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A geospatial approach to uncovering the hidden waste footprint of Lake Superior's Mesabi Iron Range

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ABSTRACT

For decades, the Lake Superior Iron District produced a significant majority of the world's iron used in steel production. Chief among these was the Mesabi Range of northern Minnesota, a vast deposit of hematite and magnetic taconite ores stretching for over 100 miles in length. Iron ore mining in the Mesabi Range involved three major phases: direct shipping ores (1847–1970s), washable ores (1907–1980s), and taconite (1947–current). Each phase of iron mining used different technologies to extract and process ore. Producing all of this iron yielded a vast landscape of mine waste. This paper uses a historical GIS to illuminate the spatial extent of mining across the Lake Superior Iron District, to locate where low-grade ore processing took place, and to identify how and where waste was produced. Our analysis shows that the technological shift to low-grade ore mining placed new demands on the environment, primarily around processing plants. Direct shipping ore mines produced less mine waste than low-grade ore mines, and this waste was confined to the immediate vicinity of mines themselves. Low-grade ore processing, in contrast, created more dispersed waste landscapes as tailings mobilized from the mines themselves into waterbodies and human communities.

1. Introduction

Worldwide, the storage and handling of tailings has become a major environmental issue for mining. The scale of tailings production is immense, since low-grade ore extraction creates significant volumes of waste for each quantity of merchantable product produced. Monitoring the environmental legacies of tailings requires the ability to map where the tailings were produced and deposited over time, which is often surprisingly difficult given the limitations of historical records. This paper uses spatial history techniques, though the creation of a historical GIS, to uncover the hidden waste footprint of iron mining across the Mesabi Range. We integrate a variety of sources to map the iron ore extracted from the Mesabi Range, their processing sites, and their waste footprints. We ask: how did iron mining footprints change over time in the Mesabi Range, and how did changing technologies affect the waste footprint over time and space? This paper is the first part of a larger project that will explore the ways that these historic waste landscapes may influence current environmental factors such as water quality and water quantity.

For the past 120 years, the Lake Superior Iron District has been the top producer of iron ore in the United States (Fig. 1). Here, iron mining has produced an enormous volume of waste in the form of gangue (waste rock) and tailings (finely ground materials left after processing of lower-grade iron ore). Much of this waste is now difficult to see from the ground, because it is concealed beneath lakes that filled abandoned mines and forests that have begun to grow over some waste piles. Nevertheless, even when the waste is hard to see, it may continue to affect the environment, particularly when it becomes mobilized into water and air.66

North American economic expansion after the Civil War required steel, which in turn required abundant sources of iron ore. The iron ranges of Minnesota, Wisconsin, and Michigan – collectively known as the Lake Superior District (Fig. 1) – were the continent's most important source of iron ("The Iron Ore Dilemma," 1945, p. 129). By 1890, more than 50% of the iron ore used by the American iron and steel industry came from the Lake Superior District. Half of a century later, by the end of World War 2, the region supplied 85% of the nation's iron ore (Harrison, 1953). After World War II, much of the Lake Superior Iron District's

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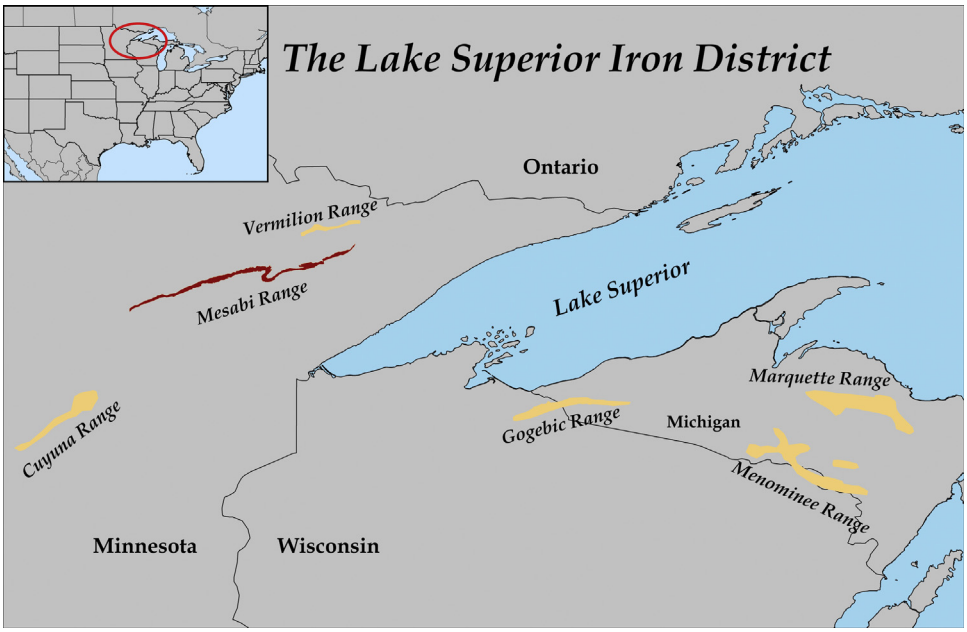

Fig. 1. The Lake Superior Iron District.

production shifted to the Mesabi Range of Minnesota. By 1980, 80% of the iron ore produced in the Lake Superior District came from this one range.

Iron mining in the Lake Superior Iron District involved three major phases: direct shipping ores (1847–1970s); washable ores (1910–1980s); and taconite (1947–Today). This paper asks: what new forms of mine waste resulted from the technological shift to lower-grade iron ore mining in the Lake Superior District? What spatial shifts in mining production and waste production occurred with the development of lower-grade iron mining? Where were tailings produced and deposited? Recent scholarship focused on extractive industries has illuminated the interdependence of technology and the environment, an approach named "envirotech" that lies at the intersection of environmental history and history of technology (Reuss and Cutcliffe, 2010). Envirotech research in mining highlights the historical intermingling of nature and culture that has effectively shaped the mining landscape (Andrews, 2008; Curtis, 2013; LeCain, 2009; Morse, 2003; Reuss and Cutcliffe, 2010). These studies rely on analytical approaches such as actor-network theory and systems theory to understand how "complex bundles of human values, institutions, and technology" such as mining systems developed and functioned (Finger, 2013). People acting as so-called "systems builders"(the innovators who work to add momentum to a technological system), the material technology, and the environment itself all acted as factors in the shaping of the Mesabi mining landscape (Bijker et al., 1987; Hughes, 1983). In the Mesabi, systems builders included the geologists who explored the region during the 1850s, the numerous land-holding agencies that leased mineral rights to mining companies, and the scientists who constructed social networks with metallurgists in the American Southeast to bring low-grade ore concentrating technologies to the Lake Superior District (Davis, 1964).

The material technologies that shaped the Mesabi include the rail lines, ore conveyors, washing plants, and tailings basins—all features that represent human expertise and knowledge. This expertise is seen in the professionalization and education of mining engineers and mine superintendents, as well as with the incorporation of chemists and metallurgists in the mining industry (Hovis and Mouat, 1996; Spence, 1970). Additionally, as more efficient technologies were introduced to a region, the abundance of redundant buildings, machines, and transportation systems within the mining landscape represents a changing production of knowledge. In the Mesabi Range, this changing production of knowledge occurred during the shifts from direct shipping ore, to washable ore, and to taconite, and these shifts had rippling effects on the larger environment of waste production.

The environmental components that shaped the Mesabi mining landscape include both the initial environmental context that enabled mining to boom, and the environmental consequences that flowed from mining. The ore formation (the Biwabik iron formation,) the region's abundance of timber, Lake Superior which allowed for shipping ore to markets, and the region's surface waters were among the environmental components necessary for profitable low-grade iron mining (Hatcher, 1950). Yet on their own, none of these environmental components made mining inevitable; each of them first had to be transformed by technology, labor, capital, and expertise. The ore body had to be explored and developed; the trees had to be logged and milled; the estuary at Duluth had to be shaped into a deep-sea port, and the surface waters had to be channeled and pumped to the processing plants.

Economic transformations helped enable these envirotech modifications of the Mesabi Range into the world's largest iron ore producer. Between 1896 and 1900, small American steel companies were replaced by large steel corporations that controlled not just steel mills, but also the iron mines that supplied those mills (Reynolds and Dawson, 2011). Processing low-grade ores required extensive technological and financial investments in beneficiation, investments that large, vertically-integrated corporations were better able to afford. Yet state power was also involved in enabling these transformations. Federal involvement in the creation of a shipping and railroad infrastructure within the Great Lakes, starting with the 1855 construction of Sault St. Marie locks, enabled 19th century expansion of the Lake Superior District (Bowlus, 2010, Reynolds and Dawson, 2011). In the 20th century, the shift to low-grade ores required government investments in infrastructure and new tax policies (Thistle and Langston, 2016).

To date, most histories of iron mining in the Lake Superior District have focused on the development of the region as a hub for direct shipping ores (de Kruiff, 1929; Hatcher, 1950; Lampa, 2004; Reynolds and Dawson, 2011), or taconite mining (Bastow, 1986;

Davis, 1964; Manuel, 2015). Washable ores have received considerably less attention. Similarly, few studies have explored the environmental impacts or waste impacts of iron mining in the region, focusing instead on business history of hematite (Reynolds and Dawson, 2011) or engineering demands of taconite (Manuel, 2015). Identifying, understanding, and managing mine wastes remains a pressing environmental challenge. Mining's environmental consequences include some waste products that are visible today, such as tailings ponds, mine-pit lakes, and gangue piles. But other transformations are obscured from our gaze: ground water pollution, asbestos contamination, and mercury mobilization. While many of the physical structures of iron mines such as rail lines, steam shovels, and shaft houses no longer remain on the landscape, their environmental footprints persist.

As evident in Arn Keeling and John Sandlos' ongoing research at the Giant Mine in the Northwest Territories, communities and public policy-makers must contend with the environmental legacies of abandoned industrial operations which continue to "exert some sort of malevolent effect during their afterlife" (Sandlos and Keeling, 2013 p. 81; see also Keeling and Sandlos, 2015). In the Mesabi Range, the valueless waste products were deposited near the mines and concentrating plants, while the valuable ore and mining profits were exported out of the region. Although historical trade journals cover the technological processes employed to produce different forms of mine waste, where the waste is located, how much waste was produced, and what the waste consists of, have remained unstudied in the broader context of Lake Superior iron mining.

In recent years, an interdisciplinary mass of scholars has turned its attention to the use and potential of GIS and related geospatial sciences to uncover and explain patterns and processes of the past. Historical geographers and environmental historians have been grappling with how to best model and analyze historical landscapes, a challenge because of the need to create complex historical datasets from original archival data. Successful examples include Geoff Cunfer's reexamination of the causes of the dust bowl, Matthew Hatvany's modeling of salt marsh evolution in the St. Lawrence Estuary, Anne Kelly Knowles' reconstruction of the landscape of the early American iron industry, and Lafreniere and Gilliland's recreation of the built environment in the nineteenth century industrial city (Cunfer, 2008; Hatvany, 2014; Knowles, 2012; Lafreniere and Gilliland, 2015). We follow these methodological approaches developed in the blossoming discipline of Historical GIS (HGIS) and apply them to the recreation of the landscape of mine waste in Minnesota's Mesabi Range.

The Mesabi Range contains a large number of abandoned mines and processing plants, places where much of the physical remains of industrial activity have been removed, leaving opaque reminders of the region's intensive mining past. This study uses integrated techniques from historical geography, environmental history, and industrial archeology to uncover a hidden landscape of waste where the remains of industry continue to interact with the environment long after the mines and processing plants have closed.

2. The three phases of mine waste

2.1. Direct shipping ore wastes

Direct shipping ores were located throughout the Lake Superior Iron District and operated mainly between 1847 and 1970. They were first mined in the Michigan iron ranges and then in Wisconsin and Minnesota. Direct shipping ores were primarily hematite, a mineral that contained the highest percentage of iron, ranging from 50 to 70% (Manuel, 2015). Direct shipping ores were extracted through selective mining processes, rather than through bulk mining. To maximize the efficiency of selective mining, engineers' goal was to handle the least amount of waste possible (Cummins and Given, 1973). The high percentage of iron in these hematite deposits meant that this ore did not require processing before it could be shipped. Rather, direct shipping ores could be shipped directly to smelters in the lower Great Lakes, where they could be processed into steel.

The waste footprint created from high-grade ore mining consisted of piles of overburden and "gangue," a form of waste rock. Overburden consists of the organic material that covers shallow ore deposits, removed by scraping the mine's surface. Gangue consists of the bedrock structures that surround underground veins, encountered when sinking a shaft and developing underground excavations (Young, 1932). To save on transportation costs, these wastes were typically located within less than a mile of each mine. Direct shipping ore mines did not produce tailings, the fine ground material left over after processing lower-grade ores. Because overburden and gangue are composed of material that was not finely ground or processed, these wastes were not particularly mobile. Unlike much of the tailings produced during lower-grade ore processing, poor rock and overburden have remained in place for decades as static features on the mining landscape of the Mesabi Range (Thurman, 1992).

2.2. Washable ore wastes

In the United States, fears over the depletion of high-grade mineral deposits became pronounced soon after World War 1. The mining industry responded with economic and technological changes that allowed the exploitation of increasingly low-grade ores. Companies came to rely on science, engineering and rationalization to turn large amounts of what had earlier been seen as waste into profits. As Logan Hovis and Jeremy Mouat argue in their study of North American copper mining, the redesigning of the North American mining system centered on the "adoption of higher-volume, nonselective methods that emphasized the quantity rather than the quality of ore brought to the surface" (Hovis and Mouat, 1996).

North American engineers developed the first intensive low-grade mining technologies to exploit the porphyry copper deposits of the American West. Porphyry copper ores, such as the ones found in Utah's Bingham Pit, contained close to 98% waste. For these mines to be successful, engineers needed to deploy an extensive bulk-mining system that could efficiently extract vast tracks of ore, coupled with a concentrating technology that could elevate the finite percentage of copper up to a merchantable content (LeCain, 2009). LeCain argues that such low-grade mining technologies acted as mechanisms of "mass-destruction," because they were engineered to extract vast quantities of material indiscriminately and efficiently. In particular, open-pit mining technology allowed mining engineers to effectively rationalize and systematize a natural system so that "nature itself was a factory carved out of natural stone" (LeCain, 2009). Similarly, the washable ore and taconite mines found in the Mesabi Range owed their existence to an innovative enviro-technological system.

After World War 1, mining companies in the Lake Superior Iron District researched new technologies to convert less concentrated, lower-grade iron deposits into profitable ores, a process called beneficiation (Birkinbine, 1919, p. 19). In the US West, beneficiation included chemical methods, such as flotation units and cyanide leaching tanks, to concentrate low-grade nickel and copper ores (Hovis and Mouat, 1996; LeCain, 2009). In the Mesabi Range, however, beneficiation relied upon mechanical methods to concentrate iron content from washable ores (Manuel, 2015; Smith, 1993). The first beneficiation technology in the Lake Superior District focused on the washable ores located primarily

in the western extent of the Mesabi Range (Counselman, 1941). Washable ores were largely composed of decomposed hematite mixed with loose sand, and typically contained between 30% and 45% iron ("Coleraine District, Mesabi Range," 1907). Because of the low percentage of iron ore and the high percentage of silica, washable ores required processing to separate the waste from the valuable ore before they could be shipped or sold.

Low-grade iron ore beneficiation occurred at beneficiation plants, facilities that required a great deal of water and therefore were typically located on water bodies located within three miles from the mine pits themselves. Lakes provided beneficiation plants with an ample supply of water that was introduced as the ore traveled across screens and classifiers, riffled tables, and through mechanisms that captured heavy material and released the lighter-fine material as tailings (Taggart, 1927). The high costs associated with constructing beneficiation plants meant that each mine did not have its own nearby beneficiation plant but instead sent their ore to plants, located from up to 5 miles from the mine. These beneficiation plants were called either "central milling plants" or "custom mills", as they were equipped to treat a variety of ores from an assortment of mines, such as the Coons-Pacific Concentrator in Eveleth, MN ("Coons-Pacific Iron Ore Treatment Plant," 1953).

Beneficiation plants produced abundant quantities of tailings, a slurry of water and extremely finely-ground, silica-laden rock. Optimally, the tailings produced from processing washable ores accounted for only 30% of the total material extracted, and the concentrated ore carried an iron percentage of just over 50% ("Work on the Mesabi Range is Extensive," 1906). But since the grade of washable ores varied by deposit, the amount of waste within each deposit could be higher, resulting in a greater production of tailings.

In the Mesabi Range, tailings were initially deposited directly into inland lakes within 1 mile of a beneficiation plant. These tailings were deposited into lakes through a system of launders (or concrete troughs), or were pumped to the lakes through pipes. Because beneficiation plants often operated in either 12 or 24 h shifts, the flow of tailings exiting the facilities required a substantial sink so that wastes would not back up and slow production (Taggart, 1927). Washable ore mining matured in the 1930s, and mining companies relied on more advanced beneficiation methods, such as heavy-media separation and sink-float methods, to reclaim the fine values found within these low-grade ores and within many of the former tailings basins (Hubbard, 1948). As the mining of washable ores intensified, these tailings basins grew in size and in number ("Nashwauk . . . ," 1958).

The production of tailings brought mine waste outside of the immediate mining landscape, extending the environmental footprint of mining some distance from the mines themselves ("By the Way," 1914). If deposited in a water body, tailings were finely ground enough so that they could migrate far from the locations they were laundered, ending up in water bodies downstream of the beneficiation plants that produced them. If deposited on land, some tailings were blown into the air and transported by air currents into nearby towns, which raised concerns among residents.

2.3. Taconite wastes

During the Second World War, as iron exports intensified for wartime steel production, depletion fears grew in the Lake Superior district. Mining engineers developed a technology allowing exploitation of taconite, an abundant yet very low value iron ore in the Lake Superior Iron District. Taconites contains up to 30% iron (Manuel, 2015). Because taconite ores are disseminated within extremely hard chert-based deposits, they are much more demanding to extract than washable ores, which could be scooped from the earth with front-end loaders. To recover the value found in taconite ores, mining companies had to first fracture the deposit with explosives, then repeatedly crush and grind the ore down to a consistency almost as fine as talcum powder (Kohn and Specht, 1958). Throughout these steps, water was introduced to the ore to help separate the waste from the value. After the taconite ore was reduced to a fineness amiable to concentration, this slurry of iron, water and waste was fed into magnetic separators and gravity classifiers, which essentially produced two products, taconite concentrates and tailings. The concentrates were de-watered, then fed into a balling drum along with more water and betonite clay (Hunt, 1951). This mixture was tumbled until the wet clay binded with the taconite forming pellets, which were collected and roasted in a furnace, in order to remove water and also to harden the pellets (Hunt, 1951). The tailings were laundered from the processing plants and deposited into either lakes or basins within 50 miles from mines. Up to 12 different mines used a typical taconite beneficiation plant.

The tailings produced from taconite processing differed from those produced from washable ore in scale and content. Rather than being primarily silica-based, like the tailings produced from washable ores, some tailings produced from taconite processing contained materials such as asbestos which presented new technological challenges for containment (Thistle and Langston, 2016). Taconite tailings were typically dumped into water bodies and basins, rather than on land, and they could migrate far from where they were originally deposited. One such case involves Reserve Mining Company, which mined taconite at the Peter Mitchell mine in Babbitt MN, at the far eastern extent of the Mesabi Range. But rather than process the ore near the mine, Reserve found it more profitable to transport the ore by rail 47 miles to a beneficiation plant in Silver Bay, on the shores of Lake Superior, where the tailings could be dumped into the lake. Assured by the Reserve Mining Co. that tailings would remain contained within a deep trench in the lake, in 1947 the State of Minnesota granted permission to Reserve to dump its tailings into Lake Superior. In 1955 the company's plant began operations (Manuel, 2015; Thistle and Langston, 2016). Yet Reserve's tailings, and the asbestiform fibers within them, mobilized through the western arm of Lake Superior, eventually contaminating the drinking water supply of Duluth (Thistle and Langston, 2016). After years of controversy, the United States filed a lawsuit against Reserve in February 1972, seeking abatement of the tailings discharges into Lake Superior. In March 1980, the dumping of taconite tailings into Lake Superior was finally halted, after a long series of federal and state lawsuits against the company. The environmental consequences of Reserve remain contested, although recent research shows that taconite miners on the Mesabi Range have an increased risk in developing mesothelioma, a fatal lung disease linked to asbestos exposure (Finnegan and Mandel, 2014).

3. Data and methods

To illuminate how the technological shifts to low-grade iron ore mining created different forms of waste in the Lake Superior basin, we designed a Historical Geographic Information System (HGIS) database. This HGIS database allows us to map and analyze the impacts of historical mining spatially, illuminating the time-space patterns of ore production and the locations where waste was produced within the Lake Superior Iron District, spatial patterns that research in the archives alone would not reveal. Our HGIS database helps us reconstruct the historical landscape of the Lake Superior Iron District, and explore how shifts in technology over time placed new demands on the environment, specifically where ore was extracted and where new waste was laundered.

3.1. Placing mines on the landscape

We constructed our HGIS by integrating a host of primary archival data, secondary textual source material, and publicly available datasets related to mining in the Lake Superior Iron District. Our first step required identifying what iron mines existed in the Lake Superior Iron District, and then locating them in space and time. The United States Geological Survey (USGS) maintains a fairly complete and accessible GIS database called the Mineral Resource Data System (MRDS), consisting of locational data for active and historical mines within the United States. The USGS database contains the spatial coordinates of individual mines stored as a point-based shapefile. We selected our data from a geographical search tool which generated a shapefile consisting of over 400 individual iron mines that once operated in the region. To remove possibly redundancies and cross-check the accuracy of the locational data within the MRDS database, we then compared this shapefile with a mineral dataset acquired from MinDat, a non-profit organization focused on developing inventories of mining properties.

We then collected historical qualitative and quantifiable data for building the HGIS which would allow us to spatially analyze changes in mining and waste production over time. This included identifying mine owners and mine operators, determining the type of ore extracted, calculating years of mine activity, and adding the annual tonnage of ore produced. Historically, the quantity of ore shipped from a mine was recorded at number of locations: on scales at the mines before the ore was shipped to ports; at the port of origin; and at the final destination, such as iron furnaces in Cleveland (Iron Trade Review). For the mining companies, it was important to keep an accurate record of annual ore shipments so that state taxes owed could be determined. Accurate ore weights also signaled to investors and shareholders the progress made during the year (Parks, 1949). For the shipping companies, an accurate measurement of how much the ore weighed was essential for calculating what they would charge the mining companies for freight, as well as in ensuring that the shipping companies were staying within their shipping quotas. Finally, the iron furnaces at the end of the transaction weighed the ore again to ensure that there were no discrepancies between the logs at the mine, the ports, and at the furnaces. The end result of all of this weighing was annual shipment logs for the Lake Superior Iron District published in mining and steel-industry trade journals. For our analysis, the quantities of ore shipped were the critical, quantifiable measurable that we used in recreating historical waste footprints.

We located our data from three key mining journals: *The Iron & Trade Review*; *Steel*; and *Skillings' Mining Review*. We extracted and entered 11,447 individual entries of iron ore shipments from mines in the Lake Superior basin for each year between 1898 and 1981, along with the quantities of taconite mined in Minnesota from 1950 to 2010 as reported in the Minnesota Mining Tax Guide, published by the Minnesota Department of Revenue. We cross-checked data for accuracy by comparing the ore shipment data from these trade journals and with mine shipment data provided in annual USGS reports.

The annual mine production data was entered into the HGIS, with a unique identifier linking each mine through time. Individual points, each representing a year of mine shipping activity at a given geographic location allow us to create a visual representation of mine shipments over time. For instance, if the La Rue mine shipped ore in 1906, 1907, 1909, and 1933, the HGIS would have four points associated for the La Rue mine, one for 1906, 1907, 1909, and 1933. These points would all share the same spatial coordinates, but each point would be representative of the individual year that the La Rue mine shipped iron ore. By adding this shipment data to our HGIS, we now had both the locational coordinates of the mines and also data that showed annual production totals per individual mine over time.

3.2. Recreating a landscape of beneficiation

Where were low-grade ore processed in the Mesabi Range and the greater Lake Superior Mining District? With the exception of modern taconite plants, the answer to this question was widely unknown. Government agencies, such as the USGS, have an inventory of the locations of active and abandoned mines, but no agency has maintained a similar inventory for the facilities that processed ores, produced tailings, and the location and extent of such tailings. Since there has been no prior investigation into the history of beneficiation in the Lake Superior district, we elected to explore not only where mines were located, but also where the low-grade ores were processed, and how much waste they produced.

To accomplish this, our next step in building the HGIS was to identify which mines were treating low-grade ores and producing tailings. This step required re-examining trade journal reports and the USGS Minerals Yearbook, an annual publication that reported mining highlights of individual minerals from the past year. After we located the mines first producing washable ores, and later taconite, we next needed to identify where these mines were treating these low-grade ores, specifically, where were the beneficiation plants? Identifying where the processing plants were located and when they operated was not as straightforward as locating the mines themselves, since there is no existing federal inventory of these facilities. To produce a database of beneficiation plants, we needed to create an entirely new historical spatial dataset from a number of historical sources.

To create an inventory of beneficiation plants within the Lake Superior District, we consulted trade journals, historical maps, Minerals Yearbooks, reports from the Lake Superior Iron Ore Association, and historical aerial imagery, searching for plant construction dates, locational information, and the names of mines that sent their ore for treatment. Next, we compared the findings from these historical records with contemporary aerial imagery looking for standing structures or structural footprints of these facilities. Since much of the Mesabi Range is heavily vegetated, forest cover often obscures a high percentage of potential structural footprints.

LIDAR data for the state of Minnesota is available to the public, which allowed us to look through the vegetation that is obscuring more of the subtle surface features. Analysis of LIDAR data helped reveal the subtle footprints that these concentrating plants left behind, helping us reaffirm and pin-point their locations (See Figs. 2 and 3).

We consulted LIDAR data provided by MNTOPO, a web-based mapping resource managed by the Minnesota Department of Natural Resources and the Minnesota Geospatial Information Office. MNTOPO utilized an airborne LIDAR survey that produced digital elevation models for the state of Minnesota. These digital elevation models filter out vegetation and show surface features that appear due to elevation changes.

Next we created a new GIS database consisting of the location, name, operating years, and owner/operator information for these historical beneficiation plants throughout the Lake Superior District. We then spatially joined the mines that were producing low-grade ores to the beneficiation plants that were processing this ore, using data from trade journals and Minerals Yearbooks, as well as comparing the operator/owner of the processing plants to adjacent low-grade ore mines. For many mines this was a simple step. If the beneficiation plant was located nearby a mine with the same name, and owned by the same mining owner, we can infer that this plant was processing ore from this mine. But smaller

Fig. 2. Contemporary aerial image of the Columbia washing plant. The vegetation makes pinpointing the plant's former location difficult (MNTOPO).

mines sent their ore to custom beneficiation plants, facilities designed to treat ores from a variety of mines rather than a single mine. We determined these processing locations by consulting annual shipment records of the mines, which often included additional information regarding the ore, such as if it was taken from a stockpile, or where it was treated. We next joined the mines and their production data to the beneficiation plant geodatabase. The resultant HGIS consisted of mine production totals for direct shipping ore mines, washable ore mines, taconite mines, and essential beneficiation information that we could use to calculate the new waste production from low-grade ore processing.

We calculated averages from plants that reported production statistics in technical reports to create a formula for the tons of tailings per ton of shipped ore. For washable ore beneficiation plants, we used data from technical reports for the Trout Lake, Hawkins, LaRue, and Harrison concentrators, as well as government surveys tailored for the iron and steel industry (Taggart, 1927; Tupper, 1912; Walling and Otts, 1967). To calculate tons of tailings produced for each ton of taconite produced, we drew on statistical reports from the Reserve, Minntac, Erie, Eveleth, and Butler taconite plants (Cummins and Given, 1973).

We next digitized the contemporary waste footprint seen on the Mesabi Range. This process involved digitizing the visible waste and mining activity seen on aerial imagery from 2012. Locating and digitizing the waste footprints from taconite plants was the easiest step, since these facilities are the most recent producers of mine waste, and have the largest waste footprints. The waste footprints produced from washable ore plants were harder to locate, as some of these tailings piles have become re-vegetated, or appear as lakes in imagery. Comparing the locations of the plants to the aerial imagery helped illuminate some of these more obscured waste footprints.

4. Results

4.1. Mapping mines

We first mapped all iron mines, historic and current, in the Lake Superior Iron District. Fig. 4 shows their locations. Historically, over 400 individual mines once operated in the six iron ranges. Some of these mines only operated for a handful of years, while others successfully functioned for nearly a century. Although mines were located throughout the district, the Mesabi and Marquette Ranges contained the most productive and long-lived mines.

We next mapped the changing dispersal of mining locations over time, as technologies shifted (Fig. 5). With the shift to low-grade ore mining, we found that spatial shifts occurred in the Lake Superior Iron District, most notably with a concentration of mining activity in the Mesabi Range, and the abandonment of mining in the Gogebic, Vermillion, Menominee, and Cuyuna Ranges.

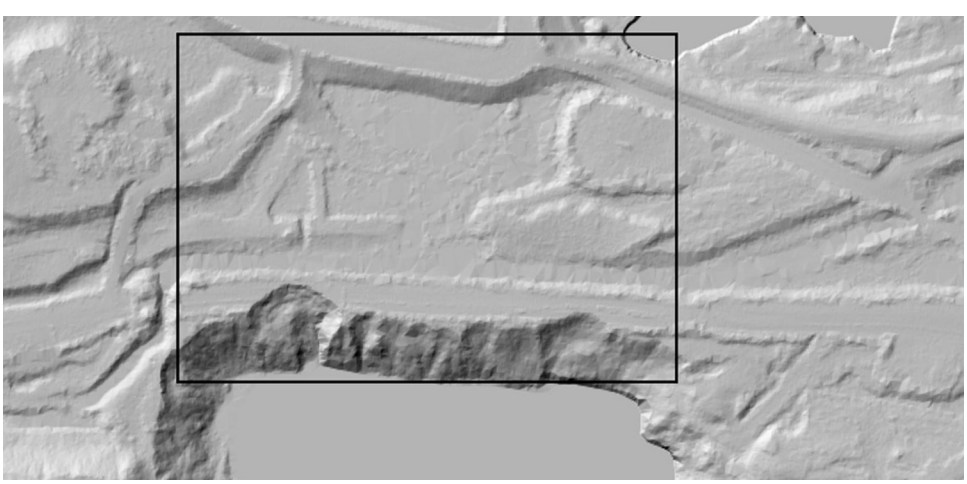

Fig. 3. LIDAR Imagery of the Columbia washing plant reveals the defined footprint of the plant not visible on aerial imagery (MNTOPO).

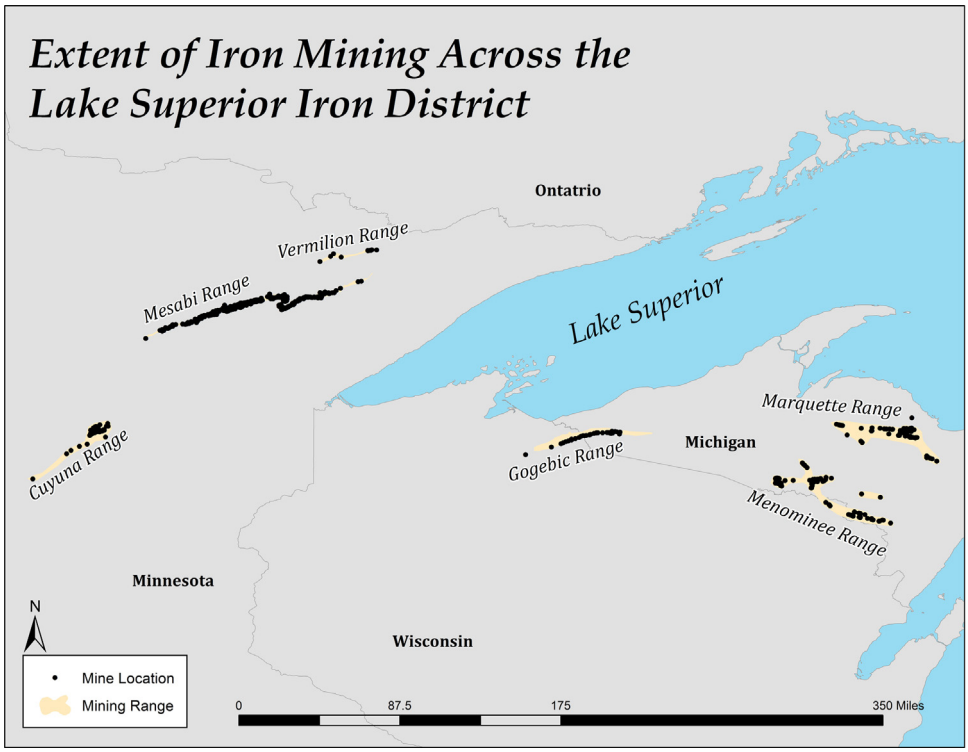

Fig. 4. Iron mines within the Lake Superior Basin.

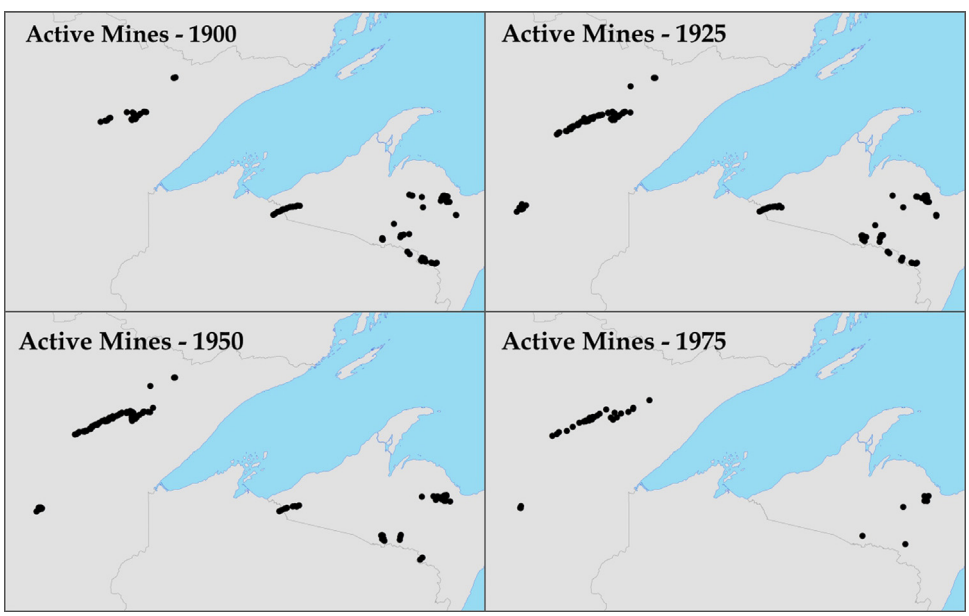

Fig. 5. Mine locations in the Lake Superior Iron District from 1900 to 1975.

We next examined how the concentration of ore production changed as mining locations changed (Fig. 6). Fig. 6 uses proportional symbols to show annual ore production totals per mine across the Lake Superior District. The transition to low-grade iron ore mining resulted in an increased production of iron ore at a shrinking number of mine locations. This created an intensification of mining activity within concentrated pockets, located primarily within the Mesabi Range. Since the Mesabi Range contained the largest quantity of low-grade ores, the mining activity in that region produced the largest quantity of low-grade ores.

4.2. Mapping technological shifts

Fig. 7 shows how different mining technologies compared in terms of ore shipments. By categorizing which technology was employed at an individual mine or processing plant, we were able to quantify how much ore was extracted and processed by a

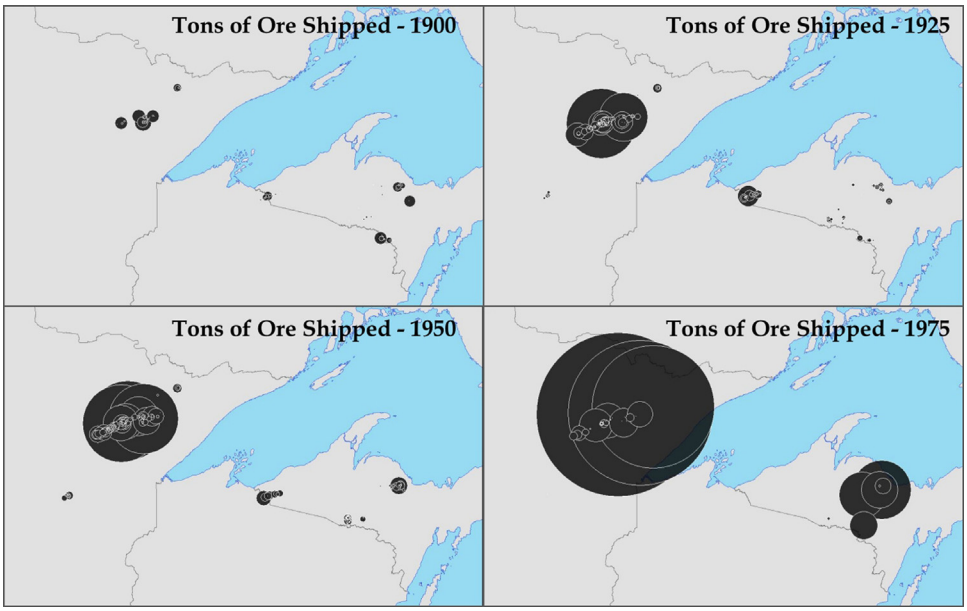

Fig. 6. Changing Quantities of Ore Shipped from Mines Within the Lake Superior Iron District.

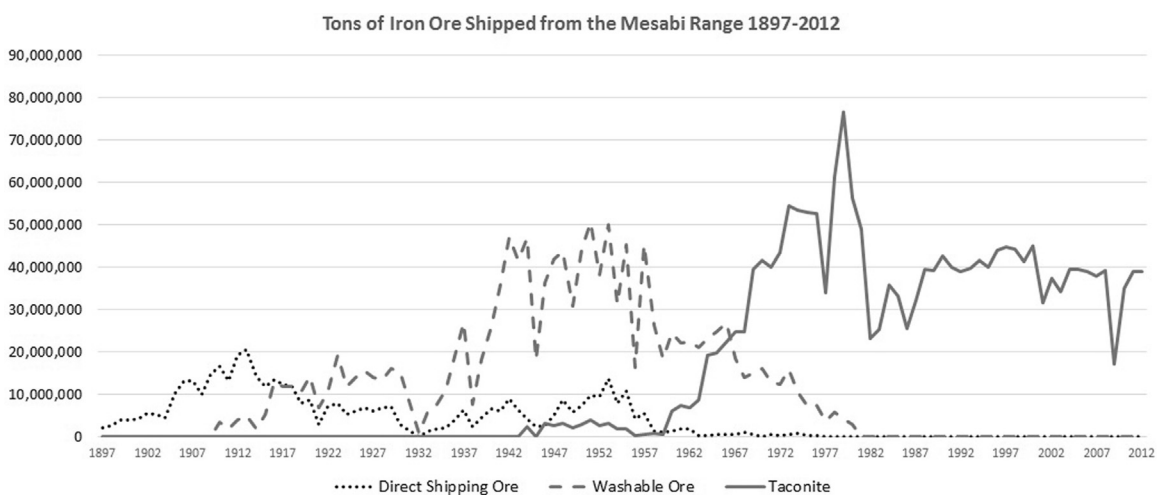

Fig. 7. Tons of iron ore shipped as produced by different mining technology within the Mesabi Range.

specific mining technology. Our analysis also shows that as mining in the Mesabi Range shifted to low-grade ores, the quantity of ore leaving the region increased dramatically between 1937 and 1972, but fell after 1981. While direct shipping ore played an important role in the Mesabi Range up to the late 1950s, the impact that low-grade ores had on the region grew from 1920 to today. Charting the ore shipments from the Mesabi Range also revealed a notable rise and fall in iron ore production from 1980 to 1982, possibly related to the economic recession of 1981.

Grouping ore shipments by technology revealed spatial shifts that occurred in iron ore extraction, shifts that were not apparent by examining the shipment data alone. For instance, as washable ores became a growing source of iron for the Mesabi Range, mining activity in Itasca Co., within the western extent of the Range, became much more pronounced. As mining shifted towards taconite, the eastern Mesabi Range retook control as the Range's primary producing region.

Additionally we see a spatial shift in beneficiation across the Lake Superior district. Fig. 8 shows the extent of low-grade iron ore beneficiation across the Lake Superior Iron District from 1910 to today. Although iron ores were beneficiated in every range within the district, the Mesabi Range contained the most beneficiation plants, owing to the abundance of low-grade washable ores and taconites found throughout the Range.

Beneficiation technologies varied across the Mesabi Range. Fig. 9 illustrates the spatial patterning of two of these technologies. As several mines could ship to a single beneficiation plant, mapping these locations was a complex task, necessary in order to quantify and map the new waste footprints that this processing created. Our HGIS, which contains the first database of iron ore processing plants in the Lake Superior basin, shows that the beneficiation of low-grade ores occurred in every mining range in the District, but the Mesabi Range contained the largest proportion of these ores and the facilities that processed them.

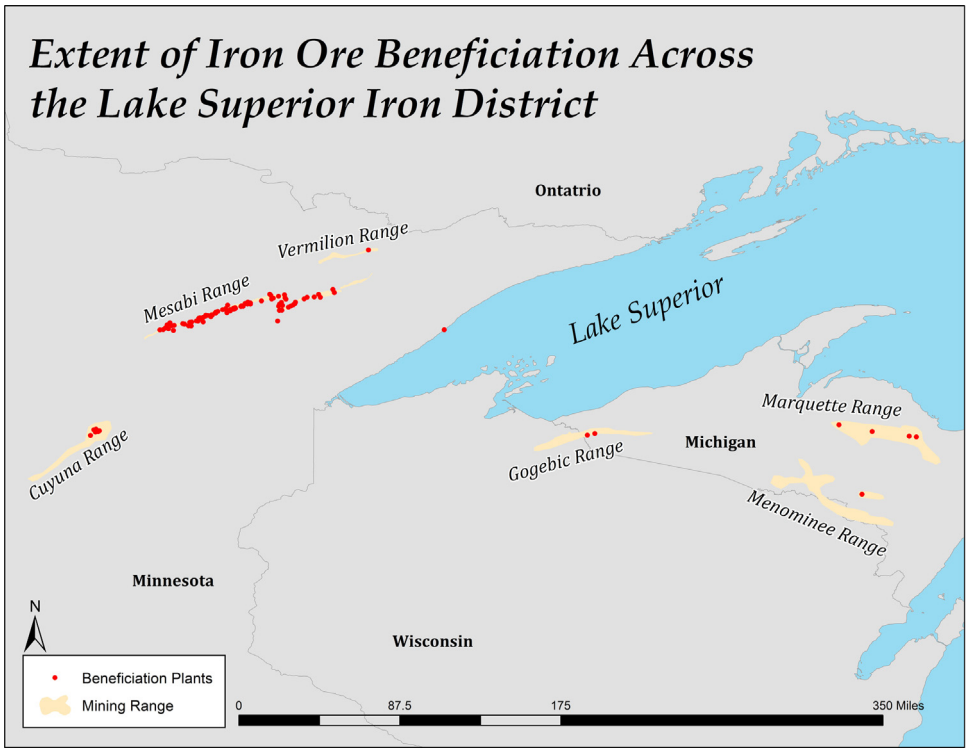

Fig. 8. Locations of beneficiation plants in the Lake Superior Iron District.

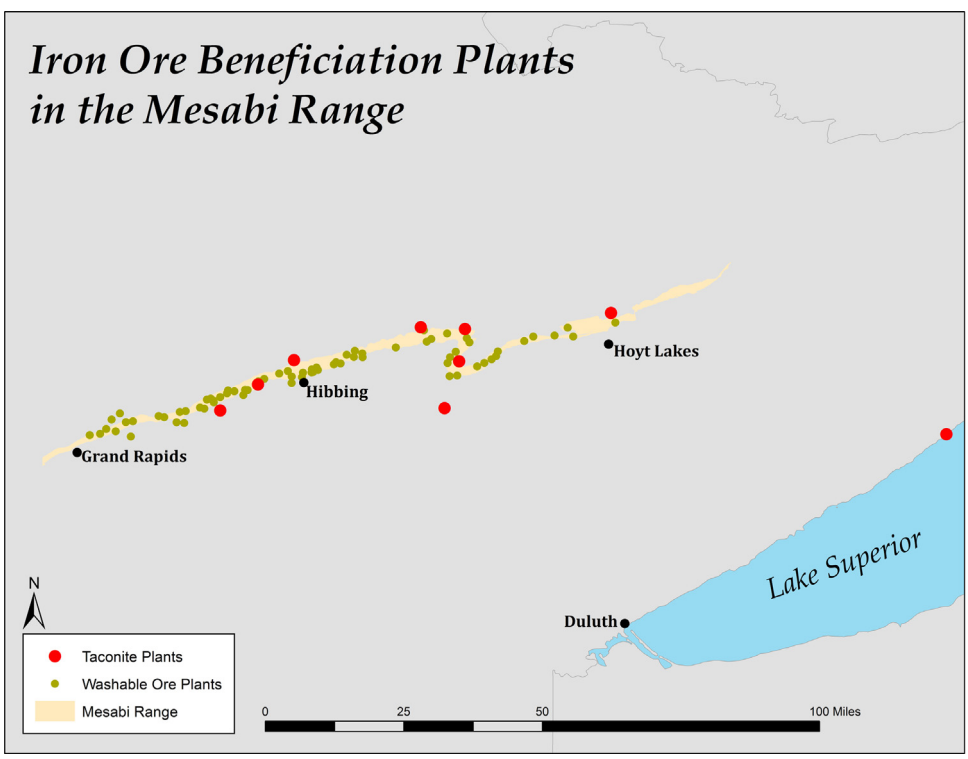

Fig. 9. Beneficiation plants within the Mesabi Range.

Creating this beneficiation plant database allowed us to identify where waste was produced and deposited from the processing of low-grade ores, and analyze how much waste each technology was producing. We will draw on this analysis in future papers that explore how mining activity has impacted watersheds in the Lake Superior Basin.

4.3. Mapping tailings

To quantify the tailings deposited by different beneficiation plants, we needed to determine the average tons of tailings produced for each ton of ore processed. Since mining companies did not report the production of tailings in the same way that they

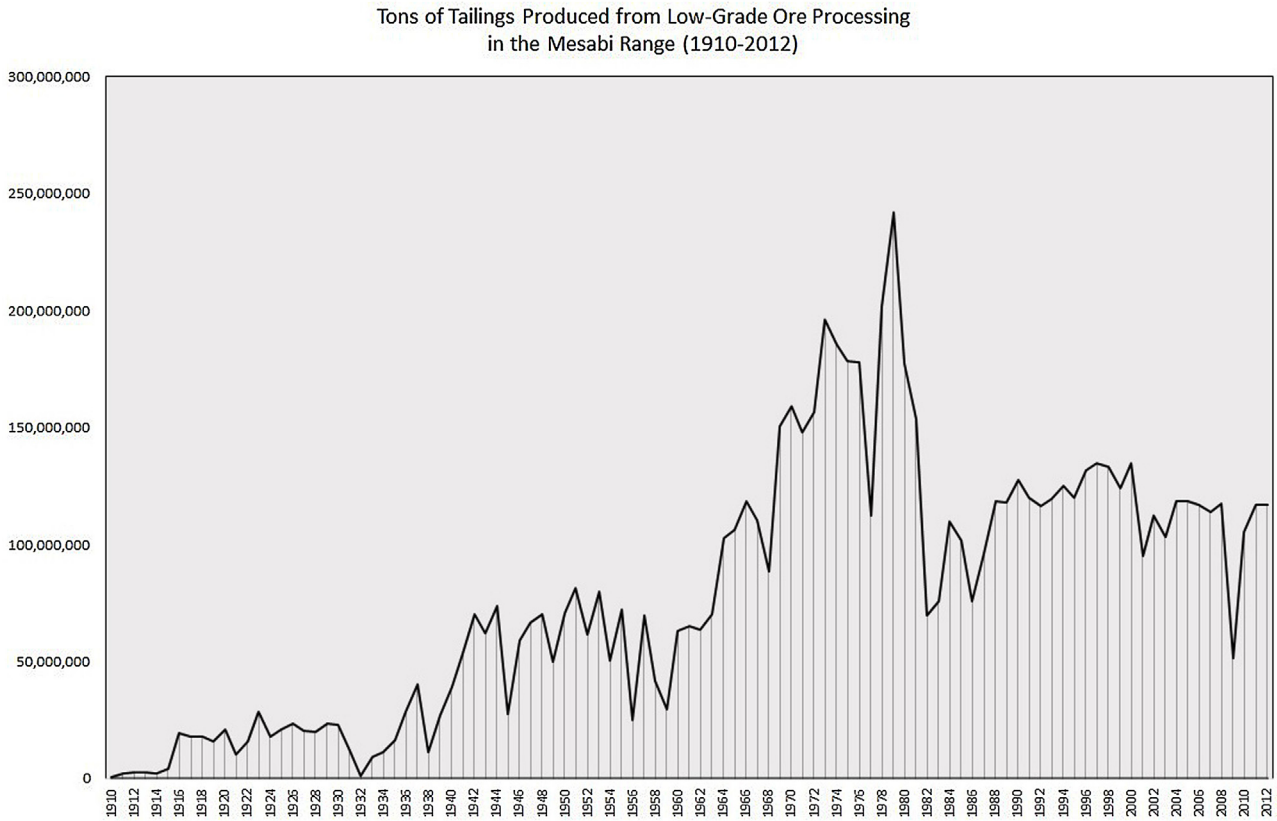

Fig. 10. Total tailings production in the Mesabi Range.

reported ore shipments, we determined tailings quantity for each ore type by consulting historical trade journals, such as the Engineering and Mining Journal and Skillings' Mining Review, as well as processing results found in mining and metallurgy handbooks, such as Taggart's *Handbook of Ore Dressing* and the Society of Mining Engineers' *SME Mining Engineering Handbook*. These reports provided production statistics for the beneficiation plants, such as tons of crude ore versus concentrates produced, the remainder of which would equal the quantity of tailings, while others provided ratios of concentration, such as 1.6 t of crude ore to 1 t of concentrates. Fig. 10 represents a hundred years of tailings deposited on the Mesabi from low-grade ore processing.

How did technological changes affect the average quantity of iron ore shipped and tailings deposited in the Mesabi Range? Fig. 11 outlines the production of ore and tailings by technology and then averages those total by individual facilities. For each technology, we divided the total quantity of ore shipped and tailings produced from all mines or processing facilities using a particular technology by the number of individual mines or processing plants using that technology. Within the Mesabi Range, 238 direct shipping ore mines shipped 469,184,394 t of iron ore and created 0 t of tailings; 78 washable ore processing plants shipped a total of 1,360,538,166 t of washable ore concentrates and created 2,035,641,670 t of tailings; and 10 taconite processing plants shipped a total of 1,972,465,460 t of taconite pellets and created 6,051,680,659 t of tailings. These data support our argument that as mining technologies changed in the Mesabi Range, production became concentrated. Fewer facilities processed an increasing quantity of ore and dumped an increasing concentration of tailings in smaller areas.

Fig. 11 shows the production statistics from the three different phases of mining in the Mesabi Range. The chart highlights the increase in tailings production, which occurred during the shift to taconite mining and ore processing. Furthermore, this chart shows that while there were a significant larger number of washable ore plants (88) than taconite plants (10), the waste footprint produced by taconite processing was nearly three-times that of washable ores. The locations of processing plants and the quantity of tailings these plants produced changed over time.

As we view the production of tailings over time we see a distinct spatial shift in where the tailings were being deposited across the Mesabi Range (Fig. 12). As low-grade iron-ore mining matured, the production of tailings within the Mesabi Range became less widespread, but the quantity of tailings grew in scale. This resulted in a high production of tailings located next to a dwindling number of processing plants.

Adding the tailings productions statistics to our HGIS allowed us to quantify and visualize the waste produced by a specific mining technology across space and time. Historically, 103 beneficiation plants were located in the Lake Superior Iron District, and 88 of these were found in the Mesabi Range. By the early 1980s, over 85% of these plants were scrapped and removed from the landscape. Today 13 beneficiation plants remain standing in the Mesabi Range, 9 of which processed taconite ores. Our survey of historical records showed that, on average, washable ore produced 1.5 t of tailings per ton of washable concentrates produced. Taconite processing produced significantly more tailings; nearly double that of washable ores, at 3 t of tailings for every ton of taconite pellets produced. As mining in the Mesabi Range progressed from direct shipping ores, to washable ores, and to taconite, the waste footprints became exceedingly larger

Knowing where production facilities existed provided us with locational data that we could use to pinpoint the visible waste footprints that these plants might have created (Fig. 13). Fig. 13 maps the extent of visible mine waste as it compares to the Biwabik Iron Ore formation that made up the Mesabi Range. The Biwabik

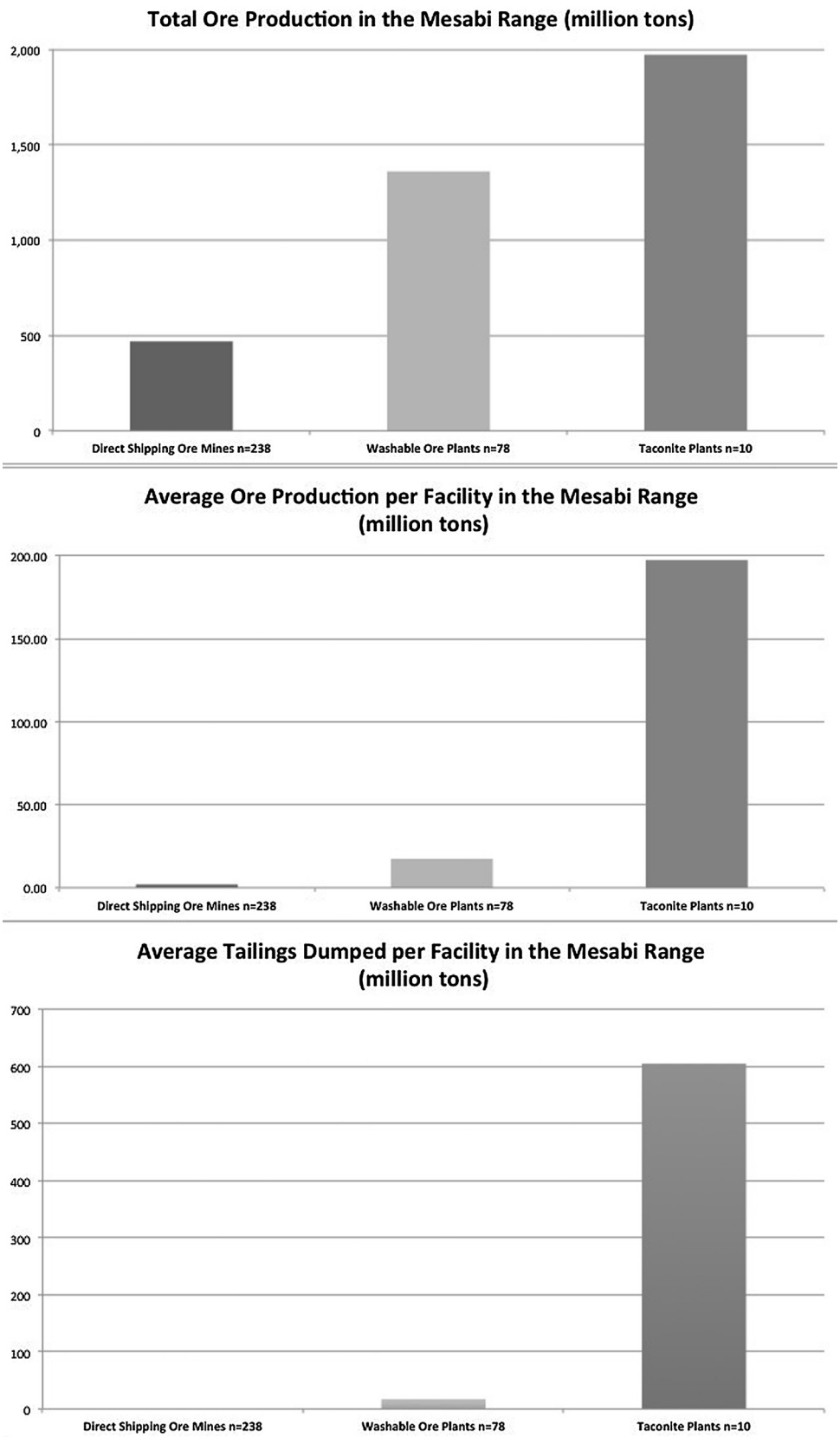

Fig. 11. Tons of Iron Ore Shipped by Individual mines or processing plants in the Mesabi Range from 1898 to 2012.

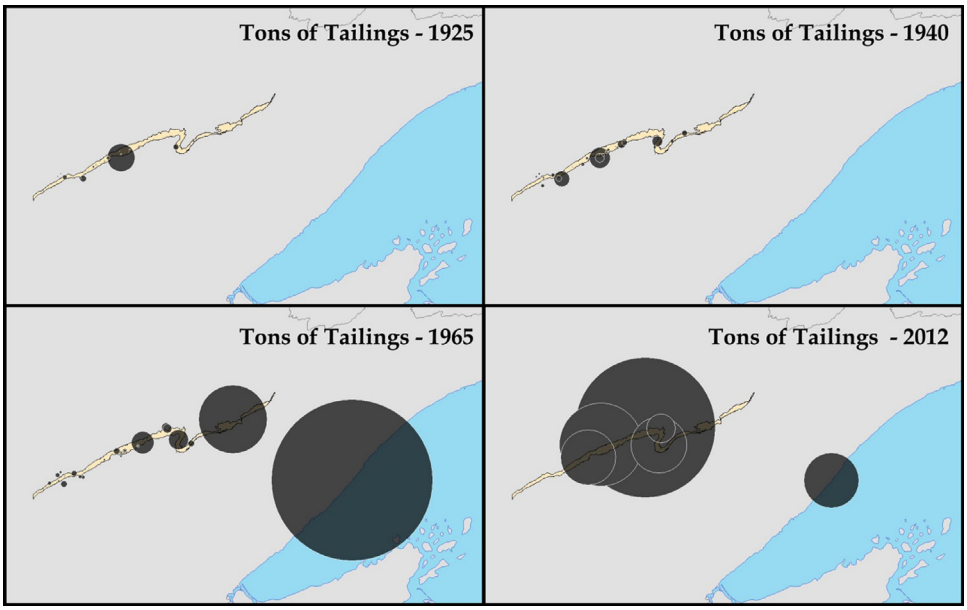

Fig. 12. Changing quantity of tailings produced in the Mesabi Range.

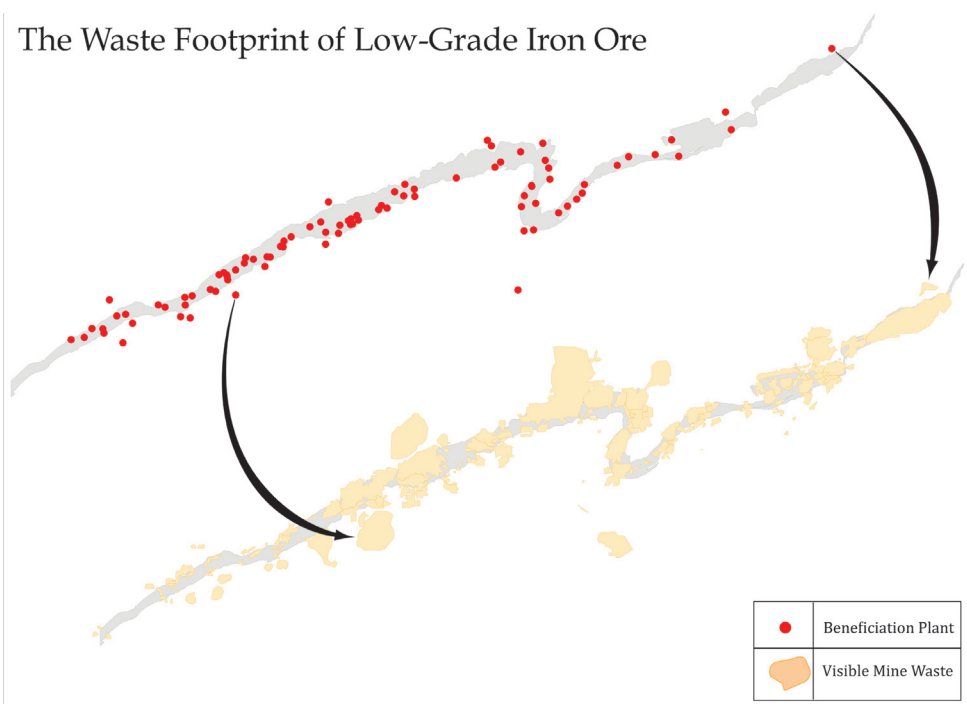

Fig. 13. The landscape of mining waste that covers the Mesabi Range.

formation was 100,000 acres in totals area, while the waste footprint totaled 125,000 acres, making the waste landscape substantially larger than the original ore body itself.

The prevalence of mining waste seen in contemporary and historical imagery was used as an important comparative factor when assigning these scrapped historical facilities locational data in our HGIS database. Since mine waste is so prevalent throughout the Mesabi Range, we decided to try to group the visible mine waste by the specific technology that produced it. This process involved analyzing the location of direct shipping ore mines and the washable ore and taconite beneficiation plants, and the occurrence of nearby mine waste.

Many locations where direct shipping ore mines once existed were later mined for either washable ores or taconite, open-pit mining processes that consumed the historical footprint left by these direct shipping ores. This succession of mining technologies made it difficult to isolate a large percentage of mining waste related to the early twentieth century direct shipping ores. We were however able to locate five direct shipping ore mines, located in relative isolation from either washable ore mines or taconite mines. To calculate the estimated quantity of surface waste produced from direct shipping ores, we vectorized the contemporary footprints from the aerial imagery and measured their extent in our HGIS. The average visible waste footprint for these five direct shipping ore mines was 120 acres. This value was assigned as the

waste footprint score of the remaining mines that were engaged with direct shipping ores in the Mesabi Range.

Since the visible waste acreage associated with washable ore mines was located adjacent at their processing plants, we again vectorized and measured the contemporary visible footprints from the aerial imagery in our HGIS. The total acreage of waste at these 71 washable ore processing plants was 60,186 acres. This results in an average of 847.69 acres of visible waste per washable ore plant.

Mining waste from taconite mining was also primarily located next to the taconite processing plants. To calculate an average waste footprint for taconite ore processing, we used the same methodology used for washable ore processing plants. The total acreage of waste at these 10 taconite processing plants was 67,175 acres in the Mesabi Range (not including Reserve Mining Co.). The waste footprint of Reserve was not calculated since the processing facility is located at Silver Bay, MN on Lake Superior, roughly 65 miles SE of the eastern extent of the Mesabi Range. This results in an average visible waste footprint of 6717.45 acres per taconite plant. From this analysis, we see that the waste footprint associated with individual mining technologies grew significantly as the Mesabi Range experienced a technological shift from direct shipping ores, to washable ores, and to taconite.

4.4. Mapping shifting concentrations of mining and waste

We hypothesized that the shift from mining direct shipping ores, to low-grade washable ores and taconite placed new demands on the environment of the Lake Superior Basin, and that this shift created intensive pockets of industrial activity located next to processing plants rather than the mines themselves. We used an average nearest neighbor analysis which measures the relative clustering or dispersal of a set of observations on a landscape. Expressed as a ratio, a nearest neighbor ratio less than 1 suggests clustering, and a ratio greater than 1 suggests dispersal. Our analysis of a hundred years of mining activity across the Mesabi range suggest a dispersion of activity over time, with the early direct shipping ore mines having a nearest neighbor ratio of 0.427, mid-century washable ore plants a ratio of 0.428, and the more recent taconite plants a ratio of 1.17.

Additionally, the average nearest neighbor analysis showed that there was an observed mean distance between direct shipping ore mines of 552 m; for washable ores, an observed mean distance of 1563 m between washable ore plants; and for taconite ores, an observed mean distance of 12,619 m between taconite plants. The average nearest neighbor analysis showed that there was a significant clustering pattern associated with direct shipping ore mines and washable ore plants, while taconite plants are not clustered.

These results suggest that as mining in the Mesabi Range shifted from direct shipping ores, to washable ores, and to taconite ores, the spatial intensity of mining became more dispersed, transitioning from a mining landscape with a large number of spatially clustered mines and ore washing plants, to one with a low number of taconite plants that are distributed at great distances from each other across the landscape. Additionally, we see that the shift to low-grade iron ore mining and processing resulted in a substantial increase in the density and size of the sites of ore extraction and waste production, which led to an increase in the scale of ore extraction and tailings production around a smaller number of mines and processing plants.

5. Discussion

The modern landscape of the Mesabi Range reflects more than 120 years of intense mining activity. While the ores that were extracted from the mines have left the region, an immense amount of mine waste remains. Today, a tremendous volume of open-pit mines and mine waste account for an area larger than the Mesabi's iron formation itself. Viewed from above, the Mesabi Range appears as a vast assortment of amorphous brown islands among a sea of green vegetation.

While the physical footprints of many of these beneficiation plants are difficult to identify today, their legacies of waste remain evident artifacts on the landscape. Today, the footprints of less than 25% of the beneficiation plants are visible from aerial imagery, yet the tailings from these plants are apparent at over 90% of the sites where these plants once operated. These tailings were first dumped directly into water bodies located nearby the processing plants, and later within constructed basins, where mining companies could reclaim this waste if a new technology was developed that could convert the tailings into ore.

Because our HGIS contains annual ore shipment data from 1898 to 2012, we were able to chart how much ore was shipped out of the Lake Superior Iron District over time, revealing spatial patterns of declines and increases in shipping totals and tailings deposition across the basin. Our HGIS reveals that as taconite mining matured in the Lake Superior basin, the waste footprint of mining became concentrated near the beneficiation plants located primarily in the Mesabi Range. Future research explores possible links between concentrations of ore mined and waste deposited, and landscape-level effects on water quality in the Mesabi Range.

This study shows that the technological shift to low-grade iron ore intensified mining production and waste deposition within the Mesabi Range. The advent of low-grade iron ore concentrating created new environmental impacts, namely tailings. Prior to 1910, iron ore tailings did not exist within the Lake Superior Iron District, but as the shift to low-grade iron ore mining intensified tailings became a dominant feature on the mining landscape. Additionally, before low-grade ore mining, mine waste existed primarily within the immediate mining landscape, where it remained as a static feature encountered by mine workers. The beneficiation of low-grade iron ores took mine waste outside of the immediate mining landscape, where it was crushed and made mobile, laundered it into lakes, and encountered by the public. This resulted in a new negotiation between industry, the state, and private landowners regarding the environmental costs of an industrial economy.

With the development of taconite mining and beneficiation during the 1950s, the facilities that processed low-grade ores also experienced spatial shifts. Many of the facilities that had processed washable ores in the region were abandoned. The shift to taconite mining during the 1970s also reduced the number of mines while increasing the quantity of ore extracted and the quantity of tailings produced near processing facilities. As ore and waste production increased, the number of mines and beneficiation plants shrank, concentrating waste products into fewer watersheds with greater individual impacts. The shift to low-grade iron ore mining in the Lake Superior District created concentrated pockets of industrial activity located around iron ore processing plants.

A limitation of this study is the fact that, while we have an accurate estimate of waste volume calculated from ore production, we underestimate of the area of the range currently covered by mine waste. The maps of current waste only include waste that was visible on maps or with LIDAR. An additional proportion of waste produced from both washable ores and taconite ores could not be mapped, because it had been deposited into lakes. Furthermore, the tremendous amount of mine waste produced from the Reserve Mining Company between 1955 and 1980 are not part of this analysis as they were dumped into Lake Superior, far from the Mesabi Range.

The technological shift to low-grade ore mining created a landscape of open-pit mines spanning across the Mesabi Range. The expansion and subsequent abandonment of low-grade ore

mining transformed the Mesabi Range from an industrial landscape of mines and processing plants, into a post-industrial landscape dominated by mine-pit lakes and mining waste.

This study has created the first database that encompasses the locations of where low-grade iron ore beneficiation took place, as well as the quantity of waste that was produced as tons of iron ore were processed. Historically, 88 iron ore processing plants once operated on the Mesabi Range. Today, only a handful of these plants remain visible, as the majority were removed for scrap decades ago. These plants now exist as ghosts on landscape, visibly absent yet environmentally persistent. Surprisingly, we found that the waste landscape of mining – the tailings basins, open-pit scars, and mine waste – today covers 125% more acreage than the original iron formation itself.

Mine waste is a key component to this study, since only successful metal mines produced ore, but all mines, whether successful or not, produced waste. Knowing how specific historical mining technologies shaped the landscape and produced waste can illuminate important aspects of the mining landscape that have often been forgotten. By understanding how mine waste was produced, we are able to accurately and systematically compare how different phases of mining impacted the environment.

The type of waste that a mine produces depends on the technological system employed at the mine. If a mine is engaged in exploiting very high-grade ores, the waste produced will generally be deposited near the mine itself. If a mine is engaged in exploiting low-grade ores, mine waste will still be found at the mine, but another form of waste, called tailings, will be found wherever that ore was processed. The location of mine waste reveals clues about a mine's history. Knowing where mine waste was dumped and how mine waste was produced illuminates the long history of a mining landscape and the technologies that were used to shape it. Waste is a ubiquitous feature within mining landscapes, found in abundance at both historical and active mining sites. While ore is shipped away from a mine, the waste a mine produces remains at, or near the mine itself. Long after a mine is shut down, abandoned, and forgotten, the waste the mine produced is often the last visible reminder of that site's industrial past.

This study shows that the technological shift to low-grade ore mining placed new demands on the environment, primarily around processing plants, which laundered millions of tons of tailings into lakes. Additionally, direct shipping ore mines produced significantly less mine waste than low-grade ore mines, and this waste was confined to the mines themselves, rarely encountered by the public outside of the active mining landscape. In contrast to direct shipping ores, low-grade ore processing delivered the legacies of mining waste into the backyards of communities.

This paper shows how the shift to low-grade iron ore mining created clusters of intensive mining and ore processing activity. The technological shift to low-grade ore mining converted what had once been seen as waste – the low-grade ore – into something of value, while creating vast new volumes of tailings. On the Mesabi Range today, over 125,000 acres of tailings, mine waste, and open pits suggest the enormous scale of low-grade iron ore mining's environmental footprint.

The mining and processing of low-grade ores has created global landscapes of mine waste. Yet much of this mine waste remains hidden. In recent memory, two of the largest human caused environmental disasters were the result of failed technological systems designed to contain tailings. With the onset of global climate change, failures at tailings basin, like the disasters recently seen at the Mount Polley mine and the Bento Rodriguez mine, are likely to increase (Kiernan, 2016). This paper adds a new methodological approach that policy makers can employ to identify and understand mine waste. Understanding where mine waste is located, and how it was created, can help the public and policy makers better manage and monitor these latent features for future generations living within these mining landscapes.

Acknowledgment

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