes, in which the chemical elements are expected to transcend institutional boundaries as they cycle between the lithosphere, hydrosphere, atmosphere, and biosphere. Just as industrial ecologists have modeled the movement of metals from the earth into goods and emissions (e.g., Graedel et al. 2004). I map the evolving network of property right relations governing metals as minerals, machinery, and pollutants. In the process, I analyze how each phase of institutional reform handled the interests of the public, the state, and private enterprise. Placing these changes in their historical context facilitates inferences into how people have perceived the metal regime over time. It permits an understanding of what each generation of policy-makers viewed as problems and what effects the political or economic circumstance of the day had on their decisions, including the laws they adopted.

I take as a point of reference the legal geography of Arizona, a state well-known for metallic mining and more recently discovered to host significant metal pollution in the air and soils of its capital city (Zschau et al. 2003, Zhuo 2010, Zhuo et al. 2012). And while Arizona serves as an analytical centerpiece, I show how the legal and biogeochemical evolution of the State was quickly and repeatedly influenced by extraterritorial concerns. In this way, I demonstrate how the inter-scalar nature of hierarchical systems of government can shape the transformation and intransigence of environmental institutions. This chapter proceeds with a brief review of the theoretical foundations for understanding rights and statecraft, before expounding on the case of Arizonan metals. I conclude by way of reflecting on the implications of this history for the sustainability of coupled human-natural systems in an industrialized world.

4.1.1 On Rights and Resources

Contrary to the colloquial use of the term, property rights do not define the relationship between people and their places or objects. Instead they shape our expectations for reasonable dealings between owners and non-owners over some possession—be it energy, matter, or information (Cohen 1927, Demsetz 1967). Property rights define what resources may be used by everyone (e.g., the atmosphere), what rights are afforded only to citizens (e.g., the right to harvest fish and game), and what can be appropriated by an individual (e.g., the right to a mineral deposit).

These shared expectations allow organizations to adopt complementary roles and procedures, thereby increasing the effectiveness of all parties and reducing the cost of deciding who can access finite resources (Coase 1960, Demsetz 1967, David 1994). Ideally, a party interested in claiming a gold deposit can focus on the laws regulating mining, while another concerned with regional air quality can direct their attention toward environmental policies. This allows for the establishment of organizations dedicated to the implementation of a certain law or legal category (e.g., U.S. Environmental Protection Agency or the Arizona Geological Survey). As conflicts over rights and resources grow in frequency, it has become clear that the value of classic institutional silos is limited.

The utility of property regimes is also affected by the scale at which they operate. Customary institutions dominate at the local level. At this scale, problems are often defined informally and adaptation measures are tailored to specific social and environmental circumstances (e.g., gendered or seasonal division of labor in traditional societies; Scott 1998, Blomley 2003). The scope of such institutions are inherently limited. Spillover effects present a significant challenge for local organizations. Such problems become more common as societies densify and often encourage calls for governance at another scale (Cohen 1927). For instance, when miners rush to exploit a new discovery, neighboring land-owners or downstream interests may call for state or federal oversight (e.g., LeCain 2009).

Larger jurisdictions (i.e., regional-to-global) incur greater negotiation and policing costs, but can exert authority over the spatially-constructed externalities of smaller scales (Demsetz 1967). There are compromises inherent to governance beyond the local level, however. As jurisdiction expands, local complexity acts contrary to the authority of the decision-makers. Political organizations operating at regional scales and above make their duties tractable by employing hierarchical structures and policy tools that standardize resources and problems (Scott 1998).

Standardization reduces the cost of transacting within the system and, under certain conditions, can result in the collective benefit of stakeholders (e.g., Libecap and Lueck 2011). But the technologies of standardization—like maps, surveys, and grading—operate by imposing discrete categories on socioecological assemblages (Scott 1998). In the process, administrative technologies legitimize only the categories of uses defined therein and externalize what remains. Property regimes establish classes of ownership only for those categories of possessions that technology renders intelligible (e.g., mineral claims vs. metals in the air). By extension, changes in technology can have a direct effect on policy change. Innovation can reduce the costs of reform, create economic opportunities that states wish to govern, or make previously intractable problems manageable (e.g., by quantifying the concentration of ambient air pollutants; Libecap 1993, Cole 2010).

Property rights can also evolve as a result of social pressures. Popular sentiment, elections, and interest groups can focus attention on matters requiring policy reform (Jones and Baumgartner 2012). However, because the financial and organizational demands of policy making are significant and the winds of reform are episodic—institutional change tends to take on a punctuated, evolutionary character (Gersick 1991, Baumgartner and Jones 1991). In other words, laws and regulations tend to exhibit regular, incremental modifications interrupted occasionally by dramatic structural change. This quasiperiodic behavior means that institutions often operate as 'carriers of history' defining the legitimate and legally-defensible solutions of today by the assumptions and incentives operating at the time of their crafting (p.205; David 1994).

Who crafts those institutions depends on the distribution of power at the time of their adoption. All else being equal, larger, wealthier, and more homogeneous groups are expected to be more effective at securing property rights (e.g., multinational mining firms vs. Arizonan industrial workers). Moreover, when owners are concerned with preventing theft, penalizing violators, and benefiting from state protection, we would expect them to advocate for clearly defined rights and boundaries (e.g., claims to gold-bearing quartz veins; Libecap 1978b). Such certainty comes with costs, however—namely those incurred for taxes, lobbying, and enforcement (Umbeck 1977, Libecap 1978a). Hence the more profitable the resource, the fewer the costs of securing it, and the more readily it can be made legible by the tools of the day, the more clearly defined we would expect to find the property regime. When the costs are higher or a resource is difficult to police, we would predict greater institutional uncertainty (e.g., claims to sand and gravel).

Uncertainty and the inequitable distribution of rights also tend to inspire conflict (Libecap 1993). When interests are in competition, policy reforms require concessions as rights and future rents are redistributed from existing stakeholders (Libecap 1993). The sovereign's right to govern is essentially the authority to manage this (re-)distribution of duties and entitlements. Popular Sovereignty assumes that this right is derived from the consent of those living within the jurisdiction of the state (Gates 1968, Clinton 2002, Lenzerini 2006). This philosophy underlies much of the Western model of government. In this view, sovereignty confers two things: the right to be obeyed within the territory (i.e., authority) and an expectation that the agents of other states do not undermine that authority (i.e., independence; Lenzerini 2006). In exchange for granting the state some deference to manage their rights, the sovereign inherits a duty to preserve the inalienable rights of its citizens (e.g., the right to be protected from metal-borne hazards; Blumm 2016, Blumm and Wood 2017). This duty is often referred to as a 'public trust' obligation.

In practice, however, state power may just as well be employed to advance the interests of bureaucrats and policy-makers (e.g., rent-seeking). It can also be used to privilege commercial interests. Land grants, tax exemptions, favorable incorporation laws, and eminent domain privileges are classic tools by which governments have promoted private enterprise (Libecap 1979). For this unequal distribution of rights to be sustained, the institutional structure must be viewed to be legitimate by enough of the populous to mitigate dissent. Legitimacy has also featured heavily in the conflicts between different scales of government (e.g., state vs. federal dispute over hazardous waste sites; Lake and Johns 1990).

Legitimacy relies upon a society-wide ideology that validates its political organization (Tainter 1988). Such ideologies are often shaped and maintained in large part by territorial narratives (Blomley 2003). These narratives have classically portrayed life beyond the boundaries of the state as anarchic and violent. An exemplary case can be found in Hobbes' classic description of life beyond English rule: "For the savage people in many places of America… have no government at all, and live at this day in that brutish manner… there be no propriety, no dominion, no mine and thine distinct; but only that to be every man's that he can get, and for so long as he can keep it" (p. 79; Hobbes 1651). Territorial narratives act to unify intra-territorial groups by placing them in literal or symbolic opposition to extra-territorial antagonists. In Hobbes case, the vilification of the Americas served to reinforce the system of sovereign oversight and private ownership operating in England at the time (Blomley 2003).

Territorial narratives must also attend to what constitutes legitimate entitlements within the state. Since the 11th century, European (and later, American) statecraft has leaned heavily on the legacy of imperial Rome for its legitimacy (McSweeney and Spike 2015). It has been the foundation of our legal tradition for so long, that it is often treated as a natural law rather than a social construct. The Roman model distinguishes between dominium (i.e., rule by the individual, private property) and imperium (i.e., rule over individuals by the sovereign, public ownership; Cohen 1927). Both imply an authority to make decisions concerning resources. That authority, however, is rarely absolute in practice (Cole 2010). To hold a right implies that someone else has a duty not to interfere with the practice(s) it allows (Cole and Grossman 2002). In the contemporary world, the web of intersecting rights and duties means that most—if not all—forms of ownership are constrained in some way. The nature and distribution of those constraints depends upon a society's ownership regime.

The archetypal property regimes (i.e., private, public, common, open access) also have their antecedents in the Roman Empire. Specifically, the Institutes of Justinian, compiled in 6th Century Byzantium, distinguished ownership rights by the characteristics of the resource (Justinian 2009). Upon discovery, precious minerals became private property; while ownership of the rivers, seas, and atmosphere was shared by all. Navigable rivers, being essential for trade at the time, warranted special mention. The public could traverse these waterways and their banks freely; and today the law asserts that sovereigns have a duty to protect their use and enjoyment by citizens.

Consistent with the philosophical traditions of western sovereignty, this duty is referred to broadly as the 'public trust doctrine' in contemporary environmental law (Blumm 2016, Blumm and Wood 2017).

How resources are provisioned and how quickly they are used or degraded, depends in large part on the system of rights and duties a society adopts (Cole 2010). In practice, no system of resource governance perfectly matches an archetypal property regime. They are all amalgamations that are relatively more of one type than another and whose actual effect depends upon how it distributes the characteristic rights of ownership between commercial, state, and public interests. In this chapter I evaluate how those rights are entitled to different interests over time, in effect studying the evolution of the subsystems for the property regime(s) affecting the use and disposition of metals.

4.2 Case Study: Metal-Related Institutions in Arizona

4.2.1 Overview

In the middle of the 19th Century, the institutions governing the appropriation and provisioning of metals in the American southwest were customary in nature. Judging from the accounts available today, ownership was predicated on discovery, use, and defense (e.g., Poston 1894, Robinson and Altshuler 1984). Governance was local and informal. While there are numerous examples of customary societies altering their environment, (Fisher et al. 2009) cases of large-scale anthropogenic change are most common among the formalized and hierarchical models of governance (e.g., Hong et al. 1994, Cortizas et al. 2002). Hence, for this study, I limit my focus to the

American and well-documented models of governance that followed the formation of the First Legislative Assembly of the Arizona Territory in 1864.

Beginning with the mining laws set forth in the Howell Code of 1864 and proceeding to the present, I employed a text-mining analysis to survey the frequency of legislative activity around metals over time (Feinerer et al. 2008). Using metal-related terms identified in a pilot study of contemporary statutes, I identified several periods of significant activity interspersed with periods of markedly less attention (Fig. 13). Focusing on eras with significant activity, I conducted a content analysis of metal-related legislative documents. By and large these acts, memorials, and resolutions addressed either mining, fossil fuels, or some form of pollution. Following the typology of rights described by Honoré, I documented the nature of rights and those entitled to them by each piece of major legislation (Honoré 1961). I made supplemental notes of corresponding duties imposed on other parties and any liberties mentioned. In the discussion that follows, I describe and interpret significant changes in the structure of property rights affecting the use and disposition of metals over time. In the process, I draw on court decisions, federal legislation, secondary sources, and—when available—primary accounts to provide context.

4.2.2 Extraction

Mining interests predate the political organization of the Arizona territory (Poston 1894). So, it should not come as a surprise that this was among the first matters taken up by the legislature. The second territorial assembly of Arizona was unequivocal in asserting its right to govern metals. In December of 1865, they declared that "precious metals are the jewels of sovereignty, and inhere in the supreme sovereign

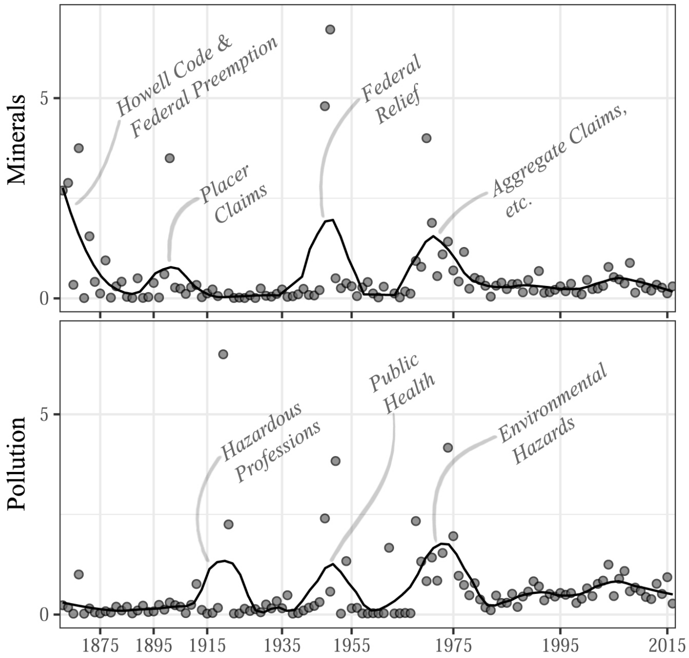

Figure 13: Legislative effort surrounding mineral extraction, public health, and the environment as indicated by the frequency of related terms. The terms "hazard", "toxic", and "nuisance" were considered pollution-related terms. While "mineral" was presumed to related to the mining industry.

power; no person can acquire absolute title to any public domain in which such precious metals may be found without the express consent of such power" (Arizona Legislature 1865a). Private interests may have discovered and occupied the rich mineral lands of the Territory—acts which classically grant the right to ownership, but the legislature insisted that such persons merely enjoyed a state-sanctioned liberty to use and enjoy an income from the resources. Their appropriation and use of metals could be limited by the state and its inherent right to govern them. And under the code drafted by territorial judge, William T. Howell, they detailed what that governance would entail (Lacy 2013).

To undercut the potential for monopolies, miners were restricted from claiming more than a single tract on any one deposit (Arizona Legislature 1865c). The extent of each claim was likewise bound by statute. While miners enjoyed the liberty to purchase others' claims, the Howell Code prevented early entrants from staking claim(s) to an entire district. This was not the only way that the Code sought to distribute Arizona's natural wealth. Following the Spanish tradition, miners were required to identify and set aside nearby lands, untouched by their excavations, for the benefit of the Territory. Such lands could later be auctioned so as to fund a standing army or public-school system.

Miners in turn benefited from the military, whose statutory duty was to defend mining and corporate interests from "tribes of hostile Indians or bands of robbers." Although the notion that hostility was a prerequisite for military action seems doubtful. That same year, Arizona's representative in Congress was calling for the removal and "subjugation" of all the Native nations in Arizona. "A sickly sympathy for a few beastly savages should not stand in the way of the development of our rich gold fields, or the protection of our enterprising frontiersmen" he testified in Washington (Poston 1865). Arizona's statesmen crafted a narrative that put indigenous communities in direct opposition to the commercial interests of the territorial and federal governments. This in turn legitimized state-sanctioned claims to tribal lands and the mineral resources therein.

As it related to the potential for conflicts between citizens, however, the Code offered greater deference. It imposed a duty on miners that restricted them from obstructing or undermining public roads and waterbodies accessible to travelers (Arizona Legislature 1865c, Ch. L Title II Secs. 21-22). This ensured the state maintained its obligation to safeguard navigation and trade. The Code also required that miners fairly compensate any private landowner whose holdings were damaged in the course of mining (Arizona Legislature 1865c, Ch. L Title II Sec. 34) Local courts and expert committees, meanwhile, were tasked with mediating any such grievances. In this way, the Code anticipated the conflicts likely to arise between mining and other legitimate land-uses. While it prioritized extractive interests, it provided a process for promoting reconciliation between citizens.

Lastly, the Code required extensive financial- and activity-reporting requirements for the era (Arizona Legislature 1865c, Ch. L Title II Sec. 17, 23-25). Such disclosures enabled the state to garner revenue by levying taxes on a mine's net proceeds. It also provided the factual basis for miners to defend their claim during arbitration. Miners who complied with the recording and reporting requirements of the Howell Code enjoyed the protection of the army and the courts, in turn.

The influence of Judge Howell's Code was to be short-lived, however. Circumstances in Nevada and Washington would soon force Arizona to change its approach to mining. Under the Treaty of Guadalupe Hidalgo, signed in 1848, all lands ceded by Mexico to the United States fell within the public domain (Umbeck 1977). Yet, a decade after the Treaty, the federal government still lacked a formal process by which its citizens could claim a legal right to minerals discovered on public lands. Such was the case when the silver and gold of the Comstock Lode was discovered in the eastern Sierra Nevada Mountains (c.a., 1859; Umbeck 1977, Libecap 1979, Smith 1993). As miners rushed to the newfound deposits, conflicts over claims ensued and camps were forced to self-organize rules for managing disputes. Committees were organized to draft laws governing the arbitration, recording, and security of claims (Libecap 1978a, Libecap 1979, Lacy 2013). Company presidents acted as judges and juries were composed solely of miners (Lacy 2013). Critically, these men were concerned with the security of their claims, not the causes of statecraft or the equitable distribution of rights and privileges.

Burdened by the debts of the Civil War and seeing a need to regulate the preponderance of activity in the West, the federal government finally adopted legislation governing minerals in the public domain—first in 1866 and again in 1872 (Libecap 1979). These federal statutes were heavily inspired by the camp rules of Comstock, effectively extending their logic to public lands across the Nation. The Arizona legislature responded by repealing the Howell Code, abandoning all previous claims to minerals, and adopting the much sparser federal regulations (Arizona Legislature 1866b).

The new mining laws relocated decision-making authority in Arizona from the statehouse to the mining districts, which were self-organized by the miners occupying local deposits. These districts were empowered to make "all necessary rules and regulations for the location, registry, and working of mines therein" (Sec. 1; Arizona Legislature 1866b). Moreover, the 1872 federal mining law made clear that miners held the "exclusive right of possession and enjoyment of all the surface… and of all veins, lodes, and ledges throughout their entire depth" so long as they operated "on the public domain" (U.S. Congress 1872, Ch. CLII Sec. 3). Lands adjacent to mineral claims could also be secured for the purposes of homesteading and installing critical mine infrastructure. But no parcels were reserved for the state and provisions to manage disputes between surface and mineral interests were similarly lacking. Fees were limited to the costs of survey and registry, removing an important source of revenue for territorial operations. Miners' were also obligated to report far less than the Howell Code had provided for. Federal law required mining districts to adopt rules for recording the location and date of claims, as well as the names of all parties participating in the discovery.

In short, the federal mining laws were implicitly designed to establish private claims to public metals, granting a measure of security and predictability to commercial ventures. The Howell Code had similarly intended to promote extraction, but had sought to finance state-building efforts in exchange for its natural capital. Ultimately, only the federal model survived, a law which was designed to ensure the security of wealthy commercial interests pursuing gold in western Nevada.

Institutions were not the only thing in flux during this period. By 1870, many of the readily-accessible, superficial deposits in the West had been exhausted. The majority of small, independent operations ended with them. This left only capital-intensive ventures targeting deep-vein and low-grade deposits (Libecap 1978a, Libecap 1979, Schmitz 1986, LeCain 2009). In response, federal and territorial law gradually refined the rules for claiming diffuse "placer" deposits (Arizona Legislature 1865b, 1875, 1899). Meanwhile, the industry itself was transforming.

Metal mining became increasingly dependent on wealthy backers to finance these larger operations, often based in San Francisco or the northeast (Libecap 1979, Boswell 1981). Considerably more time passed before financiers saw returns from these larger investments (Schmitz 1986). Given the notoriously volatile nature of metal prices, miners and their financial backers were compelled to mitigate uncertainty and risk wherever they could. Rules defining the expectations between owners and shareholders was a first step toward that end.

Incorporation laws, such as those enacted by the territorial assembly in 1866, established legally-biding ties between shareholders and mining firms which promoted the raising of capital (Libecap 1979). Mining corporations enjoyed the right to bring lawsuits, to enter into contracts, and to acquire property—be it landed or built (Arizona Legislature 1866a, Sec. 5). They could also be sued. And while this enable mining firms to access much-needed capital, it also created a formal obligation to shareholders. The implications of this were realized in 1919 when the Michigan Supreme Court ruled that corporations have a duty to act in the interest of their shareholders, limiting the extent to which they were permitted to prioritize the needs of employees and customers (Dodge v. Ford Motor Co. 1919). While the court's decision granted some leeway to businesses, the corporation's obligation to maximize profits became a potent narrative among private enterprise.

4.2.3 The Hazardous Professions

As ownership concentrated and skilled-miners were replaced with a predominately immigrant workforce of heavy equipment operators, mine laborers began to push for unionization as a means to address the hazardous working conditions and exploitative practices of the companies (Boswell 1981, Jiménez 1981). Under Arizona's populist and progressive first governor, W.P. Hunt, a series of worker protection acts were passed starting in 1912. These statutes declared certain industrial activities "to be injurious to health and dangerous to life and limb." (e.g., Ch. 26, 28, 50; Arizona Legislature 1912). Among the list of hazardous professions were mining, smelting, and mill laborers; furnace and coke oven operators; and electric power plant employees. The effect of these laws was to limit adult, male employees to an eight hour workday. Meanwhile, women and minors were barred from employment in these industries completely.

Organizations at the state and local level were empowered to promote compliance with these laws. The Superintendent of Schools issued employment certifications limiting entry into the workforce, while factory inspectors and school attendance officers had a duty to visit hazardous industrial sites and ensure compliance. Meanwhile, at the state-level, the Board of Health was charged with routinely evaluating the potential for industries to be "sufficiently injurious to the lives or limbs or injurious to the health or morals of minors"—and presumably women—to warrant their exclusion (Ch. 32 Secs. 5 and 19; Arizona Legislature 1912). Public health administrators thus had a lasting duty to adapt the state's regulations, so as to protect ostensibly sensitive populations from the physical and moral hazards of the metal-dependent professions.

During this same period, the elected office of the State Mine Inspector was established (Ch. 33; Arizona Legislature 1912). The Inspector was granted the authority to enter onto mine sites, identify unsafe or unlawful conditions, and compel operators to remedy hazards. Included in the statutes are a host of technical and performance standards promoting emergency response capabilities (e.g., access to rescue equipment, fire protection measures, maintaining accurate maps; Ch. 33 Sec. 17-26). Several statutes also suggest an early recognition of the effects of air pollution on occupational health (e.g., Sec. 24). Mine operators had a duty to ensure an "adequate amount of pure air" was circulated through underground workings and that a spraying system should be in place to manage "dust and gases." Even more specifically, carbon dioxide levels were prohibited from exceeding 25% of the air by volume, except after blasting. Combined, these represent the earliest cases of ambient air standards in Arizona statutes.

On paper, the Office of the Mine Inspector embodied the state's right to govern the metal trades. The firms of the hazardous industries had a corresponding duty to comply with the legislated standards lest they risk fines, incarceration, or having their operations halted. The accounts of federal health professionals cast some doubt, however, as to whether these standards were widely applied. After touring the operations of the Globe-Miami District, one noted that "several mines were devoid of either dust control or precautions against accidents which, even I could see, were needed… My interviews with the [Company] doctors were not very enlightening. …I was irritated to find few of them taking the dust problem seriously. Most of them denied that there was any unusual incidence of tuberculosis among the miners… Several had the label of the 'Loyal Legion' the anti-labor organization of the day." (pg. 249; Hamilton 1943). Company doctors during this era had a reputation for protecting their employer at the cost of the workers. Accounts from the period note several instances of doctors dismissing lead or mercury poisoning as cases of alcoholism or some other fault of the afflicted (Hamilton 1929). Such biases were sadly common throughout the metal-dependent industries (Rosner and Markowitz 1985, Berney 1993).

Under the Mine Inspector and hazardous profession laws, the state legislature imposed specific duties on mine operators, including company doctors. But there were several barriers to change at the firm-level which are worth identifying. First, the study of toxicology was in its infancy and much of the extant research came from European sources—which even medical professionals often dismissed as "socialist" and "feminine" (pg. 141; Hamilton 1943). Even without the prejudice of the profession, accessing international journals would have incurred significant transaction costs. Second, doctors of the era relied heavily on clinical symptoms for diagnosing metal poisoning (e.g. wristdrop, lead line; Hamilton 1943). These were ambiguous metrics requiring careful interpretation. Third, company doctors were likely to suffer from implicit biases. Their positions were after all a reaction by firms to mitigate the liability of worker compensation laws (Hamilton 1929). Moreover, tension between labor and management at Arizona's mines was significant. Without a means for addressing grievances, workers suffered in silence until conditions grew desperate enough to spark protest, and often violence. The trauma of violence and conflict encourages simplistic and polarized views of increasingly complex issues (Coleman 2011). Even individually, any one of these forces would have represented a significant barrier to change.

So, while the worker protection laws established state and corporate duties to protect the inalienable rights of laborers in the metal trades, their effect appears to have been inconsistent or inconsequential. Uncertainty and information asymmetry limited the ability of workers' advocates to identify violations of their rights. The resources to address this uncertainty were limited to corporate and federal officials. In the latter case, the scope of their jurisdiction generally limited their capacity to address conditions at any one mine. As for private enterprise, corporate and professional narratives placed blame on the carelessness and subversive intent of workers, thereby undermining the legitimacy of laborers' claims.

4.2.4 Federal Relief

While corporate-labor relations were slow to adapt during this period, private enterprise did manage to transform its organizational structure in important ways. In an attempt to constrain market volatility and control demand, mining firms of the early 20th Century expanded into railroad, electrical, and manufacturing ventures (Chandler 1990, Sheridan 2012). The major copper firms also attempted to fix prices in the face of a global depression. But rather than stabilize their profits, their price-manipulation efforts inadvertently stimulated competition from the Central African Copperbelt—ultimately undercutting their control of the market (Schmitz 1986).

Arizona's legislature attributed the subsequent contraction of the domestic copper industry to a concerted effort "of foreign governments, foreign corporations, concessionaries of foreign governments, including American citizens, all acting in concert against the economic peace and welfare of our people." Per the legislature, the conspirators were "snatching the means of livelihood from our people and transferring our employment to the under-fed, under-clothed, under-paid foreign native in order to produce cheaper copper" (Arizona Legislature 1932). Unaware or unwilling to accept the industry's role in the financial crisis, the legislature framed foreign and domestic antagonists as the enemy of its people (Fig. 14). In the process, their rhetoric implied that the labor movements challenging corporate mining practices in both Arizona and northern Mexico were somehow aligned with African miners as part of a grand, global conspiracy (Boswell 1981, Gonzales 1996).

Several measures were taken in response. First, the State established the Department of Mineral Resources (Arizona Legislature 1938). The Department was charged with facilitating the extraction of mineral resources in the state, investigating the barriers to mineral development, and conducting geological investigations that were of interest to private firms. Much in the same way that Arizona's territorial government had set out to map the distribution mineral deposits the century prior, the Department acted as a state-sanctioned effort to reduce the transaction costs of extraction (Arizona Legislature 1864, Sec. 2). These efforts facilitated mining, but did little to alter the distribution of rights or the limiting function of skyrocketing capital costs.

A more fundamental shift came with the second World War. As hostilities returned to Europe, Arizona's legislature attempted to entreat federal support for mining by linking domestic metals to national security. "There are in Arizona hundreds of deposits of ore carrying *strategic minerals*, sufficiently developed to be producers

Courtesy of The El Paso Times.

Figure 14: Propaganda circulated in the July 7, 1917 edition of the Bisbee Daily Review captures the sentiment against labor unions during the era

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if the owners or lessees were able to finance mining operations," the State wrote (*emphasis added*; Arizona Legislature 1942a). Meanwhile, the Department of Mineral Resources was directed to "exert all proper efforts to induce the United States government to station an ore buyer at a convenient point in Arizona" (Arizona Legislature 1942b).

Highway construction, energy transmission, and mineral extraction all legislatively gained some form of eminent domain powers during this era—permitting them to condemn private lands for state-sanctioned activities (Arizona Legislature 1944, Arizona Legislature 1945a, Arizona Legislature 1958). Since the days of the Howell Code, mineral leases had conferred the right to utilize the land surface as needed. Now mining companies could also access their claim via state-owned lands as necessary and condemn private lands in order to construct essential infrastructure—including roads, pipelines, and transmission lines (Arizona Legislature 1941, Arizona Legislature 1945b). In a similar spirit, the State Engineer was tasked with coordinating for a "strategic network of highways" with the U.S. Secretary of War. These infrastructure projects and the landuses they encouraged would later become a key point of contention when the federal government sought to regulate pollution, including metal emissions.

4.2.5 Public Health and Environmental Hazards

Growth in Arizona's cities surged following the wartime restructuring of its economy and infrastructure. The defense manufacturing sector expanded into civilian markets, which attracted other industries in turn. Much of this growth was from the export-oriented light manufacturing and high-technology sectors, who found

Arizona's low-humidity climate advantageous (Luckingham 1981). From 1948-1960, 290 new manufacturing firms were established in the Phoenix metropolitan area, doubling employment in this sector by 1953 and then doubling it again by 1960 (Konig 1982). These firms recruited well-educated, male, and predominately white workers—many of whom were attracted to Arizona because of the perceived health benefits and recreation opportunities afforded by the environment (VanderMeer 2010, Shermer 2013). But as the cities densified, citizens began to protest the traffic jams, pollution, rising crime rates, and housing shortages that resulted (Luckingham 1981). In hopes of preserving its image as a healthful retreat from the grime of the Steelbelt, the State passed a series of public health bills in the early 1950s.

The State Department of Health was established and ascribed the duty to protect the health of Arizona's citizens and supervise engineering projects within the state (Arizona Legislature 1954). Much like the environmental organizations that followed, the Department was organized into bureaus tasked with monitoring, remediating, and chemically analyzing threats to health (Sec.13). But unlike the environmental laws, the public health statutes did not apply separate mandates for toxins depending on their physical state. Rather, the legislature tasked the Department with regulating the planning of activities generating "industrial wastes and other deleterious matter, gaseous, liquid, or solid" (Sec 12.).

Where the hazardous profession laws emphasized shielding workers from existing pollution, the public health laws focused on preventing hazards through planning and engineering oversight. Interestingly, mining wastes—specifically the generation of waste rock, mill tailings, and smelter slag—were exempt from such oversight (Ibid, Sec. 7). Health officials were also constrained by individual rights to liberty. Specifically, officials were restricted from imposing treatments that conflicted with a person's beliefs (e.g., religious practices). Health officials could only act contrary to an individual's wishes for matters of quarantine or sanitation. Only when private actions posed an immediate and substantial danger to the collective welfare could their rights be restricted. While this power was effective at controlling infectious and acute diseases, it was ill-suited for chronic threats or for those which exhibit delayed onset—characteristics inherent to epigenetic hazards like metal poisoning (Arita and Costa 2009, Zawia et al. 2009, Bakulski et al. 2012).

By 1962, when Governor Paul Fannin addressed the Arizona legislature, it was clear that concerns surrounding the State's air quality persisted despite the public health measures. "It is generally recognized that a problem of air pollution exists throughout the United States in most metropolitan areas, and Arizona's abundance of clean, fresh air is not immune to this potential threat," he wrote. "We should profit from the experience of our neighbors to the west, rather than assume that they have a monopoly on air pollution." He was referring to the infamous Los Angeles smog which was compelling California and the federal government to contemplate regulating emissions (Nriagu 1990). But contrary to his acclaim for the State's fresh air, Phoenix was then ranked among the five worst cities in the nation for air quality (VanderMeer 2010). In spite of this, no legislative action was taken until the federal government forced the State's hand in 1967.

The federal Clean Air Act and amendments established that state and local governments had a duty to control sources of pollution (U.S. Congress 1963, 42 USC 1857 Sec. 1(a)(3)). If a state failed to promulgate air quality regulations, the federal government also enjoyed the liberty to impose them (U.S. Congress 1963, 42 USC 1857 Sec. 108(c)(2)). It justified this authority by citing its constitutional right to govern interstate commerce and anticipating that heterogeneous environmental standards would disrupt trade. The first bill Arizona adopted that year was "An Act Relating to Public Health and Safety" which made the preservation and improvement of air quality a public policy for the State (Arizona Legislature 1967).

County boards were empowered to investigate and regulate stationary sources and a Division of Air Pollution Control was formed within the State Department of Health to facilitate this (Sec 36-773 (A), Sec. 36-1702). Through the chairman, the board could exercise the police powers of the State—including subpoenaing individuals and requiring information disclosure (Sec. 36-785 (C)). They could also regulate via permit the "installation, alteration, or use of any machine" expected to contribute to air pollution (Sec. 36-779.01(A)). But counties had no authority to regulate automobile emissions, that power remained with the State Board of Health (Sec. 36-1717(A)). And there were other limitations imposed on local government. Case in point, if circumstances beyond an individual or firm's control made it so that regulatory compliance would result in an "arbitrary and unreasonable taking of property", the county board had a duty to find a less onerous option (Sec. 36-784 (A)). Local government was required to weigh the private costs and public benefits of enforcement when it might infringe on the private right of possession.

Under the 1967 law, the State defined air pollution as "one or more air contaminants or combinations thereof in such quantities and duration as are or may tend to be injurious to human, plant or animal life, or property" (Sec. 36-771(2)). Like the earlier definition of industrial wastes under the public health laws, this definition was broad and general. While this granted the state flexibility, generic statutes are also more challenging to enforce. Once again, federal actions pressured Arizona to revise its approach, in this case adding specificity but narrowly-defining the focus of air pollution regulations.

The federal Clean Air Act Amendments of 1970 created two categories of air pollution: criteria pollutants and hazardous air pollutants. The first category included those deleterious elements and compounds to be regulated by ambient air criteria (U.S. Congress 1970a Sec. 109(a)(1)) This included particulates (e.g., dust, smoke, aerosols), tropospheric ozone, sulfur dioxide, and nitrous oxides—all pollutants identified by the California Air Resources Board to be undermining air quality in Los Angeles (U.S. Congress 1970b). Lead remains the only metal explicitly included in this category.

In order to implement the Clean Air Act, the federal government mandated that the states develop plans demonstrating how they would achieve the primary and secondary standards set for each criteria pollutant (U.S. Congress 1970a). Such plans were expected to include provisions for ambient monitoring programs, emission limits, vehicle inspection, as well as land-use and transportation methods for controlling pollution (U.S. Congress 1970a, Sec. 110(a)(2)).

The imposition on private automobiles and state planning was too bold for Arizona's leadership. The State joined California and others in challenging the federal government's transportation and land-use planning requirements (EPA v. Brown 1977). The argument in the courts hinged on sovereignty and the right to govern at the state versus federal scale. The EPA argued that states' right to govern public roads also conferred upon them a duty to mitigate the resulting pollution. Since automobiles were a significant source of four out of the six ambient pollutants, federal authorities expected states to establish and enforce vehicle inspection and maintenance programs. They also required states to submit plans for promoting public transportation. If a state failed to do so, the federal government threatened to criminally sanction them (EPA v. Brown 1977).

Arizona and the other states retorted that federal executives cannot compel states to employ their sovereign authority. Ultimately the courts sided with Arizona, limiting the federal government's authority to use landuse planning as a policy tool for controlling mobile emissions. Public highways and roads, in turn, continued to operate as dispersal mechanisms for metals and related pollutants for decades. The most noteworthy case of this being leaded gasoline emissions.

The federal government had been aware of the risks posed by leaded gasoline since 1925, when a bizarre outbreak of mass insanity struck factory workers at the du Pont Chemical factory where it was manufactured (Rosner and Markowitz 1985). Yet, despite mounting evidence that lead exposure was afflicting both urban and rural communities nationwide, federal agencies could not overcome the "reasonable doubt" required to set lead emission standards for automobiles (Nriagu 1990). Instead, they addressed the health hazard indirectly by establishing standards protective of catalytic converters. Beginning in 1975, gasoline retailers were required to offer at least one unleaded grade of gasoline and producers were ordered to phase down the concentration of lead over the following decade (Nriagu 1990). Lead levels in ambient air paralleled those in gasoline, trending steadily downward until the mid-1980s.

As mentioned, lead was the only metal regulated as a criteria air pollutant. The remaining potentially-toxic metals are categorized as "hazardous air pollutants," which serves as a catch-all list for any compound or element lacking an ambient standard but likely to increase the risk of mortality or incapacitating disease (U.S. Congress 1970a Sec. 112(a)(1)). Here, metal- and metalloid-based compounds (e.g., As, Cd, Hg, Sb) are grouped alongside a host of volatile compounds (e.g., benzene). Aside from their potential for harm, what this group shares is their regulation by emission standards (i.e., release rate). These standards were to be set at levels protective of public health and the environment, while emitters were prescribed technological controls to mitigate risk.

There are several reasons why this approach was problematic. Logistically, federal administrators had the burdensome task of assessing the risk posed on a chemical-by-chemical basis, plus the added responsibility to evaluate the effectiveness and availability of technological control measures available to each industry that emitted them. In hindsight, it is perhaps not surprising that in the twenty years that followed, only eight pollutants were added to this category (Air Quality Management in the United States 2004). There is also the added complication that several hazardous pollutants do not exhibit a threshold below which there are no effects from exposure (Air Quality Management in the United States 2004). In such cases, traditional risk-management approaches are less effective than preventative measures (e.g., limits on use). But prohibitions on use are often challenged as infringements on private rights to intellectual property and impediments to innovation. A third hindrance was the focus on emission rates. To be sure, regulating ambient concentrations in well-mixed environments, like the atmosphere, is limited by the difficulty of identifying the original sources. Emission standards have the advantage of locating compliance at the point of release. For volatile compounds this is a logical approach, but for non-degradable pollutants—like metals—managing emission rates only affects how quickly they accumulate in our soils, wetlands, and waters. In the case of metals, depositional standards are more likely to be protective of human health and the environment (Air Quality Management in the United States 2004).

But arguably the most significant barrier to controlling metal emissions is that, much like greenhouse gases, their regulation has significant implications for private enterprise. Ever since Ronald Reagan required that major rule-making at the federal level must first undergo a Regulatory Impact Analysis weighing its costs and benefits, environmental policy-making has suffered considerable inertia (Reagan 1981). The political narrative in the West also pivoted during this period. Threats were no longer extra-territorial in nature, but derived from the government itself. "The people have not created this disaster in our economy; the federal government has. It has over-spent, overestimated, and over-regulated…" Reagan asserted in the announcement of his candidacy. "We must force the entire federal bureaucracy to live in the real world of reduced spending, streamlined function and accountability to the people it serves. We must review the function of the federal government to determine which of those are the proper province of levels of government closer to the people." (Reagan 1979).

While Congressional action did manage to expand the scope of hazardous air pollutant regulations, adding some 189 chemicals and compounds with the 1990 Clean Air Act Amendments, there has been little movement since then (U.S. Congress 1990). Growing polarization and partisanship since the turn of the 21st Century has obviated any serious consideration of refining federal environmental policy (Schmalensee and Stavins 2018).

To its credit, Arizona's Department of Environmental Quality—established in 1987 to administer the State's environmental laws—contemplated revisions to the hazardous air program in spite of federal intransigence. The Department evaluated the potential for setting deposition-based standards on hazardous air pollutants in 2006, but ultimately rejected the approach. They cited the cost-prohibitive nature of modeling deposition and stated that the accumulation and re-introduction of pollutants into the atmosphere was beyond the scope of their review (ADEQ 2006). Instead, the Department adopted chronic and acute ambient air standards believed to be protective of human health, an approach whose effectiveness is somewhat supported by the case of lead (ADEQ 2006).

It remains unclear if this method would have worked for other metals, however. A lawsuit was filed against the Department that same year by a local manufacturing firm and the State Chamber of Commerce (Oak Canyon v. ADEQ 2008). Ultimately, the county court decided in favor of the commercial interests and ruled that the State's hazardous air program was unenforceable. According to the ruling, the State could not establish standards for federal pollutants. This left the regulation of metals in Arizona once again beholden to federal rule-making which was itself locked in a state of gridlock.

Discussion

In the preceding analysis, I traced the social and environmental circumstances that have shaped the distribution of rights and duties affecting the modern use and disposition of the metallic elements. To briefly summarize: despite fundamentally different approaches between the Arizona and federal governments, the rights to precious metals in well-defined mineral strata were established early in the institutional record. These rich ores were soon exhausted leaving miners with major technical and financial barriers to extraction. Policy-makers responded by adapting the laws to facilitate the incorporation of mining enterprises and clarifying the processes for claiming low-grade deposits.

The shift to capital- and energy-intensive methods of extraction proceeded in parallel with rising recruitment of unskilled laborers and the ensuing tensions between workers and management. The State responded by passing a series of labor protection laws that helped define worker's right to a safe workplace. But these laws appear to have been implemented inconsistently and did little to assuage the volatility between labor and the firms.

The Depression Era and subsequent wartime production saw the extension of eminent domain powers to private enterprise for infrastructure development. The State also turned to the federal government increasingly for development assistance, be it through strategic mineral purchasing, highway funding, or the dedication of state lands to military uses. This federally-supported restructuring and active business recruiting efforts by state and local governments led to a significant growth in the western economies (Shermer 2013). As a result, cities like Los Angeles and Phoenix began to suffer from significant air pollution, alongside other urban maladies. The federal government responded by passing the well-known environmental laws of the 1960s and 1970s, the structure of which remains in place today. These created separate duties for contaminants depending on whether they were classified as "criteria" or "hazardous" air pollutants. In the long-view, it is evident that one era's solutions inspired the problems of the next, but how the rights and duties were restructured in each case depends on the nature of the resource and the stakeholders effected.

As discussed at the outset, the property rights literature permits several predictions to be made concerning the evolution of entitlements and duties. Namely, we expect that the definition of the most profitable and easily secured resources will take precedence. When costs are higher or a resource is difficult to control, statutes are instead more likely to be generic and difficult to administer. Technological innovation and state investment can of course reduce the costs of making issues tractable, while social pressures may direct public attention toward a given problem.

Much of this holds true for the case of Arizona's regulation of the metallic elements. The precious metals (e.g., Au, Ag) found in well-defined mineral veins were established in the very first acts of the legislature. As these resources were exhausted, technologies of mass extraction were developed and diffuse deposits became profitable (LeCain 2009). As expected, laws clarifying the security of low-grade placer claims were adopted. Similarly, as electrification and global conflict increased the demand for base metals (e.g., Cu, Zn), greater legislative activity was seen on this front. This included the conditional extension of the state's eminent domain authority to private mining ventures. And finally, when industrial and automobile pollution threatened major centers of commerce, well-defined limitations on the criteria pollutants were imposed.

But few lasting changes were actually set in motion by the principal sovereign authority—namely, the State government. Wealthy stakeholders, driven foremost by concerns in California and the Steelbelt, compelled (or inhibited) changes at the federal level which had a spillover effect onto state and local institutions. When there was little wealth-generating potential (e.g., aggregate mineral rights) or regulating metals threatened powerful financial interests (e.g., hazardous air pollutants), regulations remained poorly defined or inconsistently enforced. In this sense, it seems the metallic elements and greenhouse gases may share similar institutional impediments.

The combined effect of ascribing valuable mineral rights and favorable incorporation laws to early adopters beholden to affluent backers inspired a political and economic system that rapidly generated wealth, organizational capacity, and material production. The potential effects of this on America's corporate and geopolitical influence beyond its borders should not be under-appreciated (e.g., Wright 1990). And, as stated earlier, the geophysical characteristics of the resources partially encouraged this. The transaction costs required to identify and claim rights to metals in well-defined rock strata are significantly lower than doing the same for dynamic and well-mixed environments like the atmosphere and hydrosphere. This alone goes a long way toward explaining why certain rights were established earlier, by private parties, and with more certainty than others (Libecap 1993). It may also explain why imperial Rome opted for the taxonomy of ownership described by the Institutes of Justinian. Yet, it is also true that this institutional structure created a system where private costs and benefits remain far easier to define than the implications for the public and the resources we hold in common. This, despite decades of intellectual progress in environmental health and biogeochemistry.

In the West, policy-makers have repeatedly relied on the specter of an antagonist to legitimize public investments in private mineral and industrial development. First the threat was from hostile natives, then foreign natives, and finally the federal government. Much as Hobbes did in the 17th Century, this territorial narrative seems to have been effective at defending a system that prioritizes sovereign authority and the private appropriation of resources. As seen here for Arizona, the American legal environment experienced a gradual shift from market promotion to a focus on aggregate economic growth driven by vested interests during the 19th Century (Libecap 1993). The century that followed witnessed the expansion of federal authority and the rising influence of global markets, which did not so much overwrite older institutional structures as hybridize with them.

Taking a long-term perspective helps us to understand how today's rules, regulations, and norms emerged from the concerns of the past. Studies of resource and environmental governance can benefit, therefore, from research on the historically-contingent nature of its modern institutions. In the process, one might illustrate the problem-solving strategies of previous generations, while also revealing the contested and political nature of what may appear today to be standard, rational practice. Much of the discourse surrounding global change and sustainability is in response to the mounting public burden from the modern paradigm of resource governance. A society concerned foremost with keeping "mine and thine distinct" will eventually be forced to reckon with a world where everything is connected.

Chapter 5

CONCLUSION

5.1 Overview

This body of work has been concerned foremost with the non-commensal relationship between the biogeochemistry of the biotic and socio-technical systems of the Sonoran Desert. Metal pollution is among the major symptoms of this disparity. To understand the drivers behind this “silent epidemic” I adopted the approach of historical ecology, a discipline focused on the co-evolution of culture and place (Crumley 1994). Scholars of this domain have shown the merit of the consilience model in research, whereby the techniques of the sciences and humanities are integrated. In these concluding remarks, I summarize the insights gained from taking such an approach in the study of industrial landscapes. I end with a few, concise observations for sustainability in a changing world.

5.2 Recapitulation and Synthesis

Prior to this work, researchers lacked a suitable natural archive for exploring long-term, trace metal pollution in the Sonoran Desert. Through the pilot study discussed in Chapter 2, I sought to address this gap by investigating the inorganic chemistry of saguaro cactus spines inhabiting urban and rural landscapes. Radiocarbon dating indicated that the oldest rural spines were produced in the mid-1980s, while the urban samples covered back to the mid-1990s. Despite covering a relatively late phase of industrialization—one already subject to a suite of laws covering the release of metals—both landscapes show evidence of recent metal enrichment. In the city, the concentrations of numerous metals (e.g., As, Cd, Cu, Pb) rose three to seven fold between 2000-2005. Similarly, despite its remote location, the rural landscape experienced an increase in metal concentrations of 9-135 fold beginning around 2005. Moreover, by evaluating the co-linear pattern of multiple metals with an indicator of fuel combustion (i.e., V), I was able to determine that fossil fuel use was likely contributing to this pollution, at least in the urban environment.

To confirm that these trends were indicative of changes in the environment (and not an artifact of physiological changes in the cacti), I compared recent observations of ambient air chemistry to that of cactus spines grown during the same time. This validation procedure supported my expectation that changing metal concentrations in cactus spines are indicative of changes in the chemistry of the environment. This suggests that columnar cacti may provide a mechanism for studying long-term bio-geochemical change in arid settings, a novel contribution of my research.

There were inherent limitations to the approach of Chapter II, however. Most notably, I was able to observe temporal trends at only two locations. And based upon the heterogeneity of desert land uses, one could expect important spatial differences that may illuminate the source(s) of modern metal pollution. Using the ambient air data introduced in Chapter 2, I identified hot-spots of pollution for several of the metals found elevated in the cactus spines (McClain et al. 2003). These hot-spots tended to be located near dense urban areas (e.g., Phoenix), manufacturing centers (e.g., Agua Prieta), and historic mining districts (e.g., Miami). Using a mixture of historic reports, memoirs, and geospatial resources, I then investigated the political and economic factors that industrialized these contemporary hazardscapes.

Given the link between fuel combustion and metal pollution previously identified, Chapter 3 specifically explores the potential for the "energy-economy-environment" dilemma (i.e., 3E dilemma) to explain the production of metallic hot-spots in the Desert (Holdren 2008). Three key transitions are documented here. First is the shift from a utilitarian and ceremonial valuation of metals to one prioritizing scarcity and accumulation. This transition coincided with the arrival of Europeans and was solidified by American occupation, both of whom rely upon an exchange economy underwrote by precious metals.

The second transition saw the removal of constraints on metal production, principally with the arrival of the railroad. The rails connected Arizona's mines with eastern markets and, more importantly, with fossil fuel supplies. Electrification proceeded in tandem with railroad construction, creating a demand for base metals and a means for increasing production. Aside from the installation of rail- and transmission-lines, this transition was marked on the landscape by a shift to open-pit mining. The economics of scarcity were redefined as fossil fuels and automation allowed for the extraction and concentration of entire landforms.

The third transition witnessed a rapid increase in the incorporation of metals into urban landscapes. This was driven by the rise in manufacturing and the adoption of metals into the materials of daily life. The addition of lead to gasoline to promote fuel efficiency is emblematic of this shift, leading to widespread metal pollution along most travel routes. The restructuring of the western economies in response to the Second World War was the inciting event for this transition. Wartime production not only encouraged workers to gravitate to Arizona's cities, it expanded the use of metals—including the demand for leaded gasoline.

Clearly, the coupling of energy and metals has been at the heart of the industrial experience in Arizona. As the 3E dilemma proposes, metal consumption and emissions appear to have followed the rising demand for energy. Yet the historical geography of the Desert suggests the picture is more nuanced. Energy demands followed the motivations of the affluent, while metals tend to linger among the disenfranchised and forgotten. It is more the accumulation of energy demands than the democratization of access that explains the historical geography of metals. These findings represent an important contribution to the study of industrial metabolism and its capacity to transform or constrain landscapes. The novelty of this work stems from its simultaneous consideration of the economic, biogeochemical, and energetic forces shaping the unequal distribution of risk in the region.

Suspecting that the metallic hazardscapes of the Sonoran Desert were to some extent politically constructed, led me to investigate the institutional history of metal use in Chapter 4. I found that the evolution of Arizona's system of rights and duties concerning metals responded to many of the same forces described in the previous chapter. Procedures for asserting private claims to minerals hosting precious metals were set early on, followed by laws facilitating the extraction of lower-grade or less accessible ores. The hazards of mining also inspired some of the earliest environmental health laws in the state, but the degree to which they were enforced remains in doubt.

The Depression and wartime production saw the State push for federal support for metal extraction, while granting eminent domain powers for some mining activities. As manufacturing encouraged urbanization, federal and state policy-makers turned their attention to public and environmental health. Ultimately, the federal approach prevailed, separating metal pollution into two categories. Lead was regulated in the ambient air, while all other potentially-hazardous metals were governed through emission rates. I contend that neither approach is well-suited to the biogeochemistry of metals—a point which I will revisit below.

Historically, the regulation of metals has been less concerned with their inherent properties than where they occur. The biophysical characteristics of the matrices hosting metals affected how and when they were governed. Well-defined mineral bodies were quickly allocated to early appropriators, whereas metals in the atmosphere presented challenges that several generations of legislators were forced to deal with. And while the environment influenced the challenge of governing metals, society has also invested more in resolving some issues over others. The market incentivized significant expenditures in developing the means for claiming and extracting ore bodies with as little as half a percent copper. Meanwhile, the public sector has fallen short of developing effective strategies for removing metals from our atmosphere or domestic environments. When industrial ecologists describe cities as "mines of the future" many of us rightly wonder how they can provide critical resources for future generations (Li 2015). Perhaps we should also be asking: to what extent are some urban communities experiencing the biogeochemical equivalence of living in a mine shaft today?

Taken as a whole, my findings suggest that marked metal enrichment likely took place relatively recently in both urban and rural landscapes of the Sonoran Desert. Based upon the evidence presented and the timing of the change, I suspect the source of the urban metal pollution was associated with the rising popularity of light-duty trucks and sport utility vehicles at the turn of the 21st century. This coincided with low fuel costs and lagging fuel-efficiency standards (Hathaway 2018). The effect of this mode of transportation was likely enhanced by Phoenix's sprawling urban form and the failure of modern environmental regulations to adequately address the cumulative effects of non-degradable, hazardous emissions.

The source of the rural metals beginning in 2005 is less clear. While the rural landscape studied in Chapter 2 is exceedingly remote and abuts conservation lands, land use in the American southwest is a patchwork of resource preservation and national defense. Future research should investigate whether the biogeochemistry of these two objectives is in conflict. The soils of shooting ranges have been shown to host many of the same metals observed to be increasing in the rural landscape (Sanderson et al. 2018). How directly this relates to the chemistry of bombing and artillery ranges is less clear and worthy of investigation. It would prove a profound and tragic irony if the means by which we defend our homelands also serve to poison them.

5.3 The Biogeochemistry of Complex Societies

While the empirical findings summarized above may hold some utility for immediate and applied interests, this work aspires to move beyond environmental forensics. To do so, we must revisit and evaluate the implications of the social and ecological theories introduced throughout this document. Namely, we should consider how biological stoichiometry, industrial metabolism, and institutional evolution can collectively advance our understanding of the Anthropocene.

The Anthropocene demands that we consider the implications of the Earth System's current transition from the biogeochemistry of our ancestors to that of an industrialized world (Williams and Da Silva 1996, 2006; Schellnhuber et al. 2004). It requires an appreciation for the longue duree and a critical reflection on the path that brought us here.

All of non-human life and the majority of the human experience has been subject to the constraints and selection pressures of local environments. Only with the shift from subsistence to the surplus production of resources were societies able to liberate themselves from the physical and biogeochemical limits of the natural world (Smith 1990). They did so, in part, by socially differentiating and stratifying.

Organizational diversity and hierarchical control are recurring strategies of complex societies (Tainter 1988). As societies develop in material sophistication, they also tend to grow in institutional complexity and specialization (Tainter 1988). This complexity arises from the simple fact that institutions are used to solve socioecological problems. But the adoption of new institutions means that resources and energy must be continually directed toward their maintenance. In this way, institutional complexity and metabolic fluxes are implicitly coupled concepts (Tainter 1988). It follows then that the more complex a system grows the more structured its sources of energy must become (Schrödinger 1947). Such complex systems are maintained by exporting entropy and wastes to other coupled systems (Odum 1994). Resources may generate wealth and security for some, while limiting the resource potential of others, including future generations.

The imperial model of development acquires increasingly rich sources of energy through territorial expansion and resource capture. The institutional and ideological practices it employs—namely, profit incentives, private ownership, conflict, and social inequality—are routinely attributed to capitalism today, but are evidently much older than the current political economy (Richardson 1980, Smith 1990). Rome, for instance, captured the fertile valley of the Nile to flood the Empire with cheap food and it occupied Gaul to do the same with gold (Frankopan 2015). It also incorporated private property rights to promote the imperial accumulation of territory and reap the tax windfalls those institutions generated (Richardson 1980, Frankopan 2015).

This expansionist approach has its limits, however. Retaining institutional and territorial control means that near-term gains are matched with persistent maintenance and policing costs that erode reserves with time (Tainter 1988). Evidence of declining marginal returns on energy investment can be found across societies and ecosystems, suggesting that metabolic investments place fundamental limits on complexity (Odum 1969, Tainter 1988). Ultimately, the Western Roman Empire collapsed when new resource-rich territories could not be captured (Tainter 1988, Frankopan 2015).

Given this, one might assume that the fundamental constraint on imperial Rome was its reliance on organic forms of energy, which ultimately limited its territorial expansion. I have, after all, discussed above how acquiring fossil fuels liberated Arizona mining from the limits of the organic energy regime and enabled the industrialization of the Sonoran Desert. The fundamental weakness of this assumption is its myopic preoccupation with energy. While the thermodynamic paradigm emphasized by nearly all of the scholars cited above has its merits, biogeochemists have demonstrated that stoichiometric constraints can outweigh the role of energy (Sterner and Elser 2002).

The chemical "recipes" of nature, on which all life is founded, place fundamental constraints on the use and combination of elements. These constraints are passed on to both social and ecological systems. The influence of stoichiometric constraints are most significant when the chemistry of the consumer and their environment are significantly out of balance (Sterner and Elser 2002). While industrialization has liberated us from the constraints of organic forms of energy, it has also drastically altered our chemical interactions with the Earth.

The modern, industrialized world uses both matter and energy to a greater extent and diversity than any prior civilization (Smil 2014, Matos and Wagner 1998, Fischer-Kowalski et al. 2014). There has also never been a time when the chemistry that we rely upon for daily life has been more different than that which nature provided during the course of our evolution (Williams and Da Silva 1996, Sen and Peucker-Ehrenbrink 2012). In many ways, this material sophistication has been a great boon. Modern housing, sanitation, and medicine drastically reduced the risk posed by infection and traumatic injury—the principal causes of human mortality from the Paleolithic era to the Anthropocene (Eaton et al. 1988).

But modern hazards, like the so-called "diseases of civilization" that now account for seventy-five percent of all mortalities among the affluent, may well have spawned from the biogeochemical imbalance of modern life (Eaton et al. 1988, Eaton et al. 2002, Lucock et al. 2014, Fox 2018). The evolutionary discordance hypothesis posits that these modern maladies, which include cancer and degenerative disorders, are caused by the chemical mismatch between the environment in which our genome evolved and that which we are creating (Lucock et al. 2014). Modern metal burdens relate directly to this thesis and, not suprisingly, have been implicated in many of these diseases (Kozlowski et al. 2012, Gaetke et al. 2014, Fox 2018).

To truly evaluate the evolutionary discordance hypothesis, sustainability science will require new theoretical tools. Much as biological stoichiometry strives to integrate ecosystem ecology's interest in the flow of energy and matter with evolutionary biology's focus on genomic function (Elser 2006), sustainability must find the means to bridge these same concepts with that of industrial metabolism. Doing so may allow us to truly contemplate what the Anthropocene means for the evolution of life and society. At the moment, we have no rigorous or even coherent method for anticipating what happens when natural selection's system of chemical signals inciting molecular responses is hijacked by the subjective ideologies and practices that are reshaping the biogeochemical environment. Clearly a theoretical basis for studying the biogeochemistry of complex societies is needed. A project of the scale present here cannot hope to define that theory in any meaningful way. But perhaps the simplest of its connections are emerging from the inquiry that began here.

In the spirit of the Anthropocene and its charge that we ponder both the ancient and the modern, I bring us back once more to Rome in order contemplate the challenges and opportunities for sustainability in the Anthropocene.

5.4 Is Rome Burning?

This work began with the anecdotal observations of a physician to the ill-reputed Roman emperor Nero—a man, myth holds, who fiddled away while his city fell to ashes. To the extent that metals appear to be accumulating in our cities from emissions driven by the friction and combustion of luxury vehicles, perhaps we moderns have more in common with Nero than we would like to admit. Like those of us alive today, Nero lived during an era of globalization when trade and conflict linked people from across the known world (Frankopan 2015). Ancient Romans and modern Americans have another thing in common as well. In both cases, our average bodily burden of lead is several orders of magnitude greater than those peoples whose society did not rely so intensely on metals (Fig. 1).

We inherited much of our approach to governing the biogeochemical cycles from the Roman worldview. And, as the investigative journalist Andrew Nikiforuk has contended, our approach to managing energy is much like Rome's as well (2012). Rome expanded its territorial reach to acquire slaves that provided the labor that fueled the empire. Modern nations scour ever more remote corners of the earth in search of minerals to fuel and form our industrial landscapes. By 2050, metal demands are expected to reach 5-10 times what they are today (Graedel and Cao 2010). In response, some have even begun looking to the stars, contemplating the feasibility of mining metal-rich asteroids to meet tomorrow's demand (Brophy and Muirhead 2013). If we are to continue along the modern path toward increasingly complex chemical formulations and uses, clearly some adaptations are in order. Otherwise we may find that our ingenuity has crafted a world which our genome cannot inhabit.

As I describe in the preceding chapters, we have traditionally acted through a system of values that prioritize scarcity (e.g., the "precious" metals). But this belief system appears to be ill-suited for managing the trade-offs between the utility and hazards of potentially-toxic elements, such as metals. This is evidenced by the apparent inability of federal and state authorities to address pollution issues that act contrary to wealthy interests. Often this is couched behind the debate over the priority of public and private dominion, or the rights of firms versus the rights of the state.

Recent actions in the courts may offer a glimmer of hope to those who doubt that executives and administrators are apt to develop a wise response to pollution issues. Drawing from a growing precedence in environmental law and the philosophical tradition that sovereigns assume a duty to protect their citizens, a partnership of young people, lawyers, and advocates for future generations have filed a legal suit against the United States (Juliana v. United States 2016, Blumm and Wood 2017).

They assert that their public trust rights have been violated by the government's long-standing support for fossil fuel interests and call for the state to develop the means for protecting their right to a safe atmosphere. While the filing is concerned principally with the risks posed by greenhouse gas emissions, we have seen here that the metal-energy nexus is tightly coupled in the modern world. Juliana represents the potential for a fundamental shift in our environmental institutions, the likes of which have not been seen in half-a-century.

As we saw with the "hazardous profession" laws, re-writing rules and regulations does not necessarily invoke change. Institutional reform may however open the door to meaningful interventions. For instance, low metal soils can be locally sourced from areas around all major cities in the U.S. (Gustavsson 2001). This can act as a short-term intervention to mediate the risk of metal-enriched dust in many communities. The greater issue is a lack of adequate recycling mechanisms in modern society (Graedel and Cao 2010, Haff 2014).

All complex structures are maintained by the throughput of energy and matter. Industrial systems differ from many ecological ones in that they fail to co-evolve with systems that capture their wastes. Recent innovations in carbon-capture fuels, which appear to be free of contaminants, represent one approach to recycling industrial throughput (Keith et al. 2018). Complementary adaptations would have to attend to the myriad of other sources of metal emissions (e.g., brake pads, tire wear; Hjortenkrans et al. 2007).

Scholars to the Anthropocene have begun to attend to the challenging task of contemplating the governance of the biogeochemical cycles. Long-term socio-ecological research and the study of natural archives have demonstrated the profound effect of human activities on the life-supporting systems of the planet. Sustainability science must continue to provide insight and reflection on the drivers and implications of these changes. The historical ecology of place, such as was undertaken here, can provide the empirical basis for such work. But it will do little good without a broader shift in our paradigms. As Palsson and others suggest, we must attend to the fact that “we are part of a complex network of elements and relations that make up planet earth, but we are the only part that can be held responsible.” (p. 11; 2013). If we wish to leave an Earth System that can provide for future generations, as it has for us and all those who came before, we must take responsibility for the change we inspire.

NOTES

1. Mean metal concentrations in aersols measured at ambient air monitoring stations located throughout the western U.S. were calculated from data provided by the Interagency Monitoring of Protected Visual Environments program (Malm et al. 1994). Using an inverse distance weighted interpolation (IDW), I estimated the distribution of metal concentrations between stations. IDW places an emphasis on the proximity of data points and is appropriate when local sources are expected to drive variability. Hot-spots, or concentrations above the global mean (i.e., average across all stations), are depicted in figure 7.

2. The trails, wagon roads, and settlements depicted in figure 8 were digitized from the map and memoirs of an American geologist and explorer active in the Desert during the mid-19th Century (Pumpelly 1870). Silver deposits were delineated by heat-mapping silver occurrences documented in the U.S. Geological Survey's Mineral Database (Mason and Arndt 1996). Heat-mapping interpolates a surface based upon the density of point features, in this case silver occurrences. Densities falling within the upper 50th percentile of silver occurrences found across the Americas are shown here to illustrate how mining and transportation activities clustered around areas naturally endowed with precious metals. Finally, silver extraction statistics were derived from Keith et al. and depict life-of-mine production estimates (1983). All geospatial procedures were conducted in QGIS (v. 2.18.14).

3. Copper deposits were delineated using the same methods and resources described for figure 8, except that copper occurrences were queried and used as an input for the heat-map depicted. Lead production statistics were derived from Keith et al. and cover life-of-mine figures for operations between 1858-1981 (1983). Smelter locations were acquired from the U.S. Geological Survey's Mineral Database (Mason and Arndt 1996).

4. Locations were digitized by hand using the Sanborn Fire Insurance Maps for 1911, 1915, and 1958. Land uses involving oil tanks, oil pump houses, oil warehouses, bulk oil storage, and gasoline tanks were all categorized as oil and gas infrastructure. Electrical land uses refer to electrical repair shops and manufacturers identified in the map series.

5. Since the Industrial Revolution anthropogenic forces have become a dominant driver of many metals (e.g., Pb, Cu; Sen and Peucker-Ehrenbrink 2012).

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APPENDIX A

SUPPLEMENTAL MATERIAL

A.1 Supplemental Tables

Table 3: Measured concentrations of NIST 1575 (Pine Needles) compared to expected concentrations. All values are in parts per billion.

Element	Expected	Observed 1	Observed 2	Observed 3	Observed 4
Mn	675000±15000	484611	395327	499634	396466
Al	545000±30000	607374	486366	618953	488746
Fe	200000±10000	52632	39312	54224	37308
Rb	11700±100	14403	12415	14786	12573
Pb	10800±500	275	137	166	128
Sr	4800±200	6109	4989	6253	4967
Cu	3000±300	3349	2646	3348	2578
Cr	2600±200	439	301	380	559
As	210±40	40	21	42	15

Table 4: Number of samples falling outside various thresholds of reliability.

	Ag	Al	As	Cd	Cr	Cu	Ni	Pb	Sb	Zn
Below LOD	1	0	5	0	0	0	0	0	0	0
Below BEC	5	0	29	0	0	1	1	0	0	7
Below Blank mean	1	1	0	2	0	0	0	3	0	0
Above Top Std.	0	0	0	0	0	0	0	8	0	0

Table 5: Results of linear regression with mean-normalized, first-differenced observations of ambient air and saguaro spine chemistry. In a few cases, extreme values were removed to meet the assumption of normality required in linear regression. The footnotes have been included to describe their problematic features.

Site	Dep. Var.	Ind. Var.	# outliers removed	β (± s.e.)	t	p
URB	ΔEF(Pb)	$\Delta \mathrm{Pb}_{t-2}$	0	0.38 (±0.20)	1.88	0.075
			1*	0.49 (±0.22)	2.26	0.036
	ΔEF(Cu)	$\Delta \mathrm{Cu}_{t-2}$	0	0.28 (±0.22)	1.28	0.217
			2*†	0.55 (±0.22)	2.46	0.024
	ΔEF(Zn)	ΔZn	0	0.45 (±0.19)	2.35	0.028
RUR	ΔEF(Pb)	ΔPb	0	0.62 (±0.17)	3.68	0.001
	ΔEF(Cu)	$\Delta \mathrm{Cu}_{t-3}$	0	0.32 (±0.16)	2.01	0.059
	ΔEF(Zn)	$\Delta \mathrm{Zn}_{t-6}$	0	0.44 (±0.23)	1.85	0.083
			2α	0.35 (±0.14)	2.41	0.030

* Sample URB-14 had the highest observed values for ΔCu and ΔPb in ambient air.

† Sample URB-22 had the highest observed value for ΔEF(Cu) in saguaro spines.

α Sample RUR-12 and RUR-17 had the lowest observed values for ΔEF(Zn) in saguaro spines.

A.1.1 Supplemental Figures

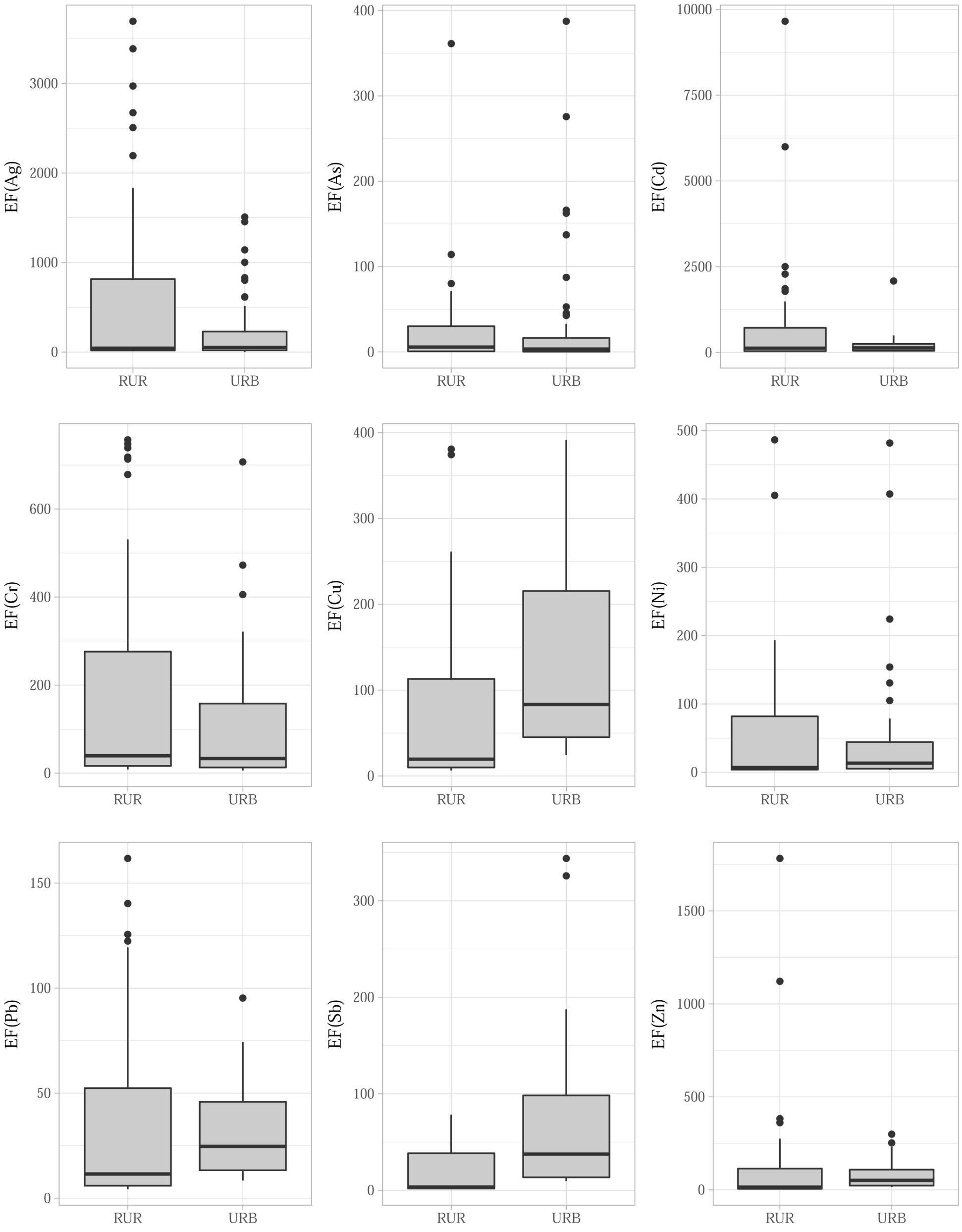

Figure 15: Box plots of enrichment factors for metals at the urban and rural study sites.