DISS. ETH NO. 28353

TOWARDS RESPONSIBLE GOLD SUPPLY CHAINS: A CASE STUDY FROM BURKINA FASO TO SWITZERLAND

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZÜRICH
(Dr. sc. ETH Zürich)

presented by

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2022

"All that is gold does not glitter; not all those who wander are lost; the old that is strong does not wither; deep roots are not reached by the frost..."
JRR Tolkien, The Fellowship of the Ring

"Sadly, sadly, the sun rose; it rose upon no sadder sight than the man of good abilities and good emotions, incapable of their directed exercise, incapable of his own help and his own happiness, sensible of the blight on him, and resigning himself to let it eat him away."
Charles Dickens, A Tale of Two Cities

Acknowledgements

Working and studying at ETH Zürich has been one of the greatest opportunities I have ever had. For that, I would like to thank my supervisor Isabel Günther for giving me the opportunity. Isabel has pushed me beyond what I thought I was capable of; it seems that great leaders bring out the best in us. It was an absolute privilege to have her as my doctoral supervisor. I will miss our daily interactions. Her passion for research, stamina for hard work, and dedication to helping those less fortunate are truly inspiring.

To my doctoral committee, Rachael Garrett from the ETH Zurich, Steve Koch from the University of Pretoria, and Servaas van der Berg from the University of Stellenbosch thank you for taking the time to review my work in-depth, discuss results and contribute to the final product.

Thank you to all my collaborators and co-authors. From NADEL, I would especially like to thank Fritz Brugger and Kenneth Harttgen, from whom I learned everything from managing fieldwork to econometrics. You have broadened my horizons. Thank you for your dedication to the projects; you were always calm and grounded and taught me how to navigate complex projects. I hope we will be able to collaborate in the future. Thank you to Bernhard Wehrli and Désirée Ruppen for your hard work processing, analysing, and interpreting the hair samples we collected from Burkina Faso. Your dedication to accurate and transparent research is commendable. Thank you also to Livia Cabernard for working with me on the urban mining project, I am happy that we could apply some of the models you developed.

Similarly, I can say something about each team member. This was the most generous team I have ever been part of, which makes me sad to leave but thankful that I had the opportunity in the first place. Special thanks to Kathrin Durizzo, who took over and ran the COVID-19 project with admirable efficiency, precision, and dedication. Thank you to Erwin Lefoll for all the translations in French and his willingness to talk about gold. Thank you to Yael Borofsky for your camaraderie. I would also like to thank Bart Kudrzycki, Dario Meili, Selina Bezzola, Adina Rom, Laura Metzger, Joschka Proksik, Rebecca Engebretsen, Samuel Tetteh-Baah, Chris Humphrey, Leonie Hensgen, Tabea Sampl, Stephan Pfister, Angelica Serrano, Megan Seipp and Chunming Sui.

Thank you to Fastenopfer and ETH4D for funding our research in Burkina Faso and Sam Bartélémy and Natacha Compaore from our local partner, Sagrasy Consulting, together with Diane Crittin and Vreni-Jean Richards from Fastenopfer and the organisation, Orcade. Thank you also to the data collection team (Isaac Kondombo, Salif Sawadogo, Issaka Sawadogo, and Mohamed Dagano) led by Zongo Tongnoma, Saybou Savadogo, and

Hermann Moussa. I also thank Martin Yameogo and Jessica Zanetti for their help. However, my biggest thanks would have to go to Anna Bugmann, for all her hard work, managing fieldwork and communications, and willingness to stay involved until the end. I am grateful to Anna Ingwersen, Kurt Barmettler, Sylvain Bouchet, and Ruben Kretschmar for providing the laboratory infrastructure and assistance for the mercury analysis and supporting the measurements and data interpretation. Thank you to ETH Sustainability, especially Christine Bratrich, Campus Info, and Life Magazine, specifically Anna Maltsev, for working with us on the urban mining project in collecting old mobile phones.

My deepest gratitude goes to all the participants of the projects. Every person who completed a survey participated in an experiment or trusted us to give some of their hair. I hope you feel I used your personal scarifies to move towards more responsible gold supply chains. None of this would have been possible without your time, trust, and contribution.

I am also indebted to my family and friends. Your selfless love and support not only carried me through this but made it enjoyable labour. I want to thank the Wieslergasse gang for many conversations about life, work, and children. *Prost*, to you all! To all my friends in South Africa, we missed you every day; thank you for your messages of encouragement.

Thank you to my family for being my inspiration, especially to my mother and father, whose tireless dedication to their children and grandchildren has given us the freedom to explore and dare that few others have. *Julle is 'n rots vir soveel mense, ook vir my.*

Last and the most of all, Johann, Anita, and Eduard. I am not going to thank you because no thanks would be enough. I would instead like to dedicate this work to you. Johann, you listened to every idea, those that made it to these pages and many more that did not. You have allowed me to dream bigger. My achievements are also yours. To our children, Anita and Eduard, you inspire me to do more on this earth. My deepest wish is that you will inherit a more just and sustainable world.

Zürich, 07.06.2022 Antoinette van der Merwe

Abstract

Gold is a metal with high direct consumer demand; more than 75% of gold is used for jewellery and investment. Gold is extracted worldwide, including in Burkina Faso, one of Africa's fastest-growing and fourth-largest gold producers. Although gold extraction has had significant benefits for the Burkinabe economy, it has also led to many environmental and social problems, especially in the artisanal gold mining sector. Artisanal gold mining is a poverty-driven, labour-intensive mining operation. The vast majority of Burkina Faso's artisanal mines operate informally and are therefore unregulated, leading to serious environmental problems like mercury pollution as well as human rights abuses, such as child labour. More than 90% of the gold produced in Burkina Faso is exported to Switzerland for refinement. Although Switzerland is also one of the largest per capita consumers of gold globally, Swiss consumers are far removed from the impacts of their gold consumption. This dissertation examines issues throughout the gold supply chain from one of the poorest countries in the world, Burkina Faso, to one of the richest, Switzerland.

Various data sources and methods are used to study issues throughout the gold supply chain. Primary survey data collected on four artisanal mines are used to assess the competitiveness of local gold markets in Burkina Faso. This survey data is also used with a field experiment and biological sampling to assess reasons why miners do not adopt safer behaviour when handling mercury. Secondary data on the location of artisanal mines in Burkina Faso supplemented with information from high-resolution satellite images are used to determine the impact of artisanal mines on local communities' wealth, health, and education.

Based on our research in Burkina Faso, we find that local gold markets are imperfectly competitive, making them vulnerable to external shocks, such as the COVID-19 pandemic. Making local markets more competitive by addressing power and knowledge asymmetries between miners and gold traders would improve the sector's resilience and ability to alleviate poverty. While artisanal mines do have a significant potential to alleviate poverty, we also observe a significant increase in temptation good expenditure. We also find that technical interventions that give miners access to personal protective equipment could have significant health benefits for individual miners. Specifically, gold traders, whom we find are particularly at risk of mercury exposure.

To understand the gold supply chain from a Swiss perspective, we use various data sources and methods. Expert interviews are used to determine the feasibility of using blockchain to enable responsible sourcing from artisanal miners and the determinants of demand for certified gold. Lastly, we study the feasibility and cost-effectiveness of expanding urban mining in Switzerland. Since many metals – including gold, which accounts for most of the value of the metals in a smartphone – lie dormant in unused electronic devices in high-income countries. To determine how to reintroduce these metals back into supply chains, we use primary survey data, a field experiment, and a life-cycle assessment.

Based on our research in Switzerland, we find that blockchain has a limited potential to reduce the high due diligence costs when sourcing from artisanal miners due to the difficulty of differentiating between the physical gold and the gold listed in the blockchain system. In addition, the gold certification landscape is highly fragmented, with various certification schemes with relatively low direct consumer demand. Demand for certified gold is driven by retailers and banks, who face different motivations and constraints when sourcing certified gold. In addition, we find a large potential to increase the secondary sourcing of metals from old mobile phones. Many people in Switzerland keep their phones at home after replacement, which constitutes a significant lost of resource. Reducing the transactional cost of recycling significantly impacted the collection of old mobile phones for recycling, which is cost-effective if we consider the environmental savings of recycling.

In this doctoral study, I show that various actors and policy initiatives throughout the gold supply chain is necessary to move to more responsible gold supply chains.

Keywords: Gold, Artisanal mining, Gold Price, Impact, Mercury, Urban Mining

Kurzfassung

Gold ist ein Metall mit hoher direkter Verbrauchernachfrage; mehr als 75% des Goldes wird für Schmuck und Investitionen verwendet. Gold wird weltweit abgebaut, auch in Burkina Faso, einem der am schnellsten wachsenden und viertgrößten Goldproduzenten in Afrika. Obwohl der Goldabbau für die burkinische Wirtschaft von großem Nutzen ist, hat er auch zu zahlreichen ökologischen und sozialen Problemen geführt, insbesondere im artisanalen Goldbergbausektor. Der artisanale Goldbergbau ist ein von Armut geprägter, arbeitsintensiver Bergbaubetrieb. Die überwiegende Mehrheit der artisanalen Minen in Burkina Faso wird informell betrieben und ist daher nicht reguliert, was zu schwerwiegenden Umweltproblemen wie Quecksilberverschmutzung und Menschenrechtsverletzungen wie Kinderarbeit führt. Mehr als 90% des in Burkina Faso geförderten Goldes wird zur Veredelung in die Schweiz exportiert. Obwohl die Schweiz auch weltweit einer der größten Pro-Kopf-Verbraucher von Gold ist, sind die Schweizer Konsumenten von den Auswirkungen ihres Goldkonsums weit entfernt. Diese Doktorarbeit untersucht die Probleme in der gesamten Goldlieferkette von einem der ärmsten Länder der Welt, Burkina Faso, bis zu einem der reichsten Länder, der Schweiz.

In der Doktorarbeit werden verschiedene Datenquellen und Methoden eingesetzt, um die Probleme in der gesamten Goldlieferkette zu untersuchen. Aus der Perspektive eines Produzenten in der Goldlieferkette werden primäre Umfragedaten, die in vier artisanalen Minen in Burkina Faso gesammelt wurden, verwendet, um die Wettbewerbsfähigkeit der lokalen Goldmärkte zu bewerten. Diese Umfragedaten werden auch in Verbindung mit einem Feldexperiment und biologischen Probeentnahmen in Burkina Faso genutzt, um die Gründe zu ermitteln, warum die Bergbauleute beim Umgang mit Quecksilber keine Sicherheitsmaßnahmen ergreifen. Sekundäre Daten über die Lage der artisanalen Minen in Burkina Faso, ergänzt durch Informationen aus hochauflösenden Satellitenbildern, werden verwendet, um die Auswirkungen der artisanalen Minen auf den Wohlstand, die Gesundheit und die Bildung der lokalen Gemeinschaften zu ermitteln.

Basierend auf den Forschung in Burkina Faso, stellen wir fest, dass die lokalen Goldmärkte nur unzureichend wettbewerbsfähig sind, was sie anfällig für externe Schocks, wie die COVID-19-Pandemie, macht. Eine Verbesserung des Wettbewerbs auf den lokalen Märkten durch die Beseitigung von Macht- und Wissensasymmetrien zwischen Bergbauleuten und Goldhändlern würde die Widerstandsfähigkeit des Sektors verbessern und könnte Armut senken. Der artisanalen Bergbau hat zwar ein erhebliches Potenzial, die Armut zu senken, doch wir beobachten auch einen erheblichen Anstieg der Ausgaben für Luxusgüter. Außerdem, stellen wir fest, dass technische Maßnahmen, die Bergbauleuten Zugang zu

persönlicher Schutzausrüstung verschaffen, zu erheblichen gesundheitlichen Vorteile führte. Dies gilt insbesondere für Goldhändler, die nach unseren Erkenntnissen besonders stark durch Quecksilber gefährdet sind.

Um die Schweizer Perspektive der Goldlieferkette zu beleuchten, werden auch verschiedene Datenquellen und Methoden verwendet. So werden Experteninterviews genutzt, um die Machbarkeit des Einsatzes von Blockchain zur Ermöglichung einer verantwortungsvollen Beschaffung bei artisanalen Bergbauleuten und die Einfkussfaktoren der Nachfrage nach zertifiziertem Gold zu ermitteln. Außerdem untersuchen wir die Durchführbarkeit und Kosteneffizienz einer Ausweitung des *Urban Mining* in der Schweiz. Denn viele Metalle - darunter auch Gold, das den größten Teil des Wertes der Metalle in einem Mobiltelefon ausmacht - befinden sich in ungenutzten elektronischen Geräten in Ländern mit hohem Einkommen. Zu diesem Zweck verwenden wir primäre Umfragedaten, ein Feldexperiment und eine Lebenszyklusanalyse.

Basierend auf den Forschung in der Schweiz, stellen wir fest, dass Blockchain nur ein begrenztes Potenzial hat, die hohen Kosten für die Sorgfaltspflicht bei der Beschaffung von artisanalen Bergbauleuten zu reduzieren. Denn es ist schwierig zwischen dem physischen Gold, und das gold im Blockchain-System gelistet ist, zu unterscheiden. Darüber hinaus ist die Goldzertifizierungsbranche stark fragmentiert, mit verschiedenen Zertifizierungssystemen und einer relativ geringen direkten Verbrauchernachfrage. Die Nachfrage nach zertifiziertem Gold wird von Einzelhändlern und Banken getrieben, die bei der Beschaffung von zertifiziertem Gold unterschiedlichen Motivationen und Auflagen haben. Außerdem sehen wir ein großes Potenzial, die Sekundärbeschaffung von Metallen aus alten Mobiltelefonen zu steigern. Viele Menschen in der Schweiz behalten ihre Mobiltelefone nach dem Austausch zu Hause, was einen erheblichen Ressourcenverlust bedeutet. Die Senkung der Transaktionskosten des Recyclings hat sich erheblich auf die Sammlung alter Mobiltelefone ausgewirkt. Dies ist kosteneffizient wenn wir die Umwelteinsparungen durch das Recycling berücksichtigen.

In dieser Doktorarbeit zeige ich, dass es notwendig ist verschiedene Akteure und politische Initiativen in der gesamten Goldlieferkette zu verändern um eine verantwortungsvolleren Goldlieferketten zu erhalten.

Stichwörte: Gold, Artisanaler Bergbau, Goldpreis, Auswirkungen, Wohlstand, Quecksilber, Urban Mining

Contents

Chapter 1

Introduction

1.1 Relevance and motivation of research

1.1.1 Why is gold important?

Throughout human history, metals have had a profound impact on our development. Even in prehistoric times, the discovery of metals and the ability to handle them defined existence, such as the Copper Age, the Bronze Age, and the Iron Age. Metals are also increasingly essential in the modern economy and the Information Age. Driven by economic development, demand for metals has expanded drastically in the twenty-first century. Demand for metals is expected to increase even further to enable the transition to a low-carbon economy (Ali et al., 2017; Vidal et al., 2013). New technologies such as electric cars and smartphones have increased the demand for metals that had negligible demand before, such as rare earth metals (UNCTAD, 2020). In 2013, Vidal et al. (2013) estimated that if production of base metals continued to increase at the same rate, we would match the production of all human history within 15 years.

Most metals are used as an intermediary product in, amongst many others, construction, vehicles, electricity supply, and electronic equipment. For example, in Switzerland, most of the copper is used as an intermediary good: 14% of copper was used in construction, 15% in machinery and equipment, 5% in electronic equipment such as radios, phones, televisions, and 5% in motor vehicles (calculated from Exiobase; Wernet et al., 2016). In this regard, gold is a unique metal because it has a high direct consumer demand. Although gold is also used as an intermediary good, for example, in the production of smartphones, gold as a consumer good is a considerably larger market. Since 2010 jewellery and the private demand for investment in gold made up between 78 - 87% of the global demand for gold, the demand for gold investment from central banks and other institutions was between 2-15%, while technology and other intermediary uses were between 7-11% of global demand (World Gold Council, 2021c, see Chapter 6). Therefore, the direct private consumption of gold through jewellery and bullion bars significantly impacts the total demand for gold.

Gold as a consumer good has a long history of cultural meaning. Gold is still given as dowry, and one of the most important symbols of relational ties, symbolising the importance of birth, personal milestones, and families unifying in wedlock in countries such as India, China, and the Middle East (Liu, 2016). For centuries, gold has also had monetary significance as a legal tender and investment vehicle; some of the earliest coins were made of gold and silver. Even when economies moved to paper money, the value of most currencies was still physically backed by gold until the First World War (Bordo, 1981). After the Second World War until shortly after the Vietnam War, under the Bretton Woods system, all currencies were valued to the US dollar, which was fixed to gold (Eichengreen et al., 1997). The differentiation between jewellery and investment is often blurred; in modern-day India, many people buy gold jewellery as an investment in order to sell it again for cash when they need to (Ali, 2006).

Although central banks still hold gold as a central reserve, gold is freely traded in world markets. Investment in gold is also popular for private investors as gold is still considered a safe investment and inflation hedge (Worthington & Pahlavani, 2007; Beckmann & Czudaj, 2013). While investment in commodities is often considered a safe investment, many commodities such as oil or staple crops are depleted when consumed. However, gold does not erode and is indestructible, meaning it could be indefinitely recycled or directly sold (Ali, 2006; Liu, 2016). Since the stock of gold available depends not only on the amount available in ore (estimated 50,000 tonnes) but also on all gold that has ever been mined and can still be located, gold investment is less vulnerable to shocks (World Gold Council, 2021a).

1.1.2 The gold supply chain

Meeting the growing demand for metals has become more energy-intensive and expensive (Rötzer & Schmidt, 2018). Previously demand for metals was met with the discovery of new high-grade ore deposits and improved extraction technologies (Verbrugge & Geenen, 2019; Rötzer & Schmidt, 2018; Vidal et al., 2013). However, the ore grade (the concentration of the metal in the rock) of discoveries continuously decreases. With increased mining costs, we would need to urgently diversify the supply of metals, including increasing the metal recycling rate (Vidal et al., 2013; Rötzer & Schmidt, 2018). For example, only a few decades ago, South Africa, with incredibly high-grade gold deposits, produced up to 80% of the world's gold. Due to reducing gold reserves in South Africa, gold production has diversified to various countries (Figure 1.1; Verbrugge & Geenen, 2019). In 2020, the largest gold producers in the world were China (368 tonnes), Russia (331 tonnes), Australia (328 tonnes), and the United States (190 tonnes). The largest gold producing countries in Africa were Ghana (139 tonnes), South Africa (99 tonnes), Mali (94 tonnes) and Burkina Faso (93 tonnes; Figure 1.1; World Gold Council, 2021c; USGS, 2021).

Primary gold production, meaning newly mined gold, is mined either by industrial or artisanal miners. Industrial and artisanal mines are vastly different gold mining operations with different environmental and social impacts.

Industrial or large-scale mining is defined as formal mining practices undertaken by

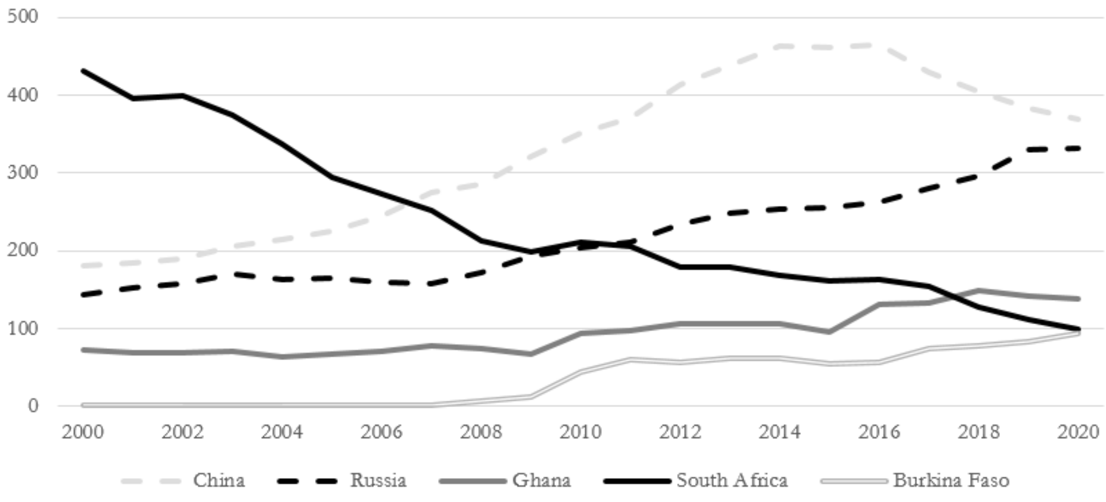


Fig. 1.1: Largest gold producing countries in 2020. China and Russia are the two largest gold producers in the world. Ghana, South Africa and Burkina Faso are the first, second and fourth largest gold producing countries in Africa. Mali, not shown in the graph, the third largest gold producing country in Africa. Data compiled from: World Gold Council (2021c) and USGS (2021)

companies with highly capital-intensive methods. Industrial mines are awarded mining licenses or concessions and regulated by the state. Governments, also encouraged by the World Bank and the IMF, have made economic growth through the expansion of industrial mining one of their central economic goals (Werthmann, 2017; Hilson & Potter, 2005). Creating a favourable environment for industrial mines would increase foreign direct investment, stimulating economic growth. In addition, gold produced by industrial mines is subjected to taxation and other payments like royalties, which could be used to provide public goods and services.

Artisanal mining is defined around the notion of a poverty-driven, highly labour-intensive, individual or group effort to extract minerals with minimal capital investment and by using basic tools (Jønsson & Bryceson, 2009). However, given the sector's heterogeneous nature, consensus on the exact definition of artisanal mining is lacking (Hilson & Pardie, 2006). Although data on artisanal mining is mainly absent, it is estimated that between 15-20% of all primary gold production is from artisanal mines (Fritz et al., 2018). Artisanal mining can often mine on lower-grade gold deposits that are not economically viable for industrial mines. In addition, artisanal miners can more easily start and stop operations than industrial mines, making them reactive to changes in gold prices (Aubynn, 2009).

Given that most artisanal mines are informal, they do not pay taxes or royalties and constitute a significant lost source of federal income. Artisanal mining is still a significant job creator; in 2013, about 95% of gold miners in the world worked in an artisanal mine (using data from STATISTA, 2015; Seccatore et al., 2014). Although various studies have found that artisanal mining has a significant potential to alleviate poverty (Fisher et al., 2009; Bazillier & Girard, 2020; Guenther, 2018; Siegel & Veiga, 2010; Kamlongera & Hilson, 2011), the sector is frequently associated with human rights abuse, such as child labour and dangerous working conditions, as well as environmental degradation, such as deforestation, cyanide and mercury pollution (Fritz et al., 2018; Hilson, 2010; Telmer & Veiga, 2009; Swenson et al., 2011; Bashwira et al., 2014; Knoblauch et al., 2020; Long et al., 2015).

The supply chain from extraction to refinement is much shorter for industrial mines than for artisanal mines. After extraction, the ore mined by industrial mines is smelted and chemically processed, usually with cyanide, to separate gold and silver from other impurities and then cast into semi-refined bars called doré (see Figure 1.2). Many industrial mines have smelting and processing facilities on the mine site that cast and export doré bars directly to refiners for further specialised processing and refinement.

In artisanal mining, however, artisanal miners remove some impurities using labour-intensive and basic methods such as mercury amalgamation after extracting the ore. Mercury is an easy, versatile and cheap way to separate gold from ore, making it the most popular method among artisanal gold miners globally. Artisanal gold miners are currently the largest anthropogenic source of mercury pollution in the world (Travnikov et al., 2015; Fritz et al., 2018). Since mercury is a non-biodegradable dangerous toxic metal that causes a range of severe health issues, including congenital disorders, deterring neurological development, and even death, making the use of mercury in artisanal gold mining is a substantial public health concern. The artisanal miners then rely on a myriad of local and regional traders, working informally, to collect gold and sell it to gold-buying houses, who smelt the gold from thousands of miners into doré bars, ready for exporting (Grätz, 2004; Guéniat & White, 2015; Telmer, 2020).

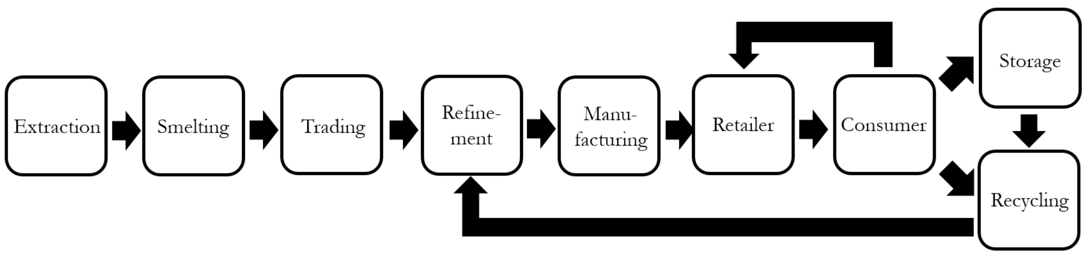


Fig. 1.2: Supply chain of gold

Specialist refineries remove more impurities from doré bars to create up to 99.999% pure gold cast in bars and coins or prepare the gold for manufacturers and jewellers. Refineries also receive recycled gold, which is any gold captured from final goods sold to consumers or ready for sale (Hewitt, 2015). About 90% of recycled gold is from articles containing high-value gold, which mostly consists of jewellery but can also include coins and bars, and 10% is from industrial waste, such as gold embedded in smartphones and other electronics (Hewitt, 2015). Although gold jewellery could be sold again in its current form as second-hand gold jewellery, the majority sold for cash is melted down. It re-enters the supply chain at a refinement facility (see Figure 1.2). Since 2010, 24-39% of gold supply was sourced from recycled gold (Hewitt, 2015; World Gold Council, 2021c). Since jewellery is made of gold alloys, which means it does not have to be 99.999% pure gold, illegally mined gold is not always refined but is also directly made into jewellery, and then introduced into the market through recycling (Hunter et al., 2021).

Theoretically, all gold that has ever been mined — an estimated 201,961 tonnes of gold — is still in circulation. In 2020, an estimated 46% of all above-ground stock was captured in jewellery, 22% in private investment and 17% in official holdings, and 15% was in other forms or unaccounted for (World Gold Council, 2021a). The percentage of total above-ground stock captured in each product type varies over time, depending on newly mined gold, and recycled gold. For example, during an economic downturn, gold investment increases relative to gold jewellery. Higher demand for gold investment would mean that a larger percentage of newly mined gold is used for gold bars and coins. People would also be more likely to sell their gold jewellery for cash, which would be recycled, refined, and more likely sold as bars and coins. The ability to capture gold from final goods and reintroduce it into the supply chain is one of the reasons why gold is considered a safe investment.

1.1.3 Switzerland and Burkina Faso: on opposite sides of the gold supply chain

Switzerland is one of the largest per capita consumers of gold. Since 2010, the consumption of gold in Switzerland has been between 3.5 and 11.7 grams per capita. This is, on average, 12 times more than per capita consumption in the United States and the United Kingdom, 11 times more than per capita consumption in India — one of the largest consumers of gold — and four times more than per capita consumption in Germany (World Gold Council, 2021c). Switzerland also plays an essential role in the global supply chain of gold, hosting four major gold refineries that refine about 70% of all gold (Guéniat & White, 2015; Herzog et al., 2015). From 2012 to 2017, Switzerland has imported between 2,236 and 3,080 metric tons of raw gold annually, at a value of CHF 65 - 109 billion, from 92 different countries (Tratschin et al., 2017). One of those countries is Burkina Faso.

Burkina Faso is an interesting case study since there were no active industrial gold mines until 2007 (except for a small industrial gold mine that was active from 1984 to 1995). However, after the liberalisation of mining regulations in 2003[1], 15 active industrial mines opened between 2007 and 2018. In 2009, gold overtook cotton as Burkina Faso's main export product (WITS, 2021). Since 2008, more than 90% of the gold produced

[1] Revisions to the national mining code in 2003 included lower tax and administrative requirements for projects in the exploration phase and restriction of state ownership to 10% in large-scale mining projects (Werthmann, 2017).

in Burkina Faso has been exported to Switzerland. Table 1.1 shows the amount of gold produced in Burkina Faso and the amount exported to Switzerland (data compiled by Guéniat & White, 2015).

Year	Official gold production in Burkina Faso (kg)			Swiss gold imports from Burkina Faso	
	Industrial mines	Artisanal mines	Total	Quantity (kg)	Percent of Burkina Faso's total production
2007	753	363	1,116	371	33
2008	5,039	443	5,482	5,985	109
2009	11,615	535	12,150	13,457	111
2010	22,477	600	23,077	21,038	91
2011	32,132	468	32,600	31,894	98
2012	29,196	973	30,169	28,658	95
2013	30,225	1,000	31,225	37,100	119
2014	29,938	1,000 to 8,000	30,938	37,372	96 to 121

Tab. 1.1: Gold export from Burkina Faso to Switzerland. Official gold produced in Burkina Faso from 2007 to 2014, disaggregated by gold in industrial and artisanal mines. And the quantity of gold imported in Switzerland from Burkina Faso, in kilograms and as percentage of Burkina Faso's yearly production. Data compiled by Guéniat & White (2015)

In 2008, 2009, 2013, and 2014, Switzerland even imported more gold from Burkina Faso than what Burkina Faso officially produced in that year. This could be due to poor data quality, exporting stockpiles of gold extracted in previous years, or, most importantly, under-reporting of gold production in Burkina Faso (Guéniat & White, 2015). A key reason for the under-reporting of gold production is artisanal miners. Since an estimated 73-95% from 2010 to 2016 of artisanal miners in Burkina Faso operate informally and therefore do not disclose their production to authorities (Lassen et al., 2016; DeJong, 2019; Guéniat & White, 2015), official records under-report gold production (Werthmann, 2017).

Although industrial mining operations drove the increase in gold production in Burkina Faso, artisanal gold miners have been active in the country since the 1980s (Werthmann, 2009). In the last ten years, artisanal mining has grown worldwide, but specifically in countries such as Burkina Faso (DeJong, 2019). Given its labour-intensity, artisanal gold mining ensures millions of people with an income and livelihood (Hilson & Potter, 2005). For example, in 2017, industrial mines in Burkina Faso directly employed 9,651 people, while an estimated 600,000 to 1 million people were involved in artisanal mining (Drechsel et al., 2019; Mondlane, 2017; Arthur & Domiter, 2017).

Despite the significant economic potential of artisanal mining, it has also been responsible for many adverse social and environmental problems. In Burkina Faso, the Parliamentary Commission of Inquiry into the Management of Mining Titles and the Social Responsibility of Mining Companies said of artisanal mines: “ones of artisanal exploitation are lawless places where prostitution, drug traffic, child labour, etc. reign” (as cited in Werthmann, 2017). In Burkina Faso, environmental issues caused by artisanal mining include destruction of landscapes, lack of rehabilitation, leaving deep pits to subterranean galleries, loss of topsoil, erosion, mercury, and cyanide pollution. Social issues include child labour, armed groups targeting mine sites leading to the internal displacement of 1.3 million people, dangerous working conditions, illicit trade flows, and corruption (Werthmann, 2017; Lanzano et al., 2021; Guéniat & White, 2015).

Due to increased concerns about human rights violations and environmental degradation, non-governmental organisations (NGOs) and other civil and activist groups in Switzerland have increasingly called attention to the gold industry. Public Eye (formerly Berne Declaration), a Swiss NGO focusing on the impact of Swiss companies in developing countries, has released multiple publications, such as “Commodities, the Most Dangerous Business in Switzerland” (2011) and “A Golden Racket: The true source of Switzerland’s ‘Togolese’ gold” (2015), which highlighted the role of Swiss companies in, among other things, human right abuses and environmental degradation in the gold supply chain, especially from gold imported from Burkina Faso via Togo.

The Swiss government has committed to addressing some of the global gold supply chain issues. In 2017, the Federal Department of Foreign Affairs commissioned an expert review study to evaluate the risk that the gold entering Switzerland contributes to human rights violations. The commission found that, amongst other things, due to the inability to trace gold from mine to consumer and the lack of transparency of gold refiners, they could not exclude the possibility that gold entering Switzerland contributed to human rights violations (Tratschin et al., 2017). The State Secretariat of Economic Affairs (SECO) and the private non-profit association of Swiss stakeholders in the gold supply chain, Swiss Better Gold Association (SBGA), have joined forces to create the Better Gold Initiative for Artisanal and Small-Scale Mining (BGI for ASM; SECO, 2021). The aim of the BGI for ASM is to increase transparency and sustainability in the Swiss gold supply chain.

Many market-based initiatives throughout the supply chain of gold products have also attempted to maintain the positive socio-economic benefits of the gold industry while decreasing some of its environmental and social costs. Initiatives include certification schemes, such as Fairtrade Gold, focused on ensuring the supply of more ethically produced gold from the artisanal mining sector. Other projects have attempted to increase the use of more efficient extraction technologies or to improve the recycling rate of gold to alleviate some pressure on primary gold sources. Many multi-lateral organisations, NGOs, and other activists recommended that host governments formalise artisanal mining in their country to give artisanal miners access to formal markets and credit, and allow the government to monitor sites (Vogel et al., 2018; Siegel & Veiga, 2010). The most extensive international action that encourages host governments to formalise is the Minamata Convention against Mercury (Hilson, Zolnikov et al., 2018).

In this doctoral project, I study various aspects of the upstream gold supply chain, such as assessing the vulnerability of local gold markets, the impact of artisanal mining on neighbouring communities, and ways to make working conditions safer in artisanal gold mines. I also study various questions in the downstream part of the gold supply chain, such as the feasibility of using blockchain to responsibly source gold from artisanal miners, the demand for certified gold, and the potential to increase gold extraction from secondary sources through the recycling of e-waste, or urban mining.

1.2 Research problem

1.2.1 Upstream gold supply chain

In the upstream part of the supply chain, we look at various research questions, including the market structure of local gold markets and their connection to the global gold market (Chapter 2), the impact of artisanal mines on neighbouring households' well-being (Chapter 3) and reasons why miners are not adopting safer practices when handling mercury (Chapter 4).

Since industrial mining consist of mainly formal mining operations, data on industrial mining is well documented and readily available through non-governmental organisations, such as the Extractive Industry Transparency Initiative (EITI) or databases such as the S&P Global Market Intelligence, Metals and Mining database. On the other hand, most artisanal mining operations are informal and unregulated (Fritz et al., 2018). Given the informality of artisanal mining operations, the size, scope, and production of artisanal mining sectors are mostly unknown. Since governments usually do not report on artisanal mining activities and miners do not disclose production, limited data from field surveys and shops that buy gold from artisanal miners are usually extrapolated to estimate artisanal gold production. Described as a "global data gap," lack of accurate and disaggregated data on artisanal mining is considered the most significant obstacle addressing issues in the artisanal gold mining sector (Lahiri-Dutt et al., 2019).

Since artisanal mining is a poverty-driven activity, gold prices are considered an essential motivation to take up artisanal mining. World gold prices are often used to estimate the number of artisanal miners in the world (Seccatore et al., 2014) and the impact of artisanal mining on neighbouring households (Bazillier & Girard, 2020). While these studies rely on the assumption that local gold markets follow world gold markets, the relationship between global and local gold markets is a critical gap in the literature. We are unaware of any studies that describe local gold markets' competitiveness and market failures or link to global markets. In Chapter 2, we use the COVID-19 pandemic to study local market dynamics in Burkina Faso, including the relationship between global and local gold prices. We find that due to existing market imperfections, exacerbated by the pandemic, local gold prices decreased significantly during periods of isolation and travel restrictions, while global gold prices reached a record high.

World gold prices have also been used to estimate the impact of artisanal mines on local communities. Due to the lack of data on the location and starting date of artisanal mines, previous studies that have tried to estimate the impact of artisanal mining on neighbouring communities' welfare had to make various assumptions. A study by Bazillier & Girard (2020) used changes in the world gold price as a temporal variation to determine the impact of price changes on communities neighbouring registered artisanal mining plots. However, since we find that local gold markets are imperfect and do not necessarily follow global gold markets, we believe that determining the impact of artisanal mines is a significant gap in the literature.

In Chapter 3, we contribute to closing this gap by considering the impact of artisanal mines on neighbouring households' expenditure, wealth, infant health, and school enrolment. We use both the impact of the world gold price, similarly to previous research (Bazillier & Girard, 2020), and a more refined analysis by considering the actual opening of an artisanal mine. Replicating previous methods and conducting a more refined analysis allows us to comment on the effectiveness of previous methods.

We contribute to the existing literature in three important ways. First, we use a more comprehensive dataset on artisanal mines developed by the governmental body responsible for artisanal mining in Burkina Faso, ANEEMAS (*l'Agence Nationale d'Encadrement des Exploitations Minière Artisanales et Semi-mécanisées*, the National Agency for the Supervision of Artisanal and Semi-Mechanized Mining), which lists about eight times the number of mines that have ever been registered. Second, we use high-resolution satellite imagery to supplement the known location of artisanal mines with starting dates based on when they appear in the images. This novel database allows a more refined analysis, with improved spatial and temporal data, to determine the impact of artisanal mines on neighbouring communities without relying on changes in the world gold price. Third, we differentiate between informal and formal artisanal mines.

Formalisation is an increasingly salient topic in artisanal mining. To minimise the impact of the artisanal mining sector, academics, NGO's and multilateral organisations have been encouraging host governments to formalise the artisanal mining sector. Formalisation would allow governments to monitor sites and give mines access to formal credit, which they could use to improve their operations and make them more efficient. Despite the emerging body of literature on formalisation in artisanal mining, we are not aware of any study that quantitatively evaluates the impact of formal or informal artisanal mines on neighbouring households and communities. This would address the important question if current ways of formalisation reduces some of the negative externalities of artisanal mines for neighbouring communities.

We find that artisanal mining has a significant positive impact on household expenditure, especially when a mine is formalised. However, given the small number of licensed mines, this effect is not significantly different from informal mines. In addition to the positive impact of artisanal mining on expenditure and wealth, we also find higher levels of school enrolment. However, we do not find strong evidence that artisanal mining has a significant impact on infant health, and similar to many quantitative studies, we find a significant increase in expenditure on alcohol and tobacco around artisanal mines.

Lastly, in Chapter 4, we study ways to improve some of the health outcomes of artisanal miners by assessing ways to increase protective behaviour against mercury use specifically. As far as we are aware, we are the first study to assess the determinants of low personal protective equipment behaviour in artisanal mines. In this study, we conducted a survey, a field experiment, and biological sampling. We also conducted two rounds of follow-up surveys with the same miners. Due to the difficulty of accessing artisanal mines and keeping in contact with the same miners, many studies on artisanal mining are cross-sectional. With the field experiment and follow-up surveys, we can also contribute to the current literature by evaluating the impact of access to protective equipment on the behaviour of a panel of miners. The lack of access to protective equipment is a more significant constraint for miners to adopt protective behaviour than personal risk perception. In addition, we find that knowledge has a small correlation to reported usage.

1.2.2 Downstream gold supply chain

This dissertation also covers various questions in the downstream part of the gold supply chain, including assessing the potential of using a blockchain system to reduce the due diligence cost when sourcing gold from artisanal miners (Chapter 5), understanding the demand for certified gold (Chapter 6) and evaluating the potential to increase the amount of gold sourced from secondary sources – known as urban mining – such as extracting gold from unused mobile phones (Chapter 7).

Many of the negative externalities in the upstream part of the supply chain can be addressed by changing consumer behaviour in the downstream part of the supply chain. Consumers in high-income countries are often far removed from the negative impact of their consumption. For example, Switzerland ranked third of 180 countries in the Environmental Performance Index, which considers local ecosystem vitality and health (Wendling et al., 2018). However, taking a larger perspective, Switzerland's global per capita footprint was more than four times larger than what the earth could sustainably manage per person in 2013 (Global Footprint Network, 2020). The large discrepancy between Switzerland's pristine local ecology and its unsustainable large global footprint is due to the number of consumer goods that are imported. Of Switzerland's total carbon dioxide emissions, 64% are emitted in foreign countries (Hertwich & Peters, 2009). About 70% of its material footprint is embodied in imports (Tukker et al., 2014). Materials include bulk materials (sand, clay, gravel, etc.), crops, fossil fuels, and mineral ores (Tukker et al., 2014). Behavioural changes in the downstream part of the supply chain could have significant benefits in communities where metals are extracted. In the second part of this dissertation, we address three questions in the downstream part of the supply chain that could potentially alleviate negative environmental and social impacts in the upstream part of the supply chain.

If consumers and retailers want to source gold more responsibly, it is important to increase transparency and traceability. Given the cost of various due diligence requirements to increase transparency, refiners source directly from a few large industrial mines. Given the small volumes that a single artisanal mine or group of miners extract, it is not profitable for refiners to source directly from artisanal mines, excluding many artisanal miners in high-risk areas from the market. Blockchain is often recommended as an alternative cost-effective system that could operate without a central authority to trace transactions throughout the supply chain and increase transparency. In Chapter 5, I conducted interviews with experts throughout the supply chain, including in the fields of blockchain, certification, and logistics, to determine if blockchain could be used to reduce refiners' due-diligence costs when sourcing from artisanal miners.

Market-based initiatives, such as certification schemes, assure more transparent and responsible sourcing. Certification schemes are a relatively new and increasingly popular way to increase transparency in mineral supply chains. However, the total market share of certified gold is relatively low; for example, in 2020, Fairtrade Gold had a market share of less than 1% in Switzerland (using data from World Gold Council, 2021c; Max Havelaar Foundation, 2020). Increasing certified gold's market share is difficult due to various factors, including consumers' low demand and willingness to pay. Since individual consumers do not frequently buy gold and do not have a good understanding of the problems in the gold industry and their preferences for certified gold, the demand for certified gold is driven by the demand from retailers. We are unaware of any studies that try to understand the determinants of low demand for certified gold or retailers' preferences for certified gold. In Chapter 6, I interviewed banking, jewellery and certification experts to understand what drives the demand for certified gold and why it is currently so low.

Lastly, sourcing gold and other metals from secondary sources, such as discarded smartphones, could alleviate pressure on natural resources and move to a more circular economy. Supply of metal from all sources – industrial and artisanal mining and recycling – would need to increase to meet growing demand (Ali et al., 2017). Nevertheless, many people in high-income countries store old electronic devices that are no longer in use, withholding the embedded metals from re-entering supply chains and so constitutes a significant lost resource. This is especially true for smaller electronic devices that are easy to store and often effortful to discard responsibly, such as mobile phones and smartphones. In Chapter 7, we investigate the general behaviour around the use of phones in Switzerland, and we conduct a randomised controlled experiment to assess various treatments to increase the recycling rate of old phones. Lastly, we conducted a cost-benefit analysis to determine the total environmental cost of increasing recycling rates against the collection cost. While many studies have focused on e-waste collection or methods to extract metals from old devices, data on collection for recycling and randomized controlled experiments to understand the collection of phones are a critical gap in the literature. Our final chapter contributes to closing this gap in the literature.

1.3 Structure of dissertation and contribution

My doctoral research is part of the Swiss Minerals Observatory research incubator group at the Institute of Science, Technology, and Policy (ISTP) at ETH Zürich. The group studies Switzerland's global impact due to the consumption of certain metals, including gold. The Swiss Minerals Observatory is divided into three work packages. In the first work package, the team creates a global overview of the flow of minerals from the country of extraction to the country of sale. Although none of my projects is located in this work package, some of the methods developed by the team in this area have been applied to determine the potential environmental savings of urban mining in Switzerland (see Chapter 7).

The second work package focuses on the local impact of mining in the country of extraction by quantifying pollution, various water demands, and socio-economic impacts. Chapters 2 to 4 that quantify some of the social impacts of mining activities on local communities are located in the second work package. Chapters 5 to 7 are located in the third work package, which addresses the issue from an end-user perspective, for example, possible contributions consumers could make to mitigate their impact on the global gold market. Table 1.2 gives an overview of each chapter, method used, and authors.

1.4 Own and co-authors' contribution

Chapter 2 was done with primary data collected from in-person and phone surveys. I discussed the focus and scope of the article with Isabel Günther. I set up the survey with input from Fritz Brugger and Isabel Günther (see Table 1.2). I organised and managed the fieldwork. I cleaned the data and conducted all analyses. I wrote the article and received valuable input and feedback from Isabel Günther and Fritz Brugger. Isabel Günther edited the paper. The chapter has been published in the Journal of African Economies.

Chapter 3 was done in close collaboration with colleagues from the Development Economics Group (see Table 1.2). I am the principal researcher on the project, mainly responsible for setting up the novel database (supplementing existing data, cleaning and compiling), conducting and interpreting all analyses, and writing up the results. Under my instruction and supervision, a research assistant labelled and sorted all satellite images used to set up the novel database. Co-authors Kenneth Harttgen and Isabel Günther have given input on a conceptual phase, assisted with various decisions made on methodological and technical aspects, and reviewed and edited the article.

Chapter 4 is my main interdisciplinary article with members from the Swiss Minerals Observatory group, Désirée Ruppen, and Bernhard Wehrli. I am the main researcher on the project. With guidance from Isabel Günther and Fritz Brugger, I set up the research question, study design, and survey. Bernhard Wehrli assisted with designing the hair sampling procedure. Although I was primarily responsible for communicating decisions to the partners in Switzerland and Burkina Faso, a Master's student also assisted in communication, and did all translations into French. Due to the deteriorating security

Ch.	Heading	Method/Data	Authorship
2	Rising gold prices but lower incomes for gold miners: evidence on market imperfections from Burkina Faso during COVID-19	Quantitative analyses with own survey data	Antoinette van der Merwe, Fritz Brugger, Isabel Günther
3	Impact of artisanal gold mines on well-being of mining communities in Burkina Faso	Quantitative analyses with secondary data from household surveys and satellite images	Antoinette van der Merwe, Kenneth Harttgen, Isabel Günther
4	Assessing constraints to adopt protective behaviour against mercury on artisanal gold mines: knowledge, risk perception and access	Quantitative analyses with own survey data, field experiment and biological data	Antoinette van der Merwe, Fritz Brugger, Désirée Ruppen, Bernhard Wehrli
5	A Blockchain is only as strong as its weakest link: transparency and artisanal gold	Qualitative interviews	Antoinette van der Merwe
6	Certified gold: too many schemes and not enough demand	Qualitative interviews	Antoinette van der Merwe
7	Viability of Urban Mining: the relevance of information, transaction costs and externalities	Quantitative analyses with own survey data and randomised controlled experiment and life-cycle assessment	Antoinette van der Merwe, Livia Cabernard, Isabel Günther

Tab. 1.2: Summary of chapters Title, type of data and authors of chapters.

on artisanal mines in Burkina Faso, researchers from ETH Zürich were not allowed to visit the artisanal mines. I managed the fieldwork remotely from Zürich, with the help of researchers and Master student located in Ouagadougou. I did all the data analysis and cleaning of the survey and experimental results. Désirée Ruppen analysed the hair samples, interpreted the results, and was the principal author of the literature on the hair, with my contributions.

Chapters 5 and 6 are two smaller chapters published as research briefs on the ETH Zürich Research Collection. For both these chapters, I interviewed experts in, amongst other fields, blockchain, logistics, certification, jewellery, and banking. Both research briefs are single-authored.

In Chapter 7, Isabel Günther and I were responsible for the research question and study design (both large-scale survey and experiment). I was responsible for setting up and managing the experiment, collecting, cleaning, and analysing the data. In order to do a cost-benefit analysis of our project, Livia Cabernard (from the Swiss Minerals Observatory group) conducted a multi-regional-input-output analysis with a life-cycle analysis to quantify the benefits of recycling. I gave Livia Cabernard the analysis's input values and determined the recycling cost. I wrote the article, with inputs from Livia Cabernard on her analysis and valuable feedback from Isabel Günther on the article's format, layout and content. See Table 1.2 for overview of co-authors.

Other activities during doctoral studies

Other publications related to my doctoral research include a publication in the OECD Development Cooperation Report 2021 on the impact of digitisation on low-income areas (see Van der Merwe & Brugger, 2021) and a policy brief on mobile phones usage in Switzerland (see Van der Merwe & Günther, 2020).

The study on personal protective equipment in Burkina Faso (see Chapter 4) has further developed into a retort study. Retorts are simple tools artisanal miners could use to protect themselves from dangerous mercury fumes. Despite the considerable potential of retorts to reduce mercury exposure, we found that most miners do not even know what retorts are. One of the most common critiques against retort distribution projects is that retorts have not been designed in collaboration with miners and, therefore, do not fit miners' preferences and needs. In this ongoing project, I am working with various researchers from ETH Zürich to assess the possibility of co-designing a retort with miners in Burkina Faso.

Also related to our research project in Burkina Faso, I co-authored an article with Fritz Brugger, Anna Bugmann, and Zongo Tongnoma on the interconnectedness of mercury and gold supply chains in Burkina Faso (see A. Bugmann et al., 2022), and I produced a short video on our project for a general audience ("True cost of gold: mercury and artisanal gold mining", 8 July 2021).

Throughout my doctoral studies, I was also involved in other research projects. During the COVID-19 pandemic, I initiated a new research project with colleagues at the Development Economics Group to see how poor South African communities managed during the pandemic and with lockdown regulations. The project has been extended to Ghana, Benin, Kenya, and Burkina Faso. Cross-sectional results from the baseline surveys from South Africa and Ghana have been published in World Development (see Durizzo et al., 2021) and results from follow-up surveys have been published in Review of Income and Wealth (see Durizzo et al., 2022). Results from the study have also been published on ETH Zürich channels, including interviews with ETH Zürich Corporate Communications, Institute for Science, Technology and Policy, and ETH magazine, Globe ("Poorest face dilemma in Africa's cities", 14 January 2021). I also co-authored an article with Yael Borofsky about the lockdown in South Africa in Mail and Guardian ("A smarter, not stricter lockdown is necessary", 11 January 2021).

The COVID-19 research project has also developed into a project on early childhood development. In this project, I consider the impact of parental involvement in early childcare centres in low-income areas in South Africa to improve children's well-being. Together with a local partner, we have concluded baseline and follow-up phone surveys and numerous focus groups.

Chapter 2

Rising gold prices but lower incomes for gold miners: evidence on market imperfections from Burkina Faso during COVID-19

Joint work with Fritz Brugger and Isabel Günther
Paper published in Journal of African Economies

Abstract: Although artisanal gold mining is known for human rights violations and environmental degradation, it is an increasingly important economic activity in many African countries, with a high potential to alleviate poverty. Due to increased demand for gold investment during the COVID-19 pandemic, the monthly international gold price has increased by 20% from January to May 2020. To understand how the COVID-19 pandemic has influenced gold miners, we analyse a panel survey of about 170 artisanal gold miners interviewed two months before the first case of COVID-19 in Burkina Faso. Follow-up surveys were done early in the pandemic and about one year after baseline. Various pre-existing local market failures caused local gold prices to decrease by about 20%-30% from January to May 2020, when international gold prices noticeably increased. Market failures include oligopsonistic market conditions on the mines, which worsened due to travel restrictions that disrupted trading routes, reduced local traders' liquidity, and made it difficult for traders to reach mines. Moreover, we find that miners have very little knowledge of international gold prices, and due to insecurity and credit constraints, they are unable to wait for local prices to recover. Once travel restrictions were lifted, the local gold price recovered close to the global gold price. To make local markets more competitive and ensure that miners benefit from rising international gold prices, governments could broadcast world gold prices on local radio, increase trading opportunities and provide access to credits for miners.

2.1 Introduction

The LBMA (London Bullion Market Association) gold price, considered the benchmark for the international gold price, has increased about 260% from 1990 to 2019. Many people in low-income and resource-rich countries took up artisanal gold mining during the same period. For example, in Burkina Faso, the number of artisanal gold miners are estimated to have increased from about 0.2 million gold miners in 2001 to 1 million miners in 2017 (Brugger & Zanetti, 2020; Mondlane, 2017; Arthur & Domiter, 2017). Unmatched by most other rural activities in countries such as Burkina Faso, artisanal gold mining promises substantial profits that could escape poverty for millions of people (Fritz et al., 2018). Fisher et al. (2009) found that people involved in artisanal mining or related services in Tanzania were less likely to be poor than people in other occupations. Other studies found that artisanal mining positively impacted household income in Ghana (Guenther, 2018) and Burkina Faso (Bazillier & Girard, 2020). Therefore, despite the sector's bad reputation concerning environmental degradation and human rights abuse, it has considerable potential to alleviate poverty.

In contrast to agricultural commodities, miners receive a large share of the international gold price. Reported local gold prices in Burkina Faso are usually between 90-95% of the world fix price (Artisanal Gold Council, 2021). This is very high compared to, for example, cotton, the second largest export commodity in Burkina Faso and the most popular cash crop, where farmers only received about 60%, of the world cotton price (Kaminski, 2011).

Thus, it is not surprising that many studies assume that miners' livelihoods are closely linked to international gold prices (Bazillier & Girard, 2020; Grynberg et al., 2021; Seccatore et al., 2014; Hruschka & Echavarria, 2011; Shandro et al., 2009). Gold prices are considered to be such a key driver to local incomes that changes in the international gold price are even used to estimate the number of artisanal miners worldwide. Using changes in international gold prices and adjusting for estimated productivity of miners in different countries, Seccatore et al. (2014) estimated 16 million active artisanal gold miners in 2017.[1] However, Bazillier & Girard (2020) have recently shown that a 1% increase in the international gold price led to a 0.1% increase in expenditure of households near artisanal mines in Burkina Faso. While Bazillier & Girard (2020) did not consider changes in savings, it is improbable — given the extreme levels of poverty in rural areas in Burkina Faso — that households' savings increased by 0.9%. The modest impact of international gold prices on households' income already questions the link between international gold prices, local gold prices, and the financial well-being of miners.

Moreover, conducting 3,400 rapid phone interviews in 22 different countries, Perks & Schneck (2021) asked respondents how current gold prices compared to prices before

[1] Other estimations of the number of artisanal miners mostly rely on governmental reports of the 70 countries that host artisanal gold miners, such as Hruschka & Echavarria (2011), who estimated 15 million artisanal gold miners in 2011. Since most artisanal miners operate informally, governmental records probably underestimate the size of the mining populations.

COVID-19 was an issue in their country. They found that in June 2020, most miners reported gold prices lower than before the pandemic, despite increasing international gold prices in the same period. The authors did not ask respondents about the changes' magnitude or how participants measured local prices. According to the authors, most local gold prices have shown some evidence of recovery by 2021 (Perks & Schneck, 2021).

Our study contributes to this emerging body of literature with a unique panel, including a baseline survey of about 300 artisanal gold miners in Burkina Faso —170 of whom were active in the gold trade —and two follow-up phone surveys with the same miners. Unlike other studies, our data collection already started before the pandemic. We conduct a quantitative analysis of the impact of COVID-19 and the surge of international gold prices on local gold prices and study the mechanisms that explain the link between the two. Although it is difficult to directly compare local and international gold prices for various reasons — including inconsistencies in the purity, assay, and weighing of gold on the local level — we can analyse relative changes in international and local gold prices over time.

We conducted surveys on four artisanal mines shortly before the Coronavirus spread across the globe (December 2019 - January 2020). We conducted two rounds of follow-up phone surveys; the first was from April to May 2020, when a state of sanitary emergency, including travel bans, was implemented in Burkina Faso. The second follow-up phone survey was about a year after the baseline survey, between December 2020 and January 2021, when the Burkinabe government relaxed many lockdown regulations, but with the global health crisis still ongoing.

While the pandemic led to a surge in international gold prices, it had the opposite effect on local gold prices, which fell from an average price bracket of XOF 25,000-XOF29,999 per gram in January 2020 to less than XOF 20,000 per gram in May 2020. Due to various market imperfections, the impact of COVID-19 and the measures to combat it were much more prominent in local gold markets and caused this diverging trend. First, local travel restrictions hindered traders from reaching sites. International travel restrictions dislocated existing trading routes, which meant that many private buying companies (locally known as *comptoirs*) could not export gold and did not have sufficient cash to buy gold from miners through gold traders (or collectors). As a result, the number of gold collectors available to miners decreased from 2.6 in January 2020 to 1.2 in May 2020. Second, information asymmetries about international gold prices are large. Our survey reveals that more than 95% of miners do not know the international gold price. Even if miners knew international prices, many would not wait for prices to improve since miners are highly dependent on their income from gold without any access to credit (Hinton, 2005; Brottem & Ba, 2019; Telmer & Veiga, 2009). In addition, since gold is highly lootable, keeping gold until prices recovers can put miners in danger (Ross, 2004; Bertran Alvarez et al., 2016).

2.2 Context

Artisanal mining has been practiced throughout Burkina Faso since the 1980s but has grown substantially in the last 15 years (Werthmann, 2017; DeJong, 2019). In 2018, the Burkinabe governmental body responsible for artisanal mines, ANEEMAS (*l'Agence Nationale d'Encadrement des Exploitations Minière Artisanales et Semi-mécanisées*, the National Agency for the Supervision of Artisanal and Semi-Mechanized Mining) surveyed 63 (not randomly selected) mines out of about 2,300 artisanal mines sites in Burkina Faso identified from satellite images. They found that more than half of the mines started operations only after 2000. Presently, an estimated 0.6-1 million people are directly or indirectly involved in artisanal mining in Burkina Faso (Arthur & Domiter, 2017; Mondlane, 2017), out of an adult population of 10.5 million (15 years and older; World Bank, 2021). In some areas, two out of three households have at least one family member involved in artisanal mining (Brugger & Zanetti, 2020).

Due to the small quantities of gold that a group of miners extracts, gold accumulates from the mines to the larger *comptoirs* (private buying companies) through a myriad of local and regional traders, known as gold collectors (Grätz, 2004; Guéniat & White, 2015; Telmer, 2020). Independent intermediary gold traders or collectors travel from nearby cities and towns to buy gold from miners. They then sell the gold to the *comptoirs*, most of whom are situated in Ouagadougou, who then export the gold. The *comptoirs* often try to extend their power on the mine site by directly taking control of the sites or prefinancing operations with the precondition that miners will sell gold to them exclusively (A. Bugmann et al., 2022). *Comptoirs* have been known to use intimidation and force to secure exclusive buying rights to miners' gold (Engels, 2017).

Artisanal miners in Burkina Faso are often exposed to violent conflict. Due to increased terrorist activities, the government has implemented a state of emergency in the north of Burkina Faso, in the areas bordering the Sahel, since December 2018 (Reuters, 2018). ANEEMAS reported that 86% of mines that they recently surveyed had experienced some form of conflict (although it is not specified what type of conflict; ANEEMAS & Effigis Geo-Solutions Inc., 2018). One of the participants in our study mentioned during the phone survey in May 2020 that: "Our problem today is the case of the bad people who attack the villages and the gold sites. It is the attack of the sites that worries us, not COVID-19."

In this fragile state, the first case of COVID-19 was confirmed in Burkina Faso on 9 March 2020 in the capital city of Ouagadougou. With 146 confirmed cases on 26 March 2020, Burkina Faso's government declared a sanitary emergency in addition to the security state of emergency in the north (WHO, 2020; US Embassy in Burkina Faso, 2021). The sanitary state of emergency included various regulations, such as promoting handwashing, discouraging shaking hands, and mandatory mask usage in public spaces. Moreover, city-wide quarantines, curfews from 19:00 to 05:00, and a travel ban were implemented. The travel ban included closing the airports in Ouagadougou and Bobo-Dioulasso from

21 March to 1 August 2020, only allowing freight and cargo planes to enter the country (US Embassy in Burkina Faso, 2021; Garda World, 2021). Except for commercial traffic, all other land borders were closed and are still closed as of 27 August 2021. City-wide quarantines have disrupted the interconnection of roads between various towns and the centre, Ouagadougou, making traveling within the country difficult. However, all city quarantines and curfews were lifted on 4 May and 3 June 2020, respectively (US Embassy in Burkina Faso, 2021). In addition, public markets have been closed until 20 April 2020. The gold miners' market is essential for selling gold, buying necessary supplies, and crushing ore. It is difficult for miners to continue work without the support and structure found in the market. During our final phone survey in January 2021, the Burkinabe government has relaxed most of the social distancing and related regulations; with no restrictions on public transport, airports and schools were open, and no restrictions on the number of people that were allowed to gather (Hale et al., 2020).

2.3 Sampling and data

We first visited four artisanal mines, Sandouré, Ronguin, Zomnkalga, and Galong-Tenga in the Centre-North of Burkina Faso (see Figure 2.1) from November 2019 to January 2020 for a research project on mercury use and the health of artisanal miners.[2] We included various questions about knowledge and use of mercury and personal protective equipment, as well as questions about local gold markets, socio-demographics of miners, and contact details (see Appendix 2.A for all survey questions relevant to this article). Due to the security situation on the mine sites, our local partner[3] requested that only local Burkinabe fieldworkers could visit the mines. Researchers trained the enumerators in Ouagadougou before fieldwork and remotely managed the project via phone.

Due to the informal operations of small-scale gold miners, artisanal mines do not have records of workers on a mine. Moreover, enumerators were not allowed to walk around freely on the mine sites. Given the tense security situation and that artisanal mining is mostly illegal or informal, artisanal miners are skeptical of strangers. Artisanal miners often fear that strangers are from the government trying to stop their activities or from an industrial mine exploring the area to expand mining activities, which would displace them. Therefore, we were not able to do a census on the mine, and random sampling of miners was impossible.

We resorted to combining a geographic systematic sampling technique and snow-ball sampling technique. Enumerators identified a central point on the mine that the local partner considered safe from which they could spread out. From this central point, enu-

[2]Two ethical review boards, the Comite d'éthique institutionnel pour la recherche en sciences de la sante (IRSS) in Burkina Faso (N/Ref. A38-2019/CEIRES) and the ETH Ethics Commission in Switzerland (2019-N-141), reviewed and approved the research project.

[3]Our local partner was Sagrasy Consulting, a Burkinabe consulting firm that assists various organisations, researchers, and NGOs with development services, such as project management, monitoring, or training (sagrasy.com/).

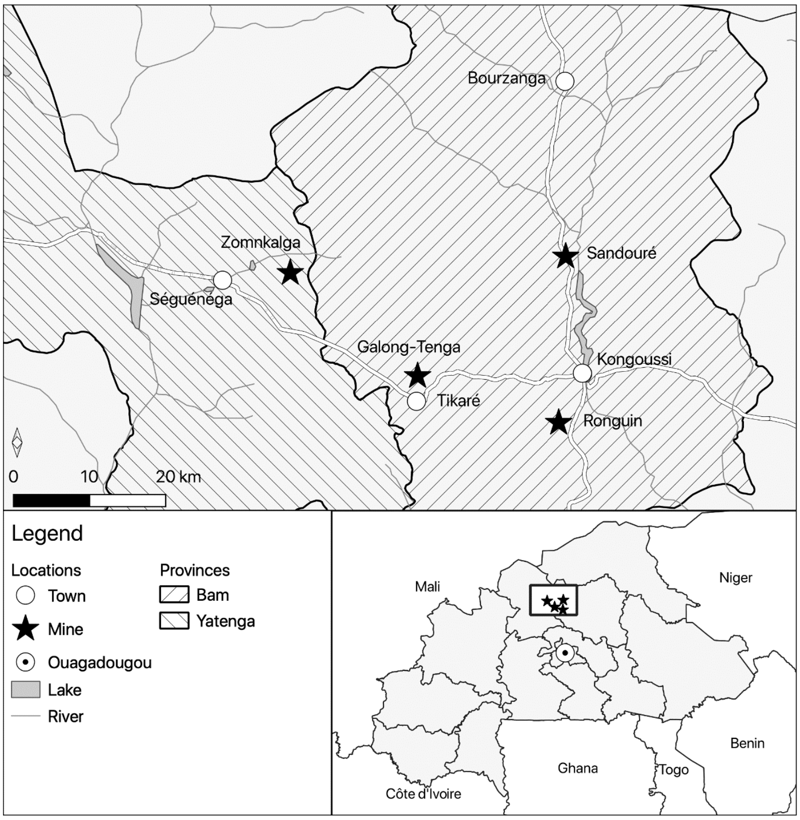


Fig. 2.1: Fieldwork study area. Location of the four artisanal mines where we conducted fieldwork from November 2019 to January 2020.

merators would split up into four directions (labelled the north, south, west, and east axes). An enumerator would walk in their dedicated direction until they crossed paths with a miner and then ask them if they wanted to participate in the survey. Since miners often work in groups, the enumerator would also ask the first miner to suggest other members of their group who want to participate in the survey. If no more miners in the group wanted to participate in the surveys, the enumerator continued on the original axis that he walked on to approach the next participant.

Due to security concerns, our local partners' availability, and time constraints, we could only spend about four days per mine site. In the available time, the team approached 302 miners, of whom 26 did not want to participate in the study. Enumerators surveyed 52 people at Galong-Tenga, which, according to enumerator's estimations, is about 30% of the total mining population, 64 people at Sandouré (10-25% of estimated mine population), 88 people at Ronguin (20-30% of estimated mine population), and 72 people at Zomnkalga (30% of estimated mine population). Although our purpose was not to identify a representative sample of all artisanal miners in Burkina Faso, sampling about 300 miners from four different sites gave us some heterogeneity and variation in studying the local markets.

Due to the COVID-19 situation, we conducted two rounds of follow-up surveys via phone, which were initially planned as in-person surveys. During the first phone survey,

	In-person baseline surveys	**1st follow-up phone survey**	**2nd follow-up phone survey**
Date	25-27 Nov; 2 Dec 2019; 7-13 Jan 2020	20 Apr to 17 May 2020	23 Dec 2020 to 8 Jan 2021
Number of people approached/ numbers available	302	245	245
Did not want to take part	26	4	4
Could not get hold of person	N/A	59	108
Total surveys completed	276	182	133
People that sold gold in the last 30 days (final sample size)	168	117	97

Tab. 2.1: Sample details. We approached 302 miners during the first round of fieldwork and contacted the same people in two follow-up phone surveys.

we reached 182 people (out of 245 from which we obtained a phone number during the baseline (see Table 2.1); four did not want to participate, and the other 59 could not be reached. For the second phone survey, we completed 133 interviews (see Table 2.1). Of the total sample, 168, 117, and 97 in each survey round reported that they sold gold in the last month and were of particular interest for this study (see Table 2.1). All the following tables and figures apply only to these individuals actively involved in gold trading in the month prior to surveying.

We had a high attrition rate between phone surveys of about 30% to the second survey round of the numbers that we could not reach. About a third were already invalid, and two-thirds could not be reached (voicemail or rang without answer). From baseline to the third survey round, we had an attrition rate of 42%; of these, 95% went straight to voicemail or rang without answer, and the other numbers were invalid. According to the enumerator who conducted the phone survey in our study, the high attrition rate in our sample could be due to various reasons, including that people work long hours on the mines and are difficult to get hold of; problems with mobile coverage in rural areas; and changing contact details due to migration.

We find some evidence of an attrition bias due to the high attrition rate. In both follow-up surveys, more miners were from Zomnkalga, and in the third survey, less participants came from Ronguin, when compared to the baseline survey. We also found that women were less likely to complete follow-up surveys. However, we did not find any other significant difference between the means in the baseline and the follow-up survey rounds (see balance table in Table 2B.1 in Appendix 2.B). While we cannot definitively conclude that the reasons why a person did not complete the follow-up surveys are somehow correlated to being involved in the gold trade, we did not find that those involved in the gold trade at the baseline survey were significantly less or more likely to complete follow-up surveys. However, when we replicate our main results on a balanced panel of miners who completed all the survey round, we do not find that the attrition bias drives our results (see 2C.1 in Appendix 2.C).

Participants in the survey had to be at least 18 years old. If we assumed the participants that said they are "older than 50 years" (8.0%) are on average 55 years old, then the average age of the miners in our sample is 33 years. Most participants are male (92%), which is consistent with information from the Ministry of Mines, which noted that the percentage of women is site-dependent; some sites have no women or as little as 5% (ANEEMAS & Effigis Geo-Solutions Inc., 2018). Participants reported low levels of schooling, with 67% of participants not having attended any schooling. The miners are less educated than the Burkinabe national average: 70% of male and 93% of female participants cannot read or write, compared to 50% and 67% of men and women older than 15 nationally. Only one participant (0.6%) has completed secondary schooling (the highest reported level of schooling), while the national average of people older than 25 that completed secondary school is 8.5% (World Bank, 2021). Most participants (95%) reported that they are from the Mossi ethnic group, the largest ethnic group in the country. However, the percentage of Mossi in the sample is much higher than the national average of about 50% (INSD and ICF International, 2012a). As the area where we conducted the fieldwork is predominantly Mossi, it seems that miners might be more likely to be locals.

Of all participants, 5% said they are the only person dependent on their income, 29% said there are two to five people dependant on their income, 36% reported six to ten dependants, and 30% said there are more than ten people dependant on their income from mining. The number of dependants in our sample is higher than the average of five dependants per miner used in the UN report on minerals in Africa (UNECA, 2011). Most respondents reported living in tiny houses: a quarter of the respondents live in houses of one or two rooms (including bedrooms and living areas). Many homes are crowded, with an average of 2.7 people sharing a room.

2.4 Results

2.4.1 Diverging prices on international and local gold markets

While COVID-19 has had an immense negative impact on the world economy, it led to the highest nominal international gold price in 2020 since at least 1978 (earliest year in data) of 66.46 USD per gram on 06 August. Gold prices also significantly increased from 47.26 USD per gram before the pandemic (average monthly price in November 2019; World Gold Council, 2020). On the other hand, measures to curb the spread of the novel Coronavirus disrupted many market interactions. Therefore, to determine the impact on local gold prices, we asked all participants who said they sold gold in the last month how much (in XOF per gram) they received the last time they sold gold. Since many miners are illiterate and we believed this could be a sensitive question, we recorded answers in brackets of XOF 5,000 to limit reporting errors.

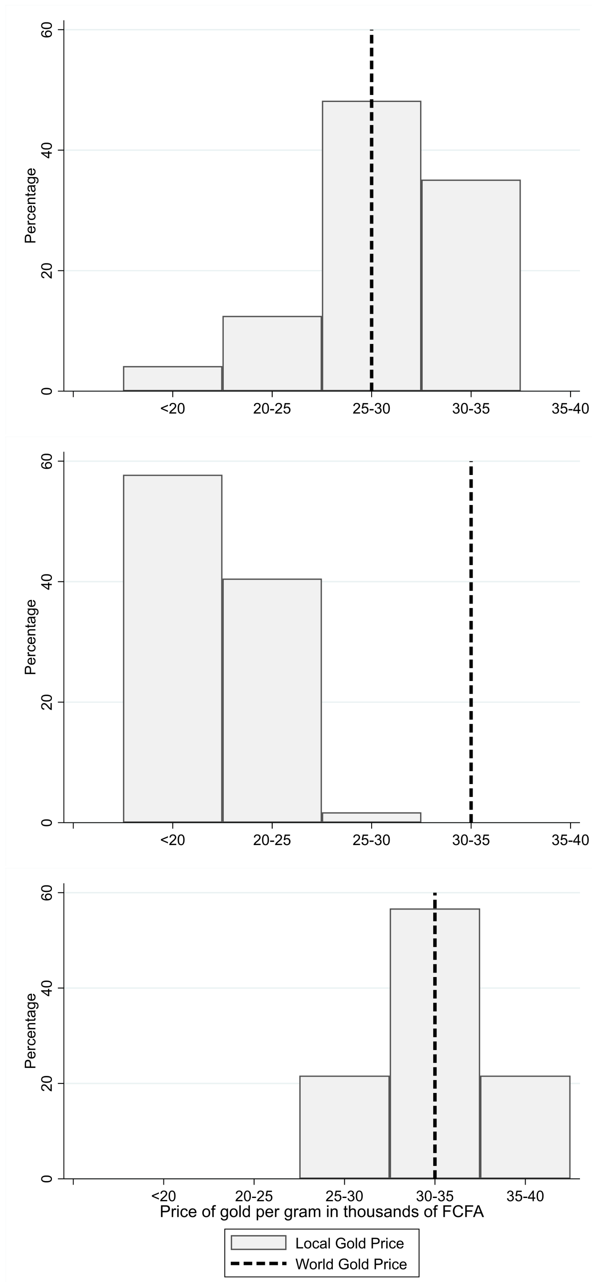


Fig. 2.2: International and local gold prices. The dashed line shows the average international gold prices. The grey bar shows the percentage of the reported local prices participants received in each price category during the same period. The first graph refers to the period before the pandemic (October 2019 – January 2020, average world gold price was XOF 28,305 per gram). The second graph refers to early in the pandemic during international travel restrictions (March to May 2020, average world gold price was XOF 31,989 per gram). The third graph refers to later in the pandemic when various regulations have been relaxed (November 2020 to January 2021, average world gold price was XOF 32,213 per gram).

During the fieldwork, this referred to gold sold from 25 October 2019 to 13 January 2020 (57 days); during the first phone survey, this referred to gold sold from 20 March 2020 to 17 May 2020 (41 days); and during the final phone surveys, this refers to gold sold from 23 November 2020 to 8 January 2021 (35 days).[4]

Figure 2.2 shows the distribution of local prices stated (grey bars) and the average international gold price during these periods (black dashed line). Figure 2.2 shows that local prices decreased significantly in May 2020 when the international gold price increased. Of all miners who sold gold in May 2020, 58% said they received less than XOF 20,000 (CHF 32) per gram, which is significantly lower than the lowest daily international gold price in March and April 2020 (CHF 49 per gram; World Gold Council, 2021b). One miner said in May 2020: "This situation of Coronavirus is going to destroy our lives because buyers were not willing to buy gold at the cost of XOF 20,000 .... So the situation is tough."

During the January 2021 phone surveys, with many social distancing and hygienic restrictions relaxed but the pandemic still ongoing, we observed that the local gold market recovered. Although the international gold price in January 2021 was in the same price bracket as in March and April 2020 (XOF 32,213 per gram), local gold prices increased significantly over the same period. The results are similar if we consider only miners that completed all three survey rounds (see Figure 2C.1 in Appendix 2.C)

The reader might also note that some miners report local gold prices even higher than global gold prices. We believe this over-reporting is due to the method used by local collectors to weigh gold. Gold collectors use electronic scales and handheld flail scales with coins and matches as counterweights when weighing gold. When using electronic scales, the gold is measured in grams. When using flail scales, the gold is measured in "strands" of gold (or *brin* in French), which is calculated as the weight of one match. Incorrect counterweights used with handheld flail scales can contribute to the high local prices compared to the gold fix price. Other studies have shown that traders in Burkina Faso inflate the buying prices by using non-standard counterweights, such as coins and matches (DeJong, 2019). For example, traders frequently use an XOF 25 coin as a six-gram counterweight, but in reality, the coin weighs about eight grams. Therefore, collectors deflate the price they offer miners by 25%. Although collectors say this is to compensate for the loss in the purity of the gold, loss in purity is usually only around 7% (Sollazo, 2018). Blore (2013) found that miners in the Democratic Republic of the Congo (DRC) typically report receiving 95% to 97% of the LBMA price for their gold. However, if the discrepancies of the counterweights are corrected, miners receive 56% to 76% of the LBMA price. However, this measurement error should be constant over each round, and we do not believe it would influence the relative difference between international and local prices.

[4]The baseline survey covers more days than the follow-up surveys (57 days vs. 35-41 days) because the pilot (Sandouré) was done a few weeks before the rest of the fieldwork, and this extended the period referred to by the questions about gold sold "in the last month". We do not find any significant difference in our main findings if we exclude the Sandouré from the analyses.

We, hence, can analyse relative changes between the international and local gold prices over time, and we observe a divergence between increasing international gold prices and decreasing local gold prices.

2.4.2 Market failures on local gold markets

The main reason for the divergence between local and international prices is that various pre-existing market imperfections were exacerbated by travel restrictions imposed to contain the COVID-19 pandemic.

Even before the pandemic, local gold markets were not perfectly competitive; 38% of miners reported monopsonistic local gold markets, with only one gold collector to whom they could sell their gold. In Zomnkalga, which is managed by the comptoir, SOMIKA, 67% of participants said there is only one gold collector available to them. Travel restrictions negatively impacted local gold prices by further reducing the number of available traders in two ways. First, international travel restrictions disrupted transnational trading and smuggling routes, which prohibited *comptoirs* from exporting gold and dried up many collector's cash reserves. With lower cash reserves, many local gold collectors could not buy more gold from miners for cash and temporarily stopped trading. Second, domestic travel restrictions made it difficult for collectors to reach mine sites. Before the pandemic, only 40% of miners said they could sell their gold directly to a processing centre or a nearby village, town, or city. The other 60% of miners relied on traders to visit them at their homes or in the mine. In the baseline survey, we find that miners who rely on traders to visit them at home are more likely to receive lower prices for their gold.

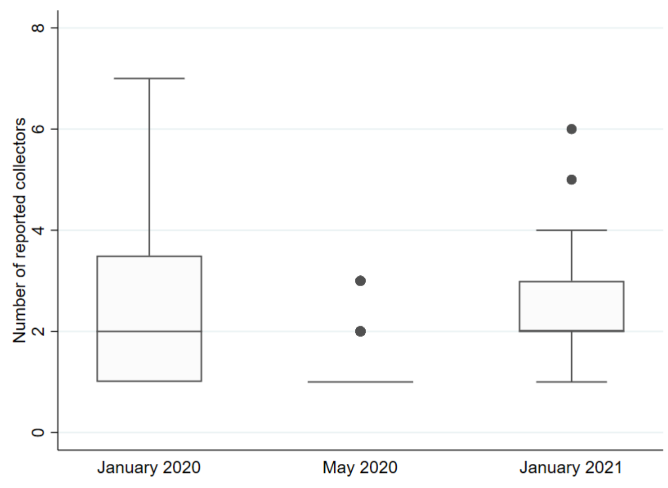


Fig. 2.3: Reported collectors in each period. The middle of the box plots shows the median values, with the outer edges of the box showing the 75th and 25th percentiles. The "whiskers" indicate the lower and upper adjacent values, and the dots indicate outliers. Since the vast majority (80%) of respondents said, there is only one buyer available in May 2020, the miners that state more than one are seen as outliers, as indicated by the dots.

As a result, in May 2020, 83% of miners reported monopsonistic local gold markets (up from 38% in January 2020), and 94% said they had difficulty finding even one buyer. The average number of gold collectors available for miners decreased from 2.6 in January 2020 to 1.2 in May 2020 (Figure 2.3). One participant mentioned in May 2020: "The cost of gold is as low as cotton... plus you could not even get a buyer because of travel restrictions". Another participant said: "There was a time, especially in early March, when even if you had gold in your possession, no local buyer would buy because travel restrictions and curfews prevented travelling."

Local markets started to recover after travel restrictions were lifted in January 2021; similar to pre-pandemic levels, 22% of the participants said they only had one available gold buyer, and the average number of reported buyers recovered to 2.4 (Figure 2.3).

Information asymmetries are a second market failure of local gold markets that led to decreasing local gold prices despite increasing international gold prices. In May 2020, 80% of respondents said that they do not know what the world gold price is, and of those who said they know, only one person gave the correct answer of the gold price on that particular day within an XOF 5,000 bracket (Figure 2.4; we did not ask this question during the baseline survey). Although fewer miners, 67% vs. 80%, said they did not know the world gold price in January 2021, still only one person knew the correct price within an XOF 5,000 price bracket (Figure 2.4).

Even if miners were aware of rising international gold prices, they would not be able to hold gold to sell it once the local market has recovered. Miners are highly dependent on their income from mining, especially in an informal environment where everything is paid with cash; miners are pressed to sell their gold as soon as possible (Hilson & McQuilken, 2014; Geenen, 2013). In particular, miners do not have access to credit markets that would help them overcome lower incomes for a couple of weeks or months (Hinton, 2005; Brottem & Ba, 2019; Telmer & Veiga, 2009). Even if miners do not face cash or credit constraints, they do not have the facilities to store gold safely until local prices recover. Gold is considered a highly lootable resource, given its small volume and high-value (Ross, 2004). Especially given the high level of violence on mine sites and possible attacks in Burkina Faso, miners are reluctant to keep gold on their person, as it puts them at risk of attacks and looting (Bertran Alvarez et al., 2016). Therefore, given cash and credit constraints and insecurity, miners cannot hold the gold until the market recovers.

Even though most miners are pressed for income, they would consider selling gold to traders on credit to reduce their risk of looting and attacks. Traders who did not have sufficient cash could buy gold from miners (at low prices) on credit. Before the pandemic (January 2020), only 6% of participants in our sample indicated that they sold gold partially on credit, meaning that the gold collectors did not pay the gold in full but agreed to settle part of the payment later or pay in kind. One year later, in January 2021 (question not asked in May 2020), 86% of miners said that during the last six months, they had to sell their gold fully or partially on credit. One of the miners said in May 2020: "Our concerns are the delay in the payment of our gold, ... sometimes I wait five to seven

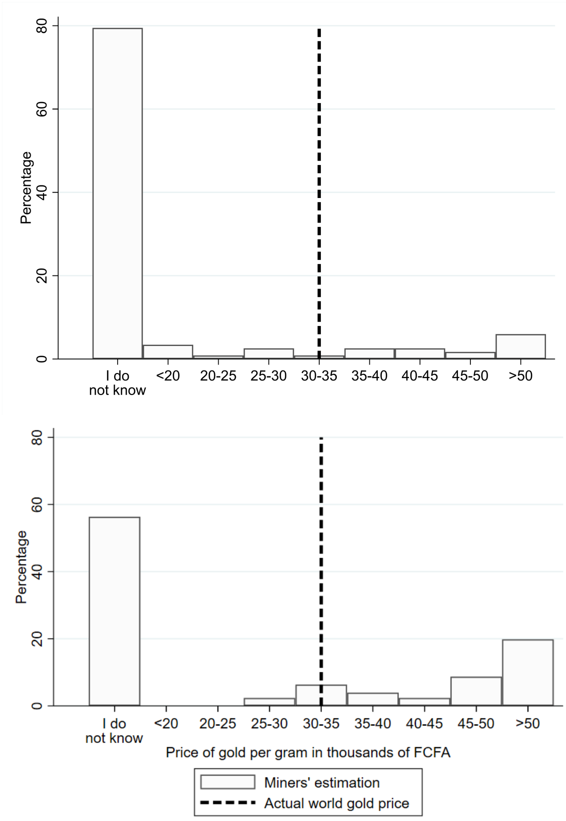


Fig. 2.4: Miners' estimated world gold price. The dashed line shows the average international gold price in the specific period, and the bars shows the percentage of miners' reported estimations of the world gold price. We did not ask this question in the baseline survey.

days before I receive my gold money. This is our current problem".

In addition to lowered local gold prices, social distancing regulations made it more difficult to continue work in the mines. While working on the site during the day was still allowed, working in the mines after 19:00 was prohibited due to curfews (many miners work night shifts). Gold markets often close to artisanal mines were closed due to the limitations on the number of people allowed to gather. Since miners rely on the gold markets to get supplies, crush ore, and trade gold, closing gold markets made it difficult to continue mining and left mines deserted, despite working on mines not being strictly prohibited. When we asked miners an open question about how the pandemic affected them most, the second most common answer after travel restrictions (mentioned by 93%) was deserted mines (mentioned by 78%).[5] In May 2020, one participant mentioned: "The gold panners

[5]Most miners mentioned "isolation" in the survey. Given that isolation was primarily mentioned in high-income countries and only mentioned by a small percentage of people in low-income settings (Durizzo et al., 2021) and given the crowded homes of respondents, we were curious why so many respondents mentioned isolation as a significant impact of the pandemic. However, the enumerators said that "isolation" did not refer to loneliness from being alone at home but to isolated or deserted mine sites.

do not come to the sites anymore... and the police patrol sometimes confiscates our motorbikes, work equipment, and other materials". Another respondent said: "In reality, the (social distancing) regulations cannot prevent us from working on the site because the authorities do not have the means to control the implementation. (However) I do not always work because there is no longer an atmosphere on the site. It is difficult to work without an atmosphere". Miners' ability to secure a livelihood were greatly affected by low local gold prices and the inability to work.

2.5 Discussion and conclusion

Although the COVID-19 pandemic is an exceptional event, external shocks and disruptions are not uncommon in local gold markets (Pijpers & Luning, 2021). Nevertheless, COVID-19 is an interesting case study because gold is often favoured as an inflation hedge and a safe investment during economic downturns when interest-bearing investments do not perform well, which led to surging international gold prices during the pandemic. On the contrary, regulations to curb the spread of COVID-19 lead to decreasing local gold prices. In addition, despite the potentially significant impact of COVID-19 on the artisanal gold mining sector and the relevance of the sector for millions of people in Africa, Asia and Latin America, the topic has not received widespread attention compared to other studies on the impact of COVID-19 and measures to reduce its spread (Hilson et al., 2021).

The contrasting impact of the pandemic on international and local gold markets is a good indication of how vastly different these two markets are. It is difficult to directly compare international and local gold markets because the international gold market is highly competitive, and local gold markets are imperfect. The gold sold on international gold markets is perfectly homogenous, with the organisations such as the LBMA verifying that it is 99.999% pure gold and correctly weighed. The international gold price is usually determined twice a day by an online auction of the largest banks representing the sum of their clients' demands. Past and present gold prices are published online and are widely available. On the contrary, gold sold at the local level are not homogenous, but semi-refined bars called doré, consisting of varying and unknown percentages of gold and secondary minerals such as silver and copper and other impurities. Local collectors — of which there are only a few per mine — routinely manipulate prices by using incorrect counterweights when weighing gold (DeJong, 2019; Sollazo, 2018).

Although not directly comparable, we believe this measurement error in local prices — due to incorrect weighing and differences in local gold's assay and purity — is constant over time, which allows us to compare relative changes in local and international gold prices. We find that international prices increased during the pandemic and local prices plummeted during periods of isolation from an average price bracket of XOF25,000 to XOF29,999 per gram to less than XOF20,000 per gram. In January 2021, with the pandemic still ongoing but travel restrictions and other social distancing regulations relaxed, the local gold prices recovered to a mean price bracket of XOF30,000 to XOF34,999 per gram.

Given this divergence between international and local gold prices, we should be cautious when interpreting studies that use the international gold price to estimate the well-being of local miners or estimate the number of artisanal gold miners worldwide (Bazillier & Girard, 2020; Grynberg et al., 2021; Shandro et al., 2009; Seccatore et al., 2014; Hruschka & Echavarria, 2011). Due to many unobserved factors, international gold prices could be a biased predictor of miners' well-being or labour allocation.

The pandemic accentuated pre-existing market imperfection of local gold markets. Due to market imperfections, external shocks could have a much larger impact on local gold markets than on more competitive world markets. Travel restrictions implemented to curb the spread of COVID-19 obstructed international and domestic smuggling and trading routes, which made it difficult for local collectors to reach mine sites to buy gold and for *comptoirs* to export gold. This decreased the average reported number of buyers available to miners and lowered local prices. We do not find that miners were aware of the increase in world gold prices, which could have further inhibited their ability to negotiate for fair prices.

Even if miners were aware of world gold prices, they would not be able to store gold until the price recovers. Due to cash constraints, lack of access to credit markets — exacerbated by high lootability of gold and dangerous conditions on the mines — miners are highly dependent on their income from mining and cannot wait for the market to recover before selling their gold. The winners are the larger *comptoirs* with liquidity to buy gold at low prices and the infrastructure to keep it safe until the market can recover and resume international trade.

If the government could improve some of these market imperfections, artisanal miners would be less vulnerable to external shocks and could even benefit from periods of higher world gold prices. Local authorities could broadcast international gold prices to miners, primarily through popular mediums such as radio, and provide better access to credits.

Government agencies could also act as central gold buyer, as it is already done by ANEEMAS in a small number of areas in Burkina Faso (outside our study area). Some evidence suggest that local gold prices in Ecuador and the Philippines, where central banks act as domestic gold buyers, were less affected by the pandemic (World Gold Council, 2021b). However, governments should take care when designing domestic purchase programs, as previous central buying programs by federal agencies have led to rent-seeking by federal buyers (Werthmann, 2017; Côte & Korf, 2018; Grätz, 2013; Hilson & Pardie, 2006). Governments who consider acting as a central gold purchaser need to, among other things, make sure they have easily accessible and widespread purchasing points, gold purchases are coordinate with other governmental agencies, employ strict measures to control and prevent corruption, and control purchases on a regional instead of national level (World Gold Council, 2021b). Studying the characteristics and dynamics of local gold markets is vital to design policies that can protect miners against external shocks and make them more likely to benefit from increases in global gold prices. This includes understanding the link between the international and local gold markets and how these linkages fail.

Appendix

2.A Survey

The following questionnaires only show the questions relevant to this study. Other questions on health, mercury, cyanide and equipment use are not included.

Baseline questionnaire

Section A: Introduction and consent

A1. Welcome to our study and thank you for showing interest in our project. We are a group of researchers and health workers working with ORCADE and the Swiss NGO Action de Carême and the Swiss university ETH Zurich. We are very interested to learn more about your work on the gold mine. By participating in this survey, you are contributing to a better understanding of the situation working on a mine in Burkina Faso and improving the lives of miners. We guarantee that your identities will be treated in strict confidentiality. If you are willing, we would like you to take part in our survey. The survey should take about 30 minutes. You are free not to take part in our survey or stop the survey at any time; you do not have to give a reason why. We will be at the mining site for a couple of days, and we will return to inform you of some of the results of the study next year in March. If you will not be here next year March or you have any other questions regarding our study, you can contact us the numbers on the business card. (*GIVE BUSINESS CARD*). The Swiss NGO Action de Carême and the Swiss university ETH Zurich fund this study.

A2. Are you willing to take part in our study?

A3. How old are you?

Section B: Demographics

B1 What is your gender?

B4 What is your ethnicity?

- Mossi
- Fulani
- Gurma
- Bobo
- Gurunsi
- Other
- Rather not say

B5 Can you read and write (any language)?

- I can write
- I can read
- I can read and write
- I cannot read and write

B6 On how many days did you listen to the radio in the last week?

B7 On how many days did you read the newspaper in the last week?

B8 What is the highest level of education?

- None / Did not attend school
- Primary education incomplete
- Primary education complete
- Secondary education incomplete
- Secondary education complete
- Technical school
- University incomplete
- University complete
- Other

B9 Where do you currently live?

- On the mine
- less than 1 hour from the mine
- 1 hour from the mine
- 2-5 hours from the mine
- more than 5 hours from the mine

B12 How many people - including you and children - live from the income you earn on this mine?

- Only me
- Two
- Three
- Four
- Five
- 6-10
- 11-15
- More than 20 people

Section D0: Gold

D0.1 Have you sold gold to a trader during the last month?

D0.4 Where did you sell the gold?

- At home
- On the mine
- Nearby processing center
- In the nearest village
- In the next town
- In another larger city
- in Ouagadougou
- Do not know
- Don't want to say

D0.5 How many gold traders do you know to whom you can sell gold to?

- Only one
- 2
- 3
- 4
- 5
- More than 6

D0.6 Do you usually sell gold to the same person?

- Yes
- Most of the time
- Sometimes
- I always sell to someone else

D0.7 How much XOF did you get per gram for the gold the last time you sold gold?

- Less than XOF 20 000 per gram
- XOF 20,000-24,999 per gram
- XOF 25,000-29,999 per gram
- XOF 30,000-34,999 per gram
- XOF 35,000-39,999 per gram
- more than XOF 40,000 per gram
- Can't remember

D0.8 How does the trader pay for the gold? Multiple options possible

- In cash
- Loan/credit
- Mercury
- I don't know
- Rather not say

Sectoin M: Thank you, contact details and gift

M3 We will visit this mine again next year and want to contact you to talk to you again. Would you give us your contact details? Be assured that anything answered in this survey, and also your contact details, will only be shared with the researchers of this project.

M4 What is your mobile phone number? (Or number where we can reach you.)

M5 Whose number is this?

- My number
- Male relative
- Female relative
- Friend
- Colleague
- Other

M6 Fieldworker, call the number to see if it works.

Follow-up survey (April – May 2020)

Section A: Introduction and consent

A4 Good day. We are a group of researchers and health workers working with SAGRASY and the Swiss NGO Action de Carême and the Swiss university ETH Zurich. We visited your mine a few months ago. You did a survey with us.

A5 Did you take a survey with us?

- Yes
- No
- Maybe
- Can't remember

Section E: Other

E6 Did you ever had to sell gold on credit in the last six months? (Only asked in second follow-up phone survey)

- Yes, I had to sell all of my gold on credit
- Yes, I had to sell some of my gold on credit
- No
- I cannot remember
- I did not have any gold to sell in the last six months

E7 How many gold traders do you know to whom you can sell gold at this moment?

- Only one
- 2
- 3
- 4

- 5
- More than 6

E8 Did you have any gold you wanted to sell in the last month?

E8.1 Did you have any problem selling the gold in the last month?

- Yes, I had difficulty finding a buyer
- Yes, I had some other issues when I had to sell the gold
- No, I was able to sell the gold as always

E9 How much XOF did you get per gram for the gold the last time you sold gold?

- Less than XOF20 000 per gram
- XOF20 000 - 24 999 per gram
- XOF25 000 -29 999 per gram
- XOF30 000 -34 999 per gram
- XOF35 000 - 39 999 per gram
- XOF 40 000 - 44 999 per gram
- XOF 45 000 - 49 999 per gram
- More than XOF50 000 per gram
- Don't want to say
- Can't remember

E10 What is the world gold price?

- Less than XOF 20 000 per gram
- XOF 20 000 - 24 999 per gram
- XOF 25 000 - 29 999 per gram
- XOF 30 000 - 34 999 per gram
- XOF 35 000 - 39 999 per gram
- XOF 40 000 - 44 999 per gram
- XOF 45 000 - 49 999 pe gram
- More than XOF 50 000 per gram
- I do not know

Section: F Covid19 impact (questions only asked in the first follow-up survey)

F1 How many people live in the house together with you (NOT including you) at this moment?

F2 How many rooms are there in the house you are living in (including bedrooms and living rooms)?

F3 How many bars of soap (or bottles of liquid soap) do you currently have at home?

F4 How many times did you wash your hands yesterday?

F5 How many days in the last week were you outside your yard?

F6 How many nights have you gone without eating anything last week?

F7 Which of the following statements reflect your daily behaviour over the past 7 days? (Fieldworker: please read out loud)

- Wore a face mask out of the house
- Always washed my hands with soap
- Avoided touching surfaces in public
- Avoided shaking hands
- Only left the house to buy food
- Never attended large gatherings, such as church or outdoor markets
- Did not go to work
- Prayed daily to stay healthy
- None of the above

F8.1 Have you heard of the Coronavirus?

F8 What are the symptoms of Coronavirus (DO NOT READ!)? Click all mentioned.

- Fever
- Coughing
- Difficulty breathing
- Aches and pains
- Blocked nose
- Runny nose
- Chills and shaking
- Headache
- Sore throat
- Loss of appetite
- Lost sense of smell
- Tiredness
- Diarrhea
- Other
- Do not know

F9 How do you inform yourself about the Coronavirus?

- Talking to friends
- Talking to neighbours
- Talking to family
- Listening to radio
- Reading the newspaper
- Watching TV
- Using the internet
- Facebook
- I do not inform myself
- Other

F10 What do you think about the government's actions to curb Coronavirus? Is it appropriate, too extreme or not sufficient?

- Their response is much too extreme

- Their response is somewhat too extreme
- Their response is appropriate
- Their response is somewhat insufficient
- Their response is not at all sufficient

F11 Did the government implement a curfew or lockdown to combat the spread of the Coronavirus in your neighbourhood?

F12 How strongly are the measures enforced in your neighbourhood?

- Very strongly
- Strongly
- Moderately
- Slightly
- Not at all
- Can't say

F13 How does the Coronavirus crisis affect you personally at the moment? - name up to three issues. Fieldworker: DO NOT READ OUT LOUD

- No impact
- I am sick
- Fear of getting sick
- Fear of dying
- Travel restrictions
- Shops being closed
- Shortage in food supply
- Increased food prices
- Unemployment, loss of income
- Fear of becoming unemployed
- Having to stay at home
- Less or no income
- Children staying at home
- Too many people staying at home – crowded house
- Isolation
- Other

Section Z: Thank you

Z1 To inform you when we will visit the mine again we will call you on your mobile phone. To make sure we can reach you could you give us a second phone number?

Z3 Thank you very much for taking the time to talk to us. We will contact you again soon to let you know when we will visit the mines again.

Do you have anything you would like to say or ask?

2.B Balance table between rounds

	(1) Baseline mean	**(2) 2^{e} survey mean**	**(3) 3^{rd} survey mean**	**(4) Diff. in means (1) & (2)**	**(5) Diff. in means (1) & (3)**
Participants were from:					
Sandouré	0.220	0.246	0.341	0.026	0.071
	(0.415)	(0.432)	(0.476)	(0.040)	(0.058)
Ronguin	0.386	0.240	0.111	-0.090	-0.244***
	(0.488)	(0.428)	(0.316)	(0.058)	(0.056)
Zomnkalga	0.245	0.330	0.349	0.176***	0.107**
	(0.431)	(0.471)	(0.479)	(0.052)	(0.053)
Galong-Tenga	0.148	0.184	0.198	0.036	0.050
	(0.356)	(0.389)	(0.400)	(0.035)	(0.040)
Age in years	33.112	34.642	35.151	1.531	0.888
	(10.125)	(10.148)	(9.405)	(0.972)	(1.244)
Gender (female = 1)	0.047	0.039	0.032	-0.056*	-0.052*
	(0.212)	(0.194)	(0.176)	(0.029)	(0.031)
Can read or write	0.231	0.274	0.254	0.043	0.023
	(0.422)	(0.447)	(0.437)	(0.041)	(0.046)
Have children younger than 15	0.762	0.782	0.786	0.020	0.024
	(0.427)	(0.414)	(0.412)	(0.040)	(0.045)
More than five dependents	0.552	0.620	0.651	0.068	0.049
	(0.498)	(0.487)	(0.479)	(0.047)	(0.062)
Years experience in artisanal mining	9.798	10.341	10.484	0.543	0.686
	(5.430)	(5.621)	(5.332)	(0.528)	(0.580)
Worked on other artisanal mines	0.798	0.777	0.794	-0.021	-0.004
	(0.402)	(0.418)	(0.406)	(0.039)	(0.043)
Observations	168	111	96	279	264

Tab. 2B.1: Mean of key variables in each round. Standard errors in brackets. Significance on the 10% level (*), 5% level (**), or 1% level (***).

2.C International and local prices with balanced panel

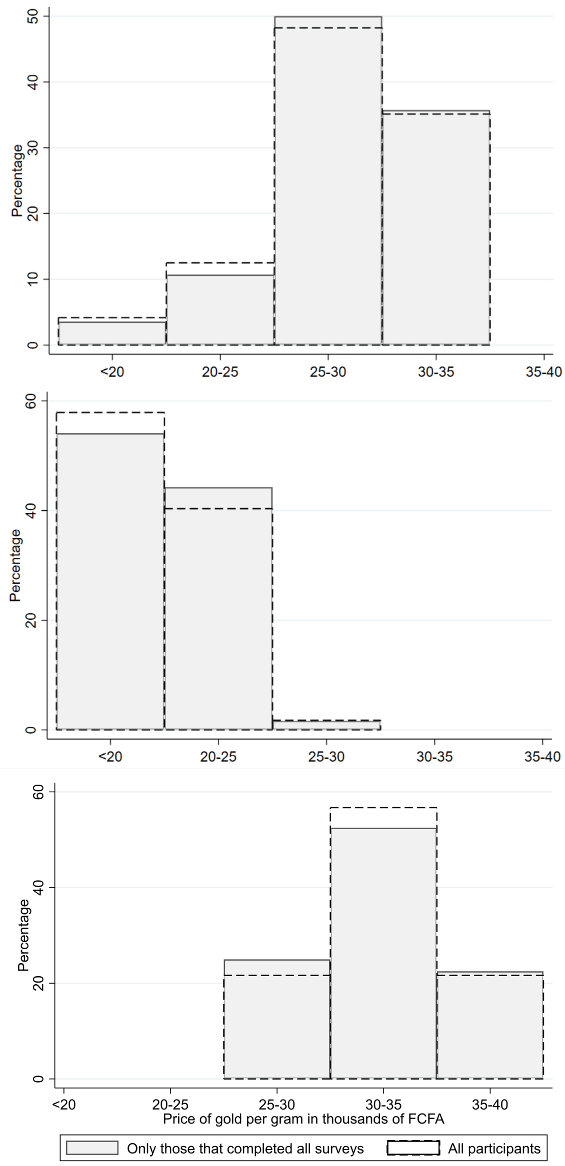


Fig. 2C.1: International and local gold prices, only considering miners who complete all three rounds. The black-dashed bar shows the percentage of the reported local prices all participants received in each price category during the same period (same as Figure 2.2). The solid grey bars only show the reported prices of miners that completed all three rounds. Although there is some difference between the two groups, possibly due to the small sub-sample of miners that completed all the rounds, the main result of a significant price drop in the second round and recovery in the third round still holds.

Chapter 3

Impact of artisanal gold mines on well-being of mining communities in Burkina Faso

Joint work with Kenneth Harttgen and Isabel Günther

Abstract: Artisanal gold mining – labour-intensive subsistence mining operations – has grown worldwide in the last two decades. Since most artisanal gold mines operate without a mining license or oversight from governments, little data exist about artisanal mining activities. This has made it difficult to determine the sector's impact on communities surrounding these mines. In this study, we analyse the impact of artisanal gold mines in Burkina Faso on neighbouring households' expenditure, wealth, health and education. We combine data on the location of 2,300 artisanal mines with high-resolution satellite images to determine the starting date of mines. Using federal records of mining licenses, we can further differentiate between formal and informal artisanal mines. In combination with pooled cross-sectional georeferenced household data, we can analyse the impact of an operating mine on well-being of households. Our results indicate that artisanal mining increase expenditure and wealth of neighbouring households by 6%. Artisanal gold mining also positively impacts education; children are about 2% more likely to be enrolled in school, also when controlling for wealth. However, we do not find that artisanal mining has any significant impact on reducing infant mortality. In addition, we find that expenditure on alcohol and tobacco are about four times more around artisanal mines than the increases in general household expenditure. Artisanal mining has both positive and negative impacts on the well-being of neighbouring households, and we do not find that licensed artisanal mines have significantly higher benefits for households.

3.1 Introduction

Artisanal gold mining – groups of miners with limited capital investment who mine gold in the world's rivers, forests, and deserts – has a potential to alleviate poverty, especially in rural communities with few other job opportunities. With a boom in international gold prices since early 2000, the artisanal mining sector has grown significantly worldwide (Fritz et al., 2018). Estimates of the number of artisanal mines in Burkina Faso indicate that the number of mines has grown from about 220 artisanal mines in 2006 to 2,277 in 2018 (Werthmann, 2017; ANEEMAS & Effigis Geo-Solutions Inc., 2018). Since the majority of artisanal miners operate informally, data is scarce, which contributes to a large variance in the estimation of the sector's size. Data availability and accuracy is also a major obstacle to understanding the sector. Described as a global data gap, the lack of data has been defined as the main problem in addressing problems in the artisanal mining sector (Lahiri-Dutt et al., 2019), such as child labour, illicit trading and environmental degradation. Despite various initiatives such as the open-source data-sharing platform DELVE by the World Bank and the NGO Pact (delvedatabase.org), the data gap in artisanal mining persists.

Due to this lack of data, the impact of artisanal mines on neighbouring communities and households is still poorly understood. We are not aware of any study that has analysed the impact of an operating artisanal mine on the local community because researchers are often unable to determine where informal mines are and when operations started. We only know of two studies that have attempted to estimate the socio-economic impact of artisanal mines. However, both studies rely on major assumptions about the location and opening of mines. Guenther (2018) assumes that all mining operations (identified from satellite images) in Ghana became active in 2006, given that before 2006 artisanal mining was not yet a major industry in Ghana. However, assuming that all mines started exactly in 2006 is a strong assumption to make, since gold mining has been practised in Ghana even before colonial rule (Ofosu-Mensah et al., 2011) and as early as 1989 the Ghanaian government already implemented programs to support and formalise small-scale miners (Hilson & Pardie, 2006). Contrarily, Bazillier & Girard (2020), using the location of formally registered artisanal mine licenses in Burkina Faso, assume that all licensed artisanal mines have been operational for the entire duration of their study (from 1998 to 2014) and instead use the changes in the world gold price as temporal variation to estimate the impact of artisanal mining. Hence, they cannot estimate the impact of an operating mine but only the effect of changing world gold prices. Although the gold price is considered an important driver to take up artisanal mining (Seccatore et al., 2014), a recent study in Burkina Faso has found the world gold price is not always a good indication of the local gold price that miners receive (Van der Merwe et al., 2022). Moreover, Bazillier & Girard (2020) only considered the impact of a subset of all mines, specifically formal artisanal mines, which could have different impact on neighbouring households compared to the many more informal mines in the country. Third, not all licenced mines have been operational since 1998. Indeed, as we show with our data, many mines that are licensed are not operational yet. Last, the authors only took into account expenditure and preliminary analyses of health and education, but did not take into consideration other measures of well-being, such as assets or temptation good expenditure.

In this study, we analyse the impact of changes in the world gold price on areas that will eventually host artisanal mines (following the methodology proposed by Bazillier & Girard, 2020), as well as a more refined analysis of the impact of artisanal mining on neighbouring communities in Burkina Faso. We are able to introduce a temporal aspect to the dataset by using high-resolution satellite images to estimate starting dates of artisanal mines, which allows us to consider the impact of an operating artisanal mines on local communities, and not only the impact of changes in the global gold price on areas with gold deposits. Moreover, we consider the effects of an artisanal mine on various indicators of well-being: households' expenditure, assets, expenditure on temptation goods, infant's health and children's education. In addition, we use an enlarged dataset with the location of almost 2,300 informal and formal artisanal mines in Burkina Faso, whereas the data set by Bazillier & Girard (2020) only considered about 300 formal mines. The dataset was produced by the governmental body responsible for artisanal mining, ANEEMAS (*Agence Nationale d'Encadrement pour l'Exploitation Minière Artisanale et Semi-Méchanisée*; National Supervisory Agency for Artisanal and Semi-Mechanized Mining).

By using data on mining licenses, we can also compare the impact of informal versus formal artisanal mines on neighbouring households. Since the vast majority of artisanal mines are informal, increasing formalisation is often proposed by scholars and policymakers – including proponents of the UN's Minamata Convention on mercury use (Hilson, Zolnikov et al., 2018) – as a way for governments to regain control of the sector and address negative externalities such as child labour and pollution (Vogel et al., 2018; Siegel & Veiga, 2009; Martin, 2019). Although many studies have mentioned some of the bureaucratic issues with low-levels of formalisation (Echavarria, 2014; Hilson, Gillani & Kutaula, 2018), potential terms of formalisation (Hilson & Maconachie, 2017) or political obstacles to formalising the artisanal mining sector (Hilson & Potter, 2005), we are not aware of any studies that has empirically examined the differences of formal (in this case licensed) and informal artisanal mines on their neighbouring communities.

Our results indicate that a 1% increase in the world gold price resulted in a 0.145% increase in expenditure for households close to a gold deposit (similar to results by Bazillier & Girard, 2020). We find that an operating mine, instead of changes in the world gold price, increases expenditure by about 6% for households close to an artisanal mine. The asset index score of households close to an artisanal mine increases by 9% in years with high gold prices and 6% when an artisanal mine opens in the area. The effects are not significantly different between being close to a formal or an informal artisanal mine. In addition, a child is 2% more likely to be enrolled in school, even when controlling for differences in wealth. However, we do not find that artisanal mining has any significant impact on reducing infant mortality. Lastly, we also find that in the vicinity of an artisanal mines, expenditure on temptation goods, specifically alcohol and tobacco, are about four times larger than general household expenditure. Therefore, artisanal mining has both positive and negative impacts on the well-being of neighbouring households, but we do not find that licensed artisanal mines have significantly higher benefits for households.

The rest of the paper is structured as follows: the second section gives a background on Burkina Faso and artisanal gold mining. The third section gives an overview of the data we use, including household data from the Demographics and Health Survey and the Living Standard Measurement Survey, and data on mines. The fourth section details the identification strategy. All results are shown in the fifth section. In the final section, we discuss the results and limitations of the study and conclude with avenues for future research.

3.2 Background

Burkina Faso is a landlocked, low-income country in the Sahel region. Despite significant progress in various socio-economic indicators over the past two decades and an average economic growth rate of 5.6% since 2001 (World Bank, 2021), Burkina Faso is still ranked 182nd out of 189 countries on the Human Development Index in 2019 (UNDP, 2020). Although the percentage of the population living on less than 3.20 international dollars per day decreased by 25% from 1981 to 2019, poverty rates are still high, with an estimated 70% of the population living below this poverty line (Roser & Ortiz-Ospina, 2013). Burkina Faso is therefore one of the poorest countries in the world.

Due to an expansion in industrial mining, which was driven by a 300% increase in global gold prices between 2005 and 2020 (see dashed line in Figure 3.1), Burkina Faso is currently ranked as the fourth-largest producer of gold in Africa, and the 14th largest producer of gold in the world (World Gold Council, 2021c). In 2009, gold overtook cotton as the primary export product in Burkina Faso, and in 2018, the export of gold was almost seven times larger than the export of cotton (WITS, 2021). Although Burkina Faso only produced about one tonne of gold in 2007, it exported about 39 tonnes of gold in 2013, accounting for 71% of exports and 16% of fiscal revenues (IMF, 2014).

Despite traditionally being an agricultural economy – with more than 80% of the country involved in agricultural activities before 2005 (World Bank, 2021) – the significant increases in the world gold price has also made artisanal gold mining increasingly profitable and also increased the share of people working in artisanal gold mining. Unlike industrial mining that is capital-intensive and therefore conducted by large-scale (often international) companies with formal mining licenses issued by governments, artisanal mines consist of individuals or groups working informally, using labour-intensive methods with basic tools and techniques to extract minerals (Jønsson & Bryceson, 2009). Mostly due to higher world gold prices, artisanal mining has increased globally drastically in the last 30 years (Fritz et al., 2018). However, the current "gold rush" in Burkina Faso is unprecedented, even on a global scale (DeJong, 2019). In 2006, an estimated 650,000 workers, directly and indirectly, derived an income from artisanal mining from around 220 mine sites (Jaques et al., 2006), which was about 12% of the total work force.[1] Ten years later, governmental statistics estimated up to 800 mining sites (DeJong, 2019) with one to two million people involved (Mondlane, 2017; DeJong, 2019), which constituted up to 29% of the total labour force in Burkina Faso. Using satellite images, ANEEMAS even identified almost 2,300 potential mine sites across the country in 2018.[2]

Most artisanal mines operate without a formal mining license or consent from the government and since only gold extracted under a formal license can be legally exported, most of artisanal gold is smuggled out of the country and will not appear on official trade flows. This makes it is difficult to estimate the percentage of the gold produced by artisanal miners (Guéniat & White, 2015). Estimations of the percentage of the gold produced by artisanal miners in Burkina Faso, therefore, range from 5-22% in 2013 (Lassen et al., 2016) to 3-27% in 2014 (Guéniat & White, 2015) and 20% in 2016 (DeJong, 2019). While artisanal gold mining gives people the possibility to earn additional incomes, recent studies only found modest effects on economic wellbeing. Guenther (2018) found that per capita income is 1.6% higher for every additional artisanal gold mine within a 10km radius of a household in Ghana. Guenther (2018) does not find any effects on expenditures of households. Bazillier & Girard (2020) find that a 1% increase in the world gold price increased household consumption within 10km of an artisanal mine by 0.12% in Burkina Faso. Given changes in the world gold price, this would be equivalent to a 40% increase in household expenditure from 1998 to 2014 in comparison to households not living close to a mine. However, it is important to note that, on average, all households in Burkina Faso shown a massive increase (370%) in household expenditure over this period.

Although artisanal mining has a positive impact on communities' income, many qualitative studies have documented several problems of living next to an artisanal mine, such as drug and alcohol abuse (Hinton et al., 2003; Thorsen, 2012), sexual violence (Bafilemba & Lezhnev, 2015), prostitution, and the spread of HIV/AIDS (Bento, 2017; World Health Organization, 2016; Banchirigah, 2006). However, data deficiencies have again made these problems difficult to understand and quantify.

Moreover, artisanal mines often create unhealthy environments. Artisanal miners use rudimentary methods that create hazardous working conditions, including shaft collapses, accidents with dynamite explosions and dust inhalation. Long et al. (2015) show occupational injury rates of artisanal miners in Ghana are incredibly high, with 45.5 injuries per 100-person years; for comparison, industrial gold miners in South Africa reported 0.84 injuries per 100-person years. Miners and workers are further exposed to toxic chemicals such as mercury and cyanide, which are used to separate gold from ore. This is especially

[1] Authors' own calculations using data on the size of the labour force from the (World Bank, 2021). Labour force include persons 15 years and older, who supplied their labour towards the production of goods and services.

[2] Since ANEEMAS artificially defined an artisanal mine as the intersecting area of a 250m-radius around points identified with any mining activity, this could inflate the number of mines (see Figure 3B.2 in Appendix 3.B). For example, the largest artisanal mine in the country, Alga, which is spread over a wide area, counts for nine artisanal mines in the database.

pertinent in the case of children and pregnant women, who are more vulnerable to the exposure of toxins and often work or live on artisanal mines (Bose-O'Reilly et al., 2008; Bose-O'Reilly et al., 2010). Miners and communities can also be exposed to lead, which can be naturally released from the soil during mining, with severe public health implications. For example, in the two villages in Nigeria, 25% of children under five died from May 2009 to May 2010 due to lead pollution from a nearby artisanal mine (Dooyema et al., 2012). Therefore, the impact of artisanal mines on neighbouring households' health, such as indicated by infant's mortality rate, can be ambiguous: while artisanal mines might create dangerous and unhealthy environments, increased income can also improve the health of miners and their families.

Likewise, artisanal gold mines that improve neighbouring households' income might allow children to stay in school for longer. On the other hand, families might take children out of school to work on an artisanal gold mine (Hilson, 2010). Forced labour and child labour on artisanal gold mines have been documented for various countries, including Burkina Faso (US Department of Labour, 2019; International Labour Office, 2005; Bento, 2017; Hilson, 2010). Children perform a variety of jobs on artisanal mines, including grinding ore, panning, going into narrow shafts (such as the "snake boys" in Tanzania, International Labour Office, 1999) and handling toxic chemicals such as mercury, installing dynamite, digging, and carrying heavy loads (Bento, 2017; Hilson, 2010; US Department of Labour, 2019). In Burkina Faso, it has also been noted that many children mine over the weekend or school holidays to pay for school fees (Hilson, 2010). In this case, working on artisanal mines enables children to stay in school longer. The impact of an artisanal mine on net school enrolment is, hence, ambiguous: children could leave school to mine full-time and increase the family's income, or increased income from mining could allow parents to keep children in school.

Many scholars and policymakers have proposed formalising the artisanal mining sector to capture the sector's benefits, such as its potential to alleviate poverty, while reducing its negative externalities, such as pollution and child labour (Hilson, Zolnikov et al., 2018; Vogel et al., 2018; Siegel & Veiga, 2009; Martin, 2019). Formalisation would give miners access to credit to move to more efficient methods that could extract more gold and generate less waste, and it would allow governments to monitor sites, increase oversight and enforce best practices. In Burkina Faso, formal artisanal mines are leniently defined as mines that have registered for a license, and do not include environmental impact assessments, any labour regulations, or additional monitoring and oversight. Despite this liberal definition, most mines in Burkina Faso are not registered; we estimate that only about 12% of the mines in our database have ever been registered for a mining license. While formalisation is recommended as an efficient method to address negative externalities in artisanal mining, given that the Burkinabe government implement relative lenient formalisation requirements by merely registering mines, the efficacy and impact of formalisation in Burkina Faso on local households is unclear.

3.3 Data

3.3.1 Household data

We use two sources of household data. First, for the outcome variables, expenditure, assets and temptation goods, we use data from the Living Standard Measurement Survey (LSMS). The LSMS is a household survey administered by the World Bank. The surveys in Burkina Faso were done in collaboration with the INSD (the National Institute of Statistics and Demography). We use the data from the LSMS surveys conducted in 1998 (n=8,478), 2003 (n=8,500), 2005 (n=8,439), 2007 (n=8,496), 2009 (n=5,940) and 2014 (n=10,831). The LSMS issued a separate list of four administrative levels (the region, province, commune and city, town or village) that households are located in. We manually looked for the geocode of each city, town or village on Open Street Maps (openstreetmap.org) and matched it with the household survey data. If the town was not on Open Street Maps, we also referred to GeoNames (geonames.org) and Google Maps.[3]

Although there are some differences between survey years, all LSMS include a range of questions that allow us to compute households' expenditure and an asset index, which we calculated with a principal component analysis. We determine the asset index score with variables indicating various assets that a household owns, their primary water and fuel source, and material of their house (see Table 3A.1 in Appendix 3.A for input variables included). We conduct the principal component analysis over the entire pooled cross-sectional database of the LSMS database to allow for comparison across time (see Appendix 3.A for more details). We have data on assets for all LSMS survey years.

Households were not asked about their expenditures in 2005 and 2007. We therefore have two years less of expenditure data (1998, 2003, 2009, 2014). For data on total household expenditure, we exclude expenditures on rent and special ceremonies (similar to Bazillier & Girard, 2020). Furthermore, data on expenditure is only disaggregated on product-level in 2003 and 2014, so our analysis on temptation good expenditure only includes these two years.

Second, we use geo-coded data on infants' mortality and school enrolment from the Demographics and Health Survey (DHS) Program run by USAID, in collaboration with the INSD in Burkina Faso. We use four rounds of DHS surveys in Burkina Faso conducted in 2003, 2010, 2014 and 2018. The DHS data include the coordinates of the cluster in which each household is located.[4]

[3] In case the enumerator cluster consisted of more than one town, we used the mid-point (two locations) or centroid (more than two locations) as the location of the cluster. If a cluster consisted of multiple towns and we could only locate one, we use the coordinates of the one town as the location of the cluster. If we could not locate the exact location on the fourth administrative level, we used the centroid of the third administrative-level using maps from GADM (gadm.org/). The same clusters were surveyed in the first years 1998 to 2007 but more clusters and slightly different clusters were sampled in 2009 and 2014.

[4] To ensure anonymity, the clusters' coordinates are given within 2km distance for urban clusters, and within 5km of rural clusters (INSD and ICF International, 2012b). LSMS and DHS also conducted surveys in 1993 and 1998, which we did not include due to high number of missing data on artisanal mines before

For the analyses on infant mortality, we use a binary variable to indicate if a baby died within their first year of life. In total, we consider 48,008 births recorded during four years of DHS surveys. We do not consider any children born in the specific survey years, since they have not yet lived a full year. We do not include any births before 2000 due to limited satellite images (see Section 3.3.2). The survey year 2003 includes 6,329 births (2000 to 2002), the 2010 survey includes 27,838 births (from 2000 – 2009), 2014 includes 7,466 births (from 2008 to 2013) and 2018 includes 6,375 births (from 2012 to 2017).[5]

We combine data from the DHS and the LSMS for net school enrolment. The 2003 and 2010 DHS surveys[6] recorded school attendance and the LSMS recorded school attendance in 2005, 2007, and 2009.

In order to control for wealth groups in the analysis of infant mortality and net school enrolment, we also created two pooled asset indices for the datasets used for infant mortality and school enrolment, using the same wealth indicators as used in the LSMS survey for the analysis of the impact of mining on wealth. Controlling for wealth groups allows us to disaggregate the potentially opposing influence of higher wealth with the negative impact of mines on health and school enrolment. Asset indices calculated with DHS and LSMS data are similar. See Figure 3A.1 in Appendix 3.A for a comparison between the DHS's cross-sectional wealth index in 2018 and our pooled asset index score for households in 2018. Figure 3.1 shows the years (bars) for which we have household data (either from DHS or LSMS data).[7] However, the questionnaire in each year is slightly different, so we do not have the same data available for each survey year (see Table 3A.2 in Appendix 3.A for summary of data available in each year).

3.3.2 Mining data

The lack of data in artisanal mining has been described as a global data gap and the main problem in addressing artisanal mining issues (Lahiri-Dutt et al., 2019). To bridge the lack of federal data on artisanal mining, some researchers have utilized satellite images combined with machine learning algorithms to find potential artisanal mines (Saavedra & Romero, 2021; Guenther, 2018; Rheault, 2018; Gallwey et al., 2020; UNODC, 2018).

2000. The DHS survey does not give any information on the municipality in which a household was surveyed in Burkina Faso, only the geocodes of the cluster in which a household is located. To create the balanced panel of municipalities surveyed in every year, we use the user-written command in STATA "geoinpoly" (Picard, 2015). "Geoinpoly" is a point-in-polygon command that places each household's geo-coordinate within the boundaries of a municipality's polygon. For municipalities' boundaries, we use GADM maps.

[5]The 2014 and 2018 surveys are special type of DHS surveys called Malaria Indicator Surveys and only include the birth of children five years and younger.

[6]Malaria Indicator Surveys, a type of DHS survey conducted in 2014 and 2018, only recorded each mother's total years of schooling, they do not record whether a child was enrolled in school in the survey year.

[7]For all outcome variables, except infant mortality, we have data for every year that a survey was conducted (shown by bars in Figure 3.1). In the case of infant mortality we have data for every recorded birth year (2000 to 2017).

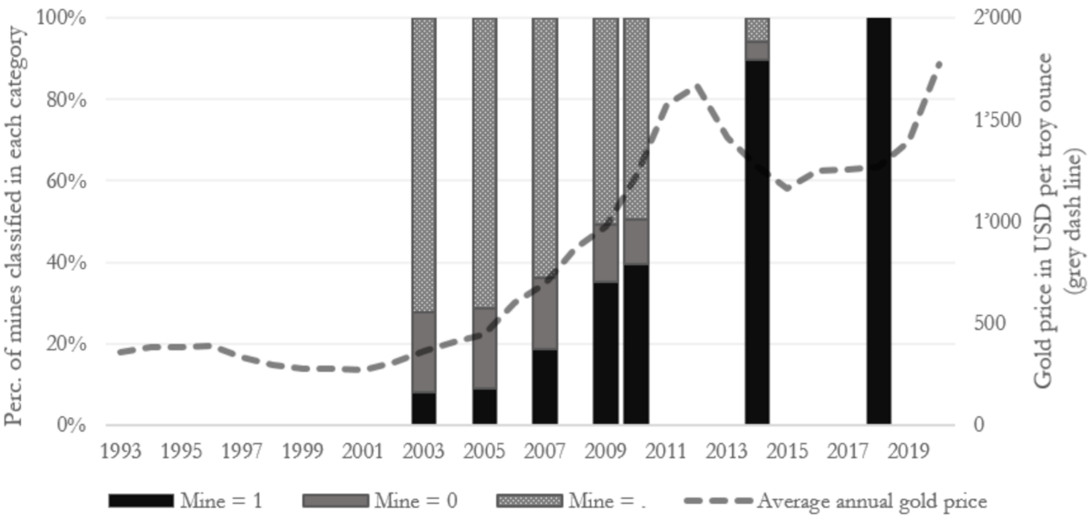


Fig. 3.1: World gold price, and mine classification in each survey year. Due to the availability of high-resolution pictures, we could not determine if every artisanal mine was operational in every year. The stacked bars show the percentage of mines that were determine operational (black segment, mine = 1), not yet operational (grey segment, mine = 0) and undetermined (dotted segment, mine = .). As the availability of images increased over time, we could identify more mines as operational or not yet operational. Bars are only shown in years with survey data. The grey dashed line shows the annual average gold price in USD per troy ounce.

See Appendix 3.B for more information on the various machine-learning methods used to identifying artisanal mines.

To identify artisanal mines, the Burkina Faso government contracted the company Effigis Geo-Solutions (effigis.com/en/) in 2018 to find artisanal mines using satellite images. However, using machine learning to identify artisanal mines showed not to be possible in Burkina Faso due to a lack of training datasets to create algorithms.[8] Moreover, the most common type of artisanal mining activity in Burkina Faso is underground mining that is more difficult to identify on satellite images than mining activity on surface, such as alluvial mining in rivers and open-pit mining (see Figure 3B.1 in Appendix 3.B for examples). Last, variations in rainfall across the country make mines visually very heterogeneous from space (see Appendix 3.B for more information). Instead, Effigis Geo-Solutions created the dataset by manually looking at satellite images, supplementing it with data from previous large-scale fieldwork, information from ANEEMAS and additional remote verification (Rheault, 2018, see Appendix 3.B for more information). This database shows about eight times more artisanal mines than used in the study by Bazillier & Girard (2020), who use data on geocoded licensed artisanal mines in Burkina Faso (2,277 as opposed to 281).

[8]We also conducted preliminary analysis using Google Earth Engine (a geospatial computing platform) but found the lack of training datasets, diversity of mines and resolution of images inhibits the efficacy of the method.

Furthermore, 30% of the licensed artisanal mines in the dataset of Bazillier & Girard (2020) do not show any mining activities according to satellite images. These mines have either been closed over time or have never been operational. Note that operations is not a requirement to obtain a license for mining in Burkina Faso.

The ANEEMAS database we use is currently the most comprehensive database of artisanal mines in Burkina Faso. However, one caveat of this database is that – excluding 63 mines surveyed as part of the project – the database only includes the coordinates of artisanal mines but no additional information, such as the year that operations started. We, hence, supplement the data by estimating if an artisanal mine was operational in a specific year using Google Earth Pro (version 5). Google Earth Pro is a free software that combines high-resolution images from various sources to create a continuous image covering most of the earth's surface over time.

We manually studied all the images of each location of potential artisanal mines and gave a binary value to categorise the presence of a mine: one if we could see any disturbance on the surface that could be a mine, and zero if we could not see any disturbance on the surface (see Figure 3C.1 in Appendix 3.C for examples). Given that the database was compiled in 2018, we assume all points have active artisanal mines in 2018. Since we do not have sufficient satellite images to determine when artisanal mines ceased operations, we assume that once a mine opens, it is operational for the duration of our study. Meaning, if we see some disturbance on the surface that looks like a mine, we assume the site is an active artisanal mine in that year and all subsequent years. This assumption could classify a closed artisanal mine as operational, which might downward bias our results. If we see a picture with no mining activity (equal to zero), we assume no mining activity in that year or any of the preceding years. We tested our method on data from the 63 mines that were personally visited by the ANEEMAS and Effigis Geo-Solutions research team to collect detailed data, including the starting date of the mine. We find a high true-positive rate (see Table 3C.1 in Appendix 3.C).

High-resolution satellite images are not available for every location in every year and more images are available in recent years than in earlier years. Hence, the number of unknown mines increases when going back in time. The stacked bars in Figure 3.1 show the percentage of mines that we could classify as operational, not operational or undetermined in each year that we have household data from DHS or LSMS. When we had a missing value, we assumed that the mine is not operational. Again, this assumption might downward bias our estimates on the impact of artisanal mines on households' expenditure, wealth, children's health and education.

Since we also want to analyse the impact of formal licensing of a mine on surrounding communities, we use data that we received from the Ministry of Mines in Burkina Faso listing all artisanal exploitation licenses (AEA) and semi-mechanised licenses (PEMS) that have been issued by the government by 2016, which includes geocodes.[9] We take a

[9]Bazillier & Girard (2020) used these licenses as the location of artisanal but do not use the additional information, such as when the license was issued or when it expired.

rather simple definition of formalisation by looking at mines that have registered for a license. Due to lack of data, we cannot take into account what standards are enforced. Despite considering a lenient definition of formalisation that simply requires mines being registered, the majority of mines in Burkina Faso are not licensed: our database shows 2,277 potential artisanal mines, of which only 12.4% were ever licensed. This share is in line with studies that found that more than 95% of artisanal gold in Burkina Faso is mined without a license (DeJong, 2019; Guéniat & White, 2015). See Appendix 3.C for more information on the data on mining licenses.

Lastly, we use data from the S&P Global Market Intelligence database on Metals and Mining Properties to also include industrial mines in our data set. The Metals and Mining database is a compilation of various companies' production and financial operations, and mining operations in the world with data on more than 35,000 industrial mines, projects and processing facilities worldwide (SNL Metals and Mining, 2020). The database provides detailed information on the 16 industrial gold mines that were ever active in Burkina Faso, including the latitude and longitude of each mine, which we verified on Google Earth Pro (see Table 3C.2 Appendix 3.C for more details).

3.4 Identification strategy

We start by following the approach by Bazillier & Girard (2020), who used changes in the world gold price and differences of households' distances to the nearest formalized artisanal deposit to calculate the impact of a change in the world price on household expenditure. We apply the same equation but include all mines (formal and informal) and estimate the following model:

$$E_{ivmt} = \alpha(\text{gold boom}_t \times \text{artisanal deposit}_v) + \beta \text{artisanal deposit}_v + \gamma' \chi_{ivt} + \delta_m + \eta_t + \epsilon_{ivt} \tag{3.1}$$

E_{ivmt} is the natural logarithm of the per capita expenditure for household i in village v in municipality m in year t. The coefficient of interest, α, shows the estimated impact of higher gold prices on expenditure for the household in village v, near an artisanal deposit. Bazillier & Girard (2020) use three different variables to measure the gold boom: (1) year dummies; (2) a "gold boom" dummy which is equal to one for all years after 2006, when the world gold price increased significantly (see Figure 3.1)[10]; and (3) the natural logarithm of the annual average world gold price (as measured by the London Bullion Market Association).

[10]Bazillier & Girard (2020) use 2004 as the cut-off for the gold boom because they do not consider the impact on assets and therefore do not include household data in 2005 and 2007. Since we also include 2005 and 2007 for the analyses on assets, we changed the gold boom cut-off to 2006, because the gold price was still relatively low in 2005 (see Figure 3.1).

The binary variable "artisanal deposit" is equal to one if the household in village v is within 10km of artisanal gold deposit and zero otherwise.[11] The location of artisanal deposits are determined as the location that will be an artisanal mine in 2018, which is the final year of the full database and include all 2,277 known artisanal mines (see Section 3.3.2).

Similar to Bazillier & Girard (2020) and Guenther (2018), we consider the threshold distance from an artisanal mine as 10km for the treatment group, meaning all households within 10km are considered exposed to artisanal mining activity. Using a minimum 10km threshold for the treatment group, allows us to absorb some potential dislocation or inaccuracies of the geo-codes (see information about the dislocation of household data in Section 3.3.1). In addition, since most miners live close to the mine, considering a larger threshold for the treatment group would probably exceed the direct impact of the mine. However, we also show the main analyses for a 20km treatment group. Moreover, and extending the analysis of Bazillier & Girard (2020), we consider two control groups, first all households farther away than 10km from any artisanal gold deposit and second, households 10 to 20km of an artisanal gold deposit. The second control group, allows us to control for some additional omitted variables by only considering households in the same general area but with the risk of high economic spillovers, which could have a downward bias on the impact.

χ_{itv} is a set of controls, including literacy, age, household size, sex of the household head, and urban area.[12] Also included are municipal fixed effects (δ_m)[13] and year fixed effects (η_t).

In a second step, we differentiate between an artisanal deposit and an artisanal mine. While an artisanal deposit is the location of a gold deposit that will eventually be extracted in an artisanal mine, it is not necessarily being mined in a particular year. An artisanal mine is a deposit that is actively mined. In the first model (Eq. 3.1), we implicitly assume (similar to Bazillier & Girard, 2020) that mines have always been operational. Improving on this specification, Eq. 3.2 includes a temporal effect of a mine's opening by using the estimated starting date of the mines as identified from satellite images:

[11] We determined if a household is close to an artisanal deposit or mine by using the user-written command "geonear" in STATA, which uses geodetic distances to determine the closest "neighbour" to a specific point, which in our case refers to the closest mine to a household (Picard, 2019).

[12] Results do not change if we exclude the major metropolitan area of Ouagadougou. Results are available upon request from the authors.

[13] If the names of municipalities listed in the LSMS database are used exactly, then there are 398 unique municipalities over the various survey years. However, if spelling mistakes or alternative spellings, and abbreviations are corrected, there are only 342 unique municipalities. For example, the name "Tin Akoff" is used in all years before 2007 but hyphenated ("Tin-Akoff") in 2009 and 2014. The correction of the municipalities have a significant impact on our results. We only show results for the corrected municipality names.

$$E_{ivmt} = \lambda \text{operating mine} + \beta \text{artisanal deposit}_v + \gamma' \chi_{ivt} + \delta_m + \eta_t + \epsilon_{ivt} \tag{3.2}$$

In this model (Eq.3.2), we analyse the impact of households being close to an operational artisanal mine. Hence, we can estimate the impact of an operating artisanal mine on neighbouring households, as opposed to the impact of changes in global gold prices on households in areas with gold deposits. Similar to the first model, "artisanal deposit" is a binary variable equal to one if a household in village v is within 10km of a known gold deposit. This allows us to control for the type of location that eventually becomes an artisanal mine; although mineral deposits are part of geological processes and exogenous, the type of place where people discover deposits are not necessarily exogenous. We include the same covariates as in Eq.3.1.

For Eq.3.2, we made four restriction to our household dataset. First, we need to classify a mine as either operational or not in each year. We, therefore, assume that all undetermined mines — meaning mines that had insufficient satellite image to determine if it was operational in a given year (see Figure 3.1) — are not operational. This assumption might lead to a downward bias of our results, by classifying an operational mine as not operational especially in earlier years when we have more undetermined mines. Second, we need to exclude all household data from the 1998 survey due to a lack of satellite images before 2000 (reduction of 8,478 observations from initially 36,217). Third, to ensure a balanced panel, we exclude all municipalities that were not surveyed in every year in our dataset (reduction of 6,774 observations). Fourth, as an additional robustness check and to allow more temporal variations, we also exclude households close to an artisanal mine that was already operational in 2003 (reduction of 3,531 observations). Note that whether a municipality was sampled in a particular year is not linked to any selection of municipalities into or out of the survey. Hence, no attrition bias applies. For the number of observations for the estimation of Eq.3.1 and Eq.3.2 and for the various dependent variables used see Table 3A.3 in Appendix 3.A.

In addition to the impact on households' expenditure, we also analyse the impact of the gold price (Eq.3.1) and artisanal mining (Eq.3.2) on asset accumulation. Given that many case studies have documented alcohol abuse on artisanal mine sites (Hinton et al., 2003; Thorsen, 2012), we also estimate the impact of artisanal mining on the expenditure on temptation goods (alcohol and tobacco) of households close to artisanal mines compared to others. About half of respondents said they did not spend anything on alcohol and tobacco (see Figure 3A.2 in Appendix 3.A), which means if we use the natural logarithm transformation, all zero expenditure values will be transformed to missing values (see Figure 3A.3 in Appendix 3.A). Alternatively, we take the inverse hyperbolic sine transformation (IHS) of temptation good expenditure, the coefficients of which are interpreted the same as the natural logarithm, but with the advantage that zero-values are transformed to zeros and not missing values (see Figure 3A.4 in Appendix 3.A). IHS has been used in many studies with right-skewed variables or variables with many zero values, such as Brune et al. (2021)

who evaluated the impact of cash transfers on temptation good expenditure.

The forth dependant variable that we consider is net school enrolment. We analyse the impact of artisanal mines on net school enrolment using both Eq.3.1 and Eq.3.2, with the following adjustments: first, we conduct a logistic regression analysis since the dependant variable "school enrolment" is dichotomous. Second, given that we move from the household to the individual level we include slightly different covariates (χ_{itv}): child's sex and age, and controlling for urban areas. In order to determine whether the impact of an artisanal mine on schooling is mediated by a change in the wealth of the household, we conduct the analysis with and without controlling for wealth.

As a fifth dependent outcome, we determine the impact of an artisanal mine on infant mortality using Eq.3.1 and Eq.3.2 with the following adjustments: we conduct a logistic regression since the variable of interest for infant mortality is dichotomous. Second, we consider if the infant was born in the vicinity of an artisanal mine by considering if the mine in their vicinity was already open in their birth year and not the survey year.[14] We, therefore, include birth year fixed effects, and not survey year fixed effects (η_t), and slightly different covariates (χ_{itv}): infant's sex and controlling for urban areas. Last, in order to disaggregate the impact of mines on infant mortality mediated by wealth, as opposed to a more polluted and dangerous environment, we conduct the analysis with and without controlling for households' wealth.

Similar to Bruederle & Hodler (2019), we further include mother fixed effects to compare siblings' mortality rates with each other, varying the presence of a mine. Comparing the survival rate of siblings with each other allows us to control for all time-invariant household characteristics. For proper identification, we only consider a specific subset of the entire database for this analysis. First, as a control group we only use mothers who live 10 to 20km away from an artisanal deposit (and not any mothers who live further than 20 km away from any mine). The reason is that with mother fixed effects, we need to determine for each child – also in the control group – whether they were born before or after the gold boom or opening of a mine. Hence, we need to allocate all children in the control group to a specific mine. Second, we only look at mothers that have already given birth to more than one child, of which at least one was born before 2006 and at least one after (Eq.3.1) and one before the opening of the mine in their vicinity and at least one after (Eq.3.2).

In our final analysis, we also differentiate between households that are close to a formal artisanal mine and households that are close to an informal artisanal mine applying Eq.3.1. We only differentiate by licensing applying Eq.3.1 due to lack of data on the temporal aspect of licensing, i.e. we do not have accurate information on the starting and expiry dates of licenses. This additional differentiating allows us to determine the impact

[14] We cannot control for possible migration because the DHS does not ask households how long they have been living in a specific location. Similar to studies such as Bruederle & Hodler (2019), we assume that all babies were born in the location that their mother completed the survey. Potential migration could have a downward bias on our results.

of formalisation through licensing on households' expenditure and wealth, as well as on children's health and education. We additionally include the effect of being close to an industrial mine.

3.5 Results

3.5.1 Descriptive statistics

Figure 3.2 (left) shows the mean per capita household expenditure (in West African francs, XOF) for households within a 10km, 10 to 20km and farther than 10km from an operating artisanal mine, as well as households within 10km of an artisanal gold deposit (including both operating and non-operating mines). Although we have data from the LSMS on expenditure in 1998, 2003, 2009 and 2014, we do not include data in 1998 because given the lack of satellite images before 2000, we cannot determine if households are close to an operating artisanal mine in this year.

Similar to Bazillier & Girard (2020), we find that the total monthly expenditure of households close to an artisanal gold deposit increased by 440% between 2003 and 2014. However, we find that households far from an artisanal mine, which include a majority of the urban areas, showed higher growth over the same period.

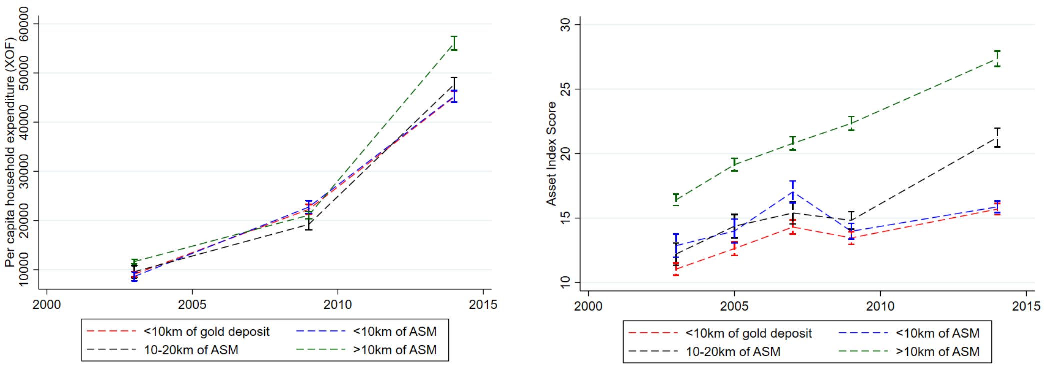


Fig. 3.2: Household expenditure and asset index score. Mean expenditure (left graph) and asset index score (right graph) with the 95% confidence interval of households less than 10km from an artisanal deposit (red), as well as less than 10km (blue), 10-20km (black), and more than 10km (green) from an operating mine at survey year. We use data from LSMS for both figures. LSMS have data on expenditure and assets for 1998, 2003, 2009 and 2014, and additional data on assets for 2005 and 2007. We do not include LSMS data for 1998 due to limited satellite images to determine if mines were operational.

We have data on assets for two more years (2005 and 2007) than data on expenditure (see Table 3A.2 in the Appendix 3.A). Figure 3.2 (right) shows the asset index score over time, again for households within 10km, 10 to 20km and farther than 10km from an operational mine and households within 10km of an artisanal gold deposit. Again, households far from an artisanal mine (including urban areas) have a higher asset index, also in later years. Interestingly, we find the highest growth in assets for households 10 to 20km away from an artisanal mine.

Figure 3.3 (left) shows the percentage of children that were enrolled in school in each survey year; again comparing those within 10km, 10 to 20km and more than 10km from an artisanal mine, as well as households less than 10km of an artisanal deposit. Also when disaggregating by primary and secondary school enrolment, those living more than 10km from a mine have higher school enrolment in every year for both primary and secondary school enrolment (see Figure 3A.5 in Appendix 3.A). Figure 3.3 (right) shows the percentage of babies born each year who died in their first year of life. Considering the entire sample, infant mortality was reduced from 10.7% of children dying in their first year in 2001 to 2.3% in 2017.[15]

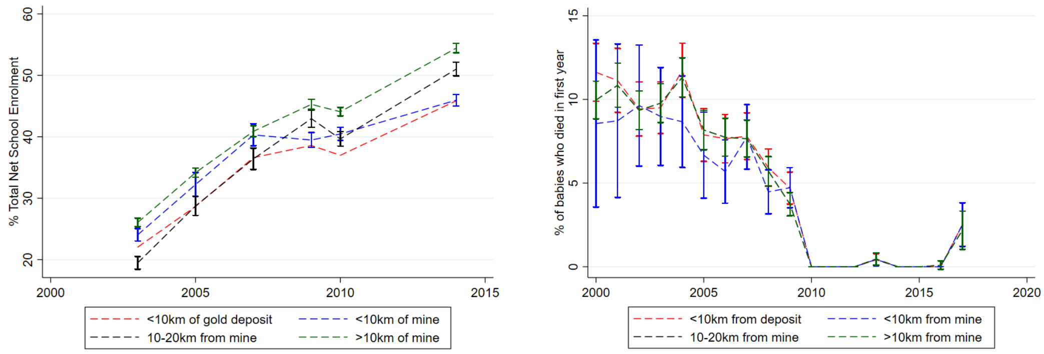


Fig. 3.3: School enrolment and infant mortality. Percentage of children enrolled in school (left) and babies who died in their first year (right) who was less than 10km from an artisanal deposit (red), as well as less than 10km (blue), 10-20km (black), and more than 10km (green) with the 95% confidence interval. We assumed babies were born in the location where mothers completed the survey. We use DHS data of all babies born after 2000 and born at least one year before each survey year. We use data from the DHS (2003 and 2010) and the LSMS (2005, 2007, and 2009) for net school enrolment.

[15] According to World Bank (2021), infant mortality decreased from 89.3 to 56.7 per 100,000 life births over the same period, which is a smaller reduction than shown by the DHS data. We show the percentage of babies that did not survive their first year, which could differ from other estimations, such as using a life table approach. Since the latest DHS survey year was a Malaria Indicator Survey, other estimations of infant mortality is not published by DHS. However, for the latest full DHS survey year (2010), the estimated infant mortality of calculated with DHS data is similar to the estimation by the World Bank, 65 versus 68.1 deaths per 100,000 life births, respectively.

3.5.2 Households' expenditure, wealth and temptation goods

We first replicate the results from Bazillier & Girard (2020) by using 281 artisanal mining licenses as the location of the artisanal deposit, using data from all years with expenditure data (1998, 2003, 2009, and 2014; Table 3.1 and Table 3D.1, Appendix 3.D for full replication). Bazillier & Girard (2020) found that expenditures of households close to a mining deposit increase by 0.12% for a 1% increase in the gold price (see Table 3D.1, Appendix 3.D). Using the location of mining licenses, we find a 0.145% increase in per capita household expenditure for a 1% increase in the world gold price (Table 3.1, column 2). Compared to Bazillier & Girard (2020), we find the gold boom after 2006 has a similar but slightly larger effect on household expenditure: 20% (Table 3.1, column 1) versus 16% (Table 3D.1, Appendix 3.D Bazillier & Girard, 2020).[16]

Dep var: ln(pc hh expenditure), Eq.1	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Database of artisanal mines:	**Licensed ASM plots only (281 mines)**		**Full database with all ASM (2,277 mines)**		
<10km of an ASM deposit	-0.059	-0.883***	-0.060	-0.895***	-0.005
	0.051	0.263	0.040	0.245	0.049
<10km ASM deposit × gold boom	0.202***		0.192***		0.111
	0.054		0.052		0.068
<10km ASM deposit × ln(gold price)		0.145***		0.146***	
		0.040		0.038	
Reference year: 1998					
2003	0.102***	0.097***	0.102***	0.091***	0.117***
	0.022	0.022	0.022	0.022	0.027
2009	0.557***	0.562***	0.516***	0.523***	0.605***
	0.044	0.044	0.047	0.046	0.065
2014	1.778***	1.776***	1.736***	1.728***	1.834***
	0.033	0.033	0.038	0.039	0.061
Constant	8.854***	8.854***	8.845***	8.845***	8.807***
	0.034	0.035	0.046	0.046	0.061
Observations	36,133	36,133	36,133	36,133	23,628
R-squared	0.605	0.605	0.606	0.606	0.629
Control group (distance to deposit)	>10km	>10km	>10km	>10km	10-20km

Tab. 3.1: Impact of world gold price on household expenditure. An ASM (artisanal and small-scale mine) deposit is a gold deposit that will be an artisanal mine in the final year of the database. All regression includes municipal fixed effects and household controls, including household size, literacy, sex, and age of household head, and a binary variable to control for households in an urban area. Standard errors below coefficients. ***p<0.01, **p<0.05, *p<0.1.

[16] Since Bazillier & Girard (2020) do not specify the year of their dataset of mines, we are unable to confirm that we use the exact same locations on mining licenses. We also do not consider any licenses that do not host any active mines, as seen on satellite images, or any licenses issued for any other minerals than gold. However, even if we include these mining licenses, we do not find significantly different results.

Using our more comprehensive dataset with the location of 2,277 mines, we get similar results than using the dataset of registered mines only (columns 3 and 4, Table 3.1). In years with higher gold prices, per capita household expenditure is about 19% higher for households close to an artisanal deposit (Table 3.1, column 3). In addition, when we use the full dataset of mines and restricting the comparison group to 10 to 20km from an artisanal deposit – which would reduce omitted variable bias but at the risk of positive spill overs – the effect of the gold boom is an 11% increase for households close to a deposit (Table 3.1, column 5, p-value: 0.103).

As a robustness check, we use comparison groups at various distances in Table 3F.1, Appendix 3.F. We find that, as expected, the relative impact of the artisanal deposit on households in a 10km vicinity increases when we increase the distance that households in the comparison group are from the mine. As a further robustness check, Table 3F.2 (column 1 and 2) in Appendix 3.F shows the results if we consider a treatment group of households within 20km of an artisanal deposit (instead of 10km). The impact of a gold boom is still 20% and the impact of a 1% price increase of gold is 0.16%.

In a second step, we introduce the temporal aspect by directly analysing the effect of an operating mine instead of analysing the effect of increasing gold prices on a gold deposit (see Eq. 3.2). Note again that for this specification we cannot include the year 1998 given the limited satellite images available for years earlier than 2000 (see Figure 3.1). In order to allow for a direct comparison between Eq.3.1 and Eq.3.2, we first replicate Eq.3.1 but excluding data from 1998. The results (column 1, Table 3.2) do not differ significantly to the full dataset (column 3, Table 3.1). We also conduct Eq.3.1 on the balanced panel dataset by only considering municipalities that were surveyed in 2003, 2009, and 2014 (see column 2, Table 3.2). Again, we do not find that omitting municipalities that were not sampled in every survey year changes our results. Any difference in effects between Table 3.1 and 3.2 must therefore come from differences in identification strategy and not differences in sample composition.

We find that the impact of an operating mine (column 3, Table 3.2) on per capita households expenditure is smaller than the impact of the gold boom on a gold deposit (column 1, Table 3.2). Given that mines opened in various years throughout the study, also in years with lower gold prices, it is expected that the impact is smaller than only considering the impact of higher gold prices. As a further robustness check, we exclude all households that were close to a mine that were already operational in 2003, which again does not have a significant impact on the results (column 4, Table 3.2). The impact of an artisanal mine on households within a larger treatment group of 20km vicinity to an operating mine is slightly larger but similar (see column 3, Table 3F.2 in Appendix 3.F).

Dep. variable: ln(pc hh expenditure)	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Model	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.2**	**Eq.2**	**Eq.2**
Dataset	**All**	**Balanced panel (municipalities surveyed every year)**				
<10km of an ASM deposit	-0.082*	-0.070	0.029	0.031	0.044*	-0.002
	0.048	0.049	0.023	0.024	0.026	0.028
<10km of operating ASM			0.039*	0.059***	0.046*	0.117***
			0.022	0.023	0.025	0.033
<10km ASM deposit×goldboom	0.184***	0.180***				
	0.055	0.057				
Reference year: 2003						
Year 2009	0.416***	0.404***	0.467***	0.438***	0.427***	0.425***
	0.048	0.051	0.044	0.047	0.016	0.017
Year 2014	1.645***	1.649***	1.709***	1.681***	1.682***	1.680***
	0.039	0.041	0.034	0.038	0.014	0.014
Constant	9.001***	9.003***	8.962***	8.945***	8.933***	8.944***
	0.045	0.047	0.046	0.049	0.073	0.112
Exclude mines that opened:	N/A (Incl. all)	N/A (Incl. all)	N/A (Incl. all)	2003 or before	2009 or before	2003 or before and 2009-2014
Observations	27,673	23,227	23,227	21,534	18,432	19,084
R-squared	0.584	0.584	0.583	0.577	0.588	0.574

Tab. 3.2: Impact of artisanal mining on per capita household expenditure. An ASM (artisanal and small-scale mine) deposit is a gold deposit that will be an artisanal mine in the final year of the database. An operating artisanal mine is an active mine as determined by satellite images. In columns 1 to 3, we include all households, irrespective of when the mine in their vicinity opened. For more temporal variation, we omit households close to a mine that were opened in 2003 or before in column 4 to 6. To determine if we have a biased estimator due to staggered opening of mines, we also exclude households close to mines that opened 2009 or before in column 5 and households close to mines that opened from 2009 to 2014 in column 6. All regression includes municipal fixed effects and household controls (household size, literacy, sex, and age of household head, and urban area). Standard errors below coefficients. ***p<0.01, **p<0.05, *p<0.1

Recent studies have shown that a difference-in-difference analysis with multiple years, with different sub-groups not being exposed to treatments simultaneously, but in a staggered manner, could lead to biased difference-in-difference estimators (Goodman-Bacon, 2021; Athey & Imbens, 2022; Borusyak & Jaravel, 2017). Although the model and results shown in Eq.3.2 and Table 3.2, is not a pure difference-in-difference analysis, it could also apply to this model since artisanal mines opened throughout the country in various years of our study. To determine the impact of the staggered opening of mines, in column 5, we eliminate the staggered treatment effect by only considering mines that opened between 2009 and 2014. In column 6, we only consider the impact of mines that opened between 2003 and 2009. The effect of living next to a mine that opened between 2009 and 2014 (column 5) is smaller than the effect of living next to a mine that opened between 2003 and 2009 (column 6). However, both are positive and significant, indicating that we do not have a significant bias due to staggered opening of mines.

In a third step, we analyse the impact of artisanal mining on households' assets and temptation good expenditure. Figure 3.4 shows the interaction terms for Eq. 3.1 in blue (both the "gold boom" dummy variable and the natural logarithm of the world gold price) and Eq.3.2 in green. The plot lines show the 95% confidence interval.

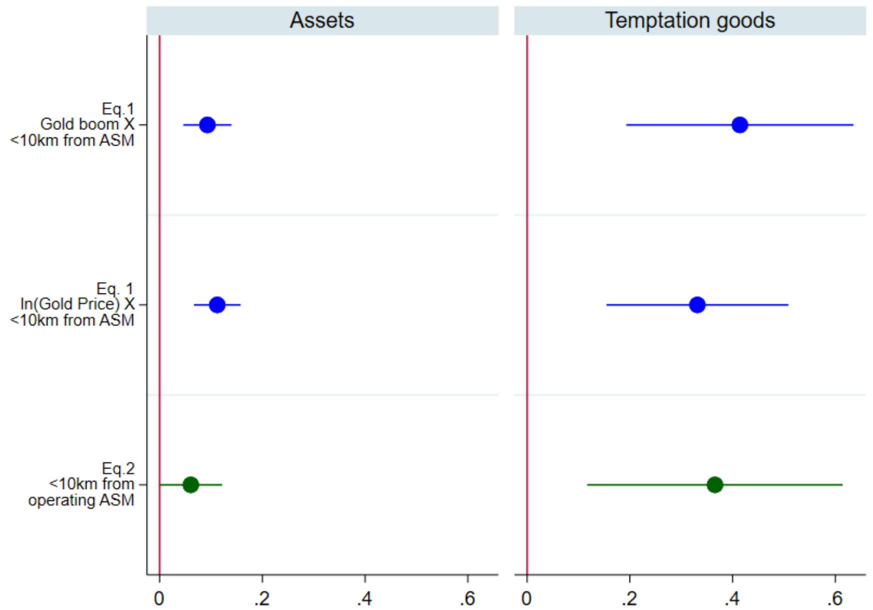


Fig. 3.4: Coefficient plots of assets and temptation good expenditure. Dependant variables are the natural logarithm of an asset index score and the inverse hyperbolic sine transformation of temptation good expenditure. Plot lines show the 95% confidence interval. For Eq. 3.1 we use all household data, for Eq.3.2 we restrict the data to municipalities sampled in every year, exclude observations in 1998 and households close to an artisanal mine that was already operational in 2003 (see Section 3.4). All regression includes municipal fixed effects and household controls (household size, literacy, sex, and age of household head) and urban area. See Table 3E.1 in Appendix 3.E for full results and Table 3F.3 in Appendix 3.F show all results considering a control group of 10 to 20km from an artisanal deposit.

Our results suggest that artisanal gold mining — whether measured by the impact of the gold boom or the actual operation of an artisanal mine — has a positive impact on the asset index score. A 1% increase in the world price increases the total asset index score within 10km of an artisanal mine by 0.11%. An operating artisanal mine leads to a 6.1% increase in the asset index score. When we consider a different control group of households with 10 to 20km (Table 3F.3 in Appendix 3.F) we find the same effect but when we consider a different treatment group of 20km within the vicinity of a mine (Table 3F.2 in Appendix 3.F), we find no effects. Therefore, our results indicate that the economic benefit of the mine, in terms of wealth, mainly occur in the immediate vicinity but we do observe some spillovers to households slightly farther away. This is different to our results on expenditure, where we find a similar impact of the mine for a treatment group of 10km and 20km from the mine, which could indicate that the economic spill over is larger in terms of cash expenditure than asset accumulation.

As suggested by many qualitative studies (see Hinton et al., 2003; Thorsen, 2012), we find a significant increase in alcohol and tobacco expenditure, much larger than for general expenditure. Households around artisanal gold deposits spend 41% more on alcohol and tobacco compare to the rest of the country, in years with higher gold prices. This is much larger than the 14% increase in total per capita household expenditure in the same areas in the same years (see Table 3F.3, column 5 that show changes in total household expenditure only considering 2003 and 2014). The effect of an operating mine is an increase of 37% in temptation goods (Table 3E.1, column 6) whereas the effect is only 10% for total expenditure (Table 3F.3, column 7, considering the same years).

3.5.3 Infant mortality and school enrolment

Figure 3.5 shows the marginal effects at the means on infant mortality for babies who were born within 10km of an artisanal mine compared to the rest of the country (see Table 3E.2 in Appendix 3.E for full results and Table 3F.4 in Appendix 3.F for a comparison group of 10 to 20km).

Compared to infants born in the rest of the country and controlling for the child's sex, age, urban areas and birth year, a baby was not significantly less likely to die within the first year when they were born within 10km of an artisanal deposit in times with higher gold prices (top left coefficient plot, Figure 3.5 or living next to an operating artisanal mine (bottom left coefficient plot, Figure 3.5). However, compared to infants born 10 to 20km from an artisanal mine, babies are 1 percentage points less likely to die (significant on the 10% level; see Table 3F.4), which is not insignificant, since the total infant mortality rate is 6.2%.

These effect shown by the left-hand side of Figure 3.5 only include basic controls, which represent the combined potentially positive effect of wealth and potentially negative effect of pollution. We, therefore, additionally control for wealth groups, which allow us to control for the increased income from artisanal mining to isolate the impact of the potentially dangerous and polluted environment around artisanal mines on infant mortality. In other words, we try to separate two likely contradictory effects. On the one hand, artisanal mining can lead to higher incomes leading to better nutrition and improved health care. On the other hand, artisanal mining can lead to worsening health outcomes due to a polluted environment. We do not find that an infant is significantly more likely to survive, also when controlling for wealth (middle coefficient plots, Figure 3.5). This indicates that there is no significant negative impact of pollution and hazardous environment on infant health. If there would be, we would expect a positive coefficient of operating mines on infant mortality once controlling for changes in wealth induced by the mines.

Fig. 3.5: Coefficient plots of infant mortality. Dependant variable is a binary variable equal to one if a child died within their first year. For Eq.3.1 we use all household data. In Eq.3.2 we restrict the data to municipalities sampled in every year, we exclude observations in 1998 due to limited satellite images to determine if a mine was already active and to allow for more temporal variation, we omit households close to an artisanal mine that was already operational in 2003. When we include mother fixed effects, we consider all mothers who live 20km from an artisanal deposit and had at least one child before the gold boom and at least one after (Eq.3.1) or at least one child before the specific mine in their area opened and one after(Eq.3.2). All analyses control for the child's sex and birth year, as well as urban areas when not controlling for mother fixed effects. See Table 3E.1 in Appendix 3.E for full results and results of a 10-20km comparison group is shown in Table 3F.4. in Appendix 3.E

The coefficient plots on the right-hand side also include mother fixed effects (see Table 3E.2, columns 3 and 6 for full results). Controlling for mother fixed effects allows us to compare the mortality risks for siblings born before and after the gold boom (top right coefficient plot, Figure 3.5) or opening of a mine (bottom right coefficient plot, Figure 3.5), which controls for all time-invariant unobserved household characteristics. Note that we consider a very specific subset of all mothers for this specification (see Section 3.4): only those who currently live within 20km of an artisanal deposit, and have had at least one child before the gold boom or opening of a mine and at least one after. This allows us to compare the mortality rate of siblings from similar households with each other, varying the presence of a mine. Hence, our treatment group with 10km vicinity of a mine remains the same as in all other specification, but our control group is constrained to mothers within 10 to 20 km of a mine. However, previous analysis for other variables (compare e.g. Tables 3.1 and 3.2 with Table 3F.1 in the Appendix 3.F) have shown that results are smaller but similar, with some loss in significance. However, we also do not find any significant effect when controlling for mother fixed effects (right-hand side, Figure 3.5).

We also consider the impact of artisanal mining on education in terms of net school enrolment (Figure 3.6). We consider two comparison groups, first, all households more than 10km from an artisanal mine and households 10 to 20km from an artisanal mine (see Table 3F.4 in Appendix 3.F). We first control only for the child's sex, age, urban areas and birth year (basic controls, left-hand side in Figure 3.6). We then control for wealth groups (right-hand side in Figure 3.6), which allows us to disaggregate the ambiguous impact of mines on net school enrolment; e.g. while increased wealth could allow families to keep children in school longer, children could also leave school in order to mine.

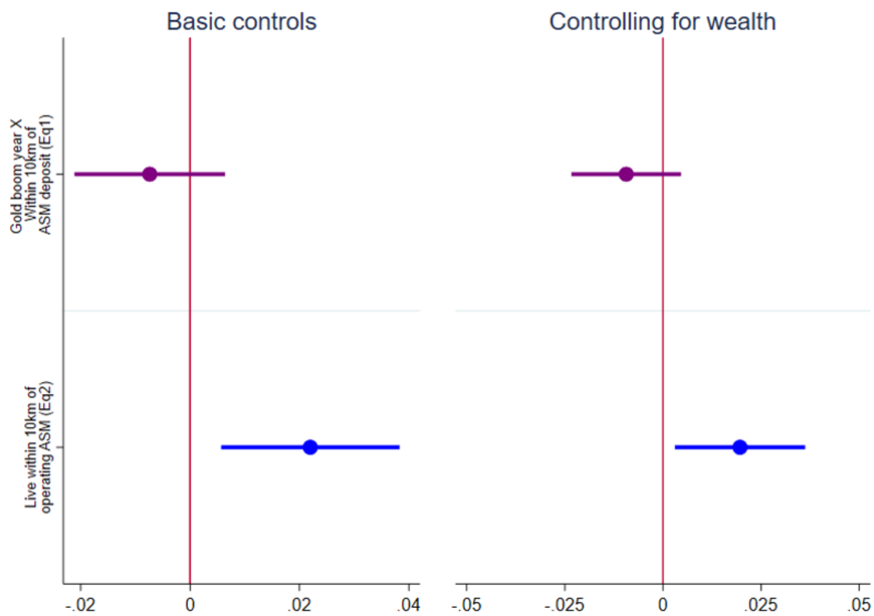


Fig. 3.6: Coefficient plots of school enrolment. Dependant variable is a binary variable equal to one if a child is enrolled in school. For Eq.3.1 we use all household data. In Eq.3.2 we restrict the data to municipalities sampled in every year, we exclude observations in 1998 due to limited satellite images to determine if a mine was already active and to allow for more temporal variation, we omit households close to an artisanal mine that was already operational in 2003. Basic controls include child's sex, age, urban areas and birth year. See Table 3E.3 in Appendix 3.E for full results and results of a 10-20km comparison group is shown in Table 3F.4. in Appendix 3.E

Using the gold boom years as an identification (Eq.3.1) we find no effects (top left-hand side Figure 3.6, see Table 3E.3 in Appendix 3.E, column 1 for full results). However, these effects turn negative once we use the control group 10 to 20 km instead of all other children (see Table 3F.4 in Appendix 3.F). Once we use the operation of a mine as an identification strategy (Eq.3.2), we observe a positive increase of 2 percentage points in school enrolment (bottom left-hand side Figure 3.6 and Table 3E.3 in Appendix 3.E, column 3 for full results). For comparison, that is about a 4% increase in the total school enrolment rate across all years, which is 42.8%. Results decrease slightly and are less strongly correlated but similar if we consider a control group of 10 to 20 km close to a mine (see Table 3F.4 in Appendix 3.F).

Controlling for wealth groups slightly decreases the impact of mines on schooling (right-hand side in Figure 3.6 and Table 3E.3 in Appendix 3.E, columns 2 and 4). Hence, in addition to changes in wealth other factors linked to mines might slightly increase schooling rates, for example increased schooling opportunities due to the large influx of people usually associated with a gold rush.

3.5.4 Formal and informal artisanal mines

Lastly, we differentiate between households close to a formal and informal artisanal mine. We only differentiate by licensing applying Eq.3.1 due to lack of data on the temporal aspect of licensing. Since many artisanal mines often mine around industrial mines, we also control for households close to an industrial mine (3% of the sample, since 2007, when the first industrial mine opened in the country). Since formal and informal operations are often in close proximity (85% of households close to an industrial mine are also close to an artisanal mine), we also differentiate between households that are only close to a formal artisanal deposit (1.2% of the sample), those that are only close to an informal deposit (21.5% of sample) and those that are close to both an informal and formal deposit (14.1% of sample). We find that the positive expenditure effect is about double for those living next to a formal mine than those living close to an informal mine (33% vs 16%, see column 1, Table 3.3). However, given the large standard errors this difference is not statistically significant; compared to all other households, expenditure within 10km of a formal mine increases by 20% but has a p-value of 0.127. Households living near an industrial mine during the gold boom show an additional 13% increase in expenditure.

When we consider the impact of licensing on assets (Table 3.3, column 2), we find that informal mines show higher assets. This could be due to the sample size and the lower variance of the asset index (in comparison to expenditure) or as found by Brugger & Zanetti (2020) that many miners send remittances to their families, which could mean that miners are less likely to invest in assets despite increase in income. We also do not find that industrial mines has any impact on assets. Our results further suggest that per capita expenditure on alcohol and tobacco is driven by households that are close to both formal and informal mines (see Table 3.3, column 3).

Dependent variable	**(1) ln (pc hh exp.)**	**(2) ln (asset index score)**	**(3) IHS (pc temp. exp.)**	**(4) Infant mort.**	**(5) School enrol.**
Artisanal mining					
<10km of any artisanal deposit	-0.072*	0.013	-0.285	0.000	0.029***
	0.041	0.083	0.254	0.004	0.008
Gold boom <10km of formal deposit (no informal)	0.331**	-0.083	0.363	-0.021	-0.024
	0.147	0.187	0.406	0.014	0.019
Gold boom <10km of informal deposit (no formal)	0.163**	0.129*	0.267	-0.005	-0.002
	0.064	0.069	0.257	0.005	0.008
Gold boom <10km both informal & formal deposit	0.231***	0.055	0.548**	0.004	-0.033***
	0.057	0.076	0.243	0.007	0.009
Industrial mining					
<20km of industrial mine deposit	-0.002	0.177	0.206	0.012	-0.018
	0.069	0.144	0.345	0.009	0.015
Boom <20km of industrial mine deposit	0.134*	-0.000	-0.479	-0.004	0.051***
	0.073	0.112	0.424	0.008	0.014
Observations	36,133	52,018	19,306	40,101	130,751
R-squared	0.606	0.475	0.171	-	-

Tab. 3.3: Formal and informal artisanal mines and industrial mine. An ASM (artisanal and small-scale mine) deposit, is a gold deposit that will be an artisanal mine in the final year of the database. Licensing is determined by overlapping the location of artisanal mines with data on registered mining plots from the Ministry of Mines in Burkina Faso. Columns 1 to 3 show regression coefficients and columns 4 and 5 show the marginal effects at the mean and therefore no R-square values. All regression include year and municipal fixed effects and controlling for households in urban areas. Household-level analyses (columns 1 to 3) include controls for size of the household, literacy, sex and age of household head. Individual-level analyses (columns 4 and 5) include controls for sex and age of child. Standard errors below coefficients. ***p <0.01, **p <0.05, *p <0.1

Considering the impact on infant mortality and school enrolment, we do not any reduction in infant mortality for either formal or informal mines (see Table 3.3 column 4). Industrial mining also does not have any significant impact on infant mortality. When disaggregating the impact of formalisation on schooling, we find a negative impact on net school enrolment around formal and informal artisanal mines but not around informal or formal mines only, and an additional positive impact around industrial mines (most households close to an industrial mine are also close to an artisanal mine). The higher school enrolment around industrial mines could be linked to corporate social responsibility initiatives that often invest in schools. While child labour in formal industrial mines operated by international companies are strictly prohibited, child labour might still occur on licensed artisanal mines, due to little oversights and lenient registration requirements that does require child labour restrictions.

3.6 Discussion and conclusion

Many qualitative research and case studies have shown that artisanal mining – a labour-intensive form of subsistence mining – has large potential to alleviate poverty (Werthmann, 2017; Fisher et al., 2009; Gamu et al., 2015). However the artisanal mining sector is also known for serious environmental degradation and human rights abuses. Artisanal mines can also cause significant environmental degradation, which could lead to serious health implications, such as heavy metal pollution, or deforestation, erosion and loss of top soil that reduces the agricultural capacity and contribute to food insecurity.

The impact of artisanal mines on their surrounding communities are therefore ambiguous. On the one hand, many case studies have shown evidence that artisanal mining could lead to increased income (Bazillier & Girard, 2020; Guenther, 2018). Increased income could allow families to afford better nutrition, medical care and other basic needs that would improve well-being. On the other hand, artisanal mines also create dangerous and polluted environments that could have adverse health impacts, especially for children who often work and live on artisanal mines and are more susceptible to various toxins (Bose-O'Reilly et al., 2008; Bose-O'Reilly et al., 2010; Hilson, 2010).

However, quantitatively determining the impact of artisanal mines on their neighbouring communities is extremely difficult due to the lack of information and data on the sector, which has been described as a global data gap (Lahiri-Dutt et al., 2019). Many governments do not have a complete database of the number of artisanal mines, where they are located, when mining started, how operations expanded or shut down, or the amount of gold they extract due to the rapid growth of artisanal mines in many countries, such as Burkina Faso and high-levels of informality. In Burkina Faso, we estimate only 12% of artisanal mines have ever been licensed, and even for licensed mines very little data exist. Therefore, due to these data deficiencies, quantitative estimations of the impact of artisanal mines on local communities extremely difficult.

We know of two previous quantitative studies that have examined the impact of artisanal mines on their neighbouring households (Bazillier & Girard, 2020; Guenther, 2018). Both studies needed to make additional assumptions about the location and starting dates of mines. In Ghana, Guenther (2018) used satellite images to identify artisanal mines — majority of which were alluvial mines in rivers because they are easily recognisable on satellite images — and assumed that all mines became operational in 2006, when artisanal gold mining started to become a major sector in Ghana. In Burkina Faso, Bazillier & Girard (2020) used data on registered artisanal mines in Burkina Faso, and assumed that all registered mining plots have been operational for the entire duration of their study, and instead consider changes in the world gold price as a temporal variation on households close to mining licenses.

We build on the previous studies in four important ways: first, we use a more comprehensive database of artisanal mines compiled by the Burkinabe government with satellite images, supplemented with existing governmental records of artisanal mines and subject to additional remote verification. This database is about eight times large than the database used by Bazillier & Girard (2020). In addition, overlaying this database with the one used by Bazillier & Girard (2020); we find that only about 70% of the licenses used in their study actually hosted an artisanal mine. Second, using high-resolution satellite images, we supplement the database of artisanal mines with a refined temporal dimension, by estimating in what years mines were operational. This allows us to determine the impact of an operating artisanal mine and not merely changes in the world gold price. Third, we consider a broader range of indicators of well-being, including the impact of artisanal mines on neighbouring households' various total expenditures, wealth, temptation good expenditure, infant's health and school enrolment. Fourth, we differentiate between formal and informal artisanal mines to determine if formal mines, in terms of licensing, have a significantly different impact on neighbouring households compared to informal mines.

Similar to Bazillier & Girard (2020), we find that expenditure of households in the vicinity of a gold deposit increase 19% in years with higher world gold prices.The higher expenditure around artisanal mines are expected given the importance of mining in the Burkinabe context but it is important to note that we find this result of higher expenditure even when we control for various households characteristics, being in an urban area, as well as year and municipal fixed effects. In addition, the effect is similar if we consider households that are within 20km of a deposit. We also find that the positive impact on expenditure around artisanal deposits is compounded by the distance to the mine, i.e. the larger the distance the comparison group is from the mine, the larger the relative impact of the mine on the households within a 10km radius of the mine. However, when we take a more refined analysis into consideration, by estimating the impact of an operating artisanal mine on household expenditure, instead of changes in the world gold price, we find a smaller effect (6% instead of 19%).

It is problematic to directly compare the two models presented in this paper since the first relies on fluctuations in the world gold price (similar to the model by Bazillier & Girard (2020)) and the second on the opening of an artisanal mine as temporal variation. Given that Burkina Faso is a price taker in the world gold market, the world gold price, which is exogenously determined, is the main benefit of the artisanal mine for the local neighbouring community. Researcher therefore often rely on the world gold price as a proxy for the benefits derived from mining. Directly comparing the two models, while they are measuring different trends, gives us an indication of potential shortcomings of relying on the world gold price as a proxy for the primary value of artisanal mining for local communities.

We expect the impact of an artisanal mine opening to be smaller, since artisanal mines also opened in years with lower gold prices. Another possibility is that the staggered opening of artisanal mines throughout the duration of our study could create a biased estimation as suggested by recent studies (Goodman-Bacon, 2021; Athey & Imbens, 2022; Borusyak & Jaravel, 2017). However, when we eliminate the staggered treatment effect by splitting the dataset in two – in the first only considering artisanal mines that opened between the first and middle survey years (2003 and 2009) and in the second dataset only considering mines that opened between the middle and last survey years (2009 and 2014) – we do not find staggered opening of mines causes bias estimators.

In addition, we find that the impact on wealth – as measured by a pooled asset index – is still positive but the effect is smaller. We find a 6% increase in wealth for households around an artisanal mine, both when we consider the impact of gold prices and the actual operations of an artisanal mine. A possible reason is that people who work around artisanal mines are less likely to invest in assets, despite higher incomes from mining. Brugger & Zanetti (2020) found that many people work on the mines to send remittances home to their families. According to Brugger & Zanetti (2020) the size of the mine has a significant impact on the labour allocation of households around the mines; large mines are often more productive and attract workers from all over the country and neighbouring countries who fully substituted their income from agriculture with income from mining. These workers are also more likely to send remittance to family that live far from the mine. Various characteristics of the mine, such as size and productivity, would therefore have a significant impact on how people allocate their income, for example, whether they invest in assets in the area or if they send remittances to family. A limitation of our study is that we are unable to control for any mine characteristics, which could be the reason why the impact on assets around artisanal mines are smaller than the impact on expenditure.

Despite the positive effect on income and wealth, artisanal mines are also known for environmental degradation and human rights abuses that could have detrimental impacts on neighbouring households' well-being. In Burkina Faso, a parliamentary commission on social responsibility of mining in Burkina Faso said artisanal mines are "lawless places where prostitution, drug traffic, child labour etc. reign" (as cited in Werthmann, 2017). Similar to many qualitative studies that documented high alcohol and drug consumption around artisanal mines (Hinton, 2005; Thorsen, 2012), we find that reported expenditure on temptation goods (alcohol and tobacco) increased significantly. From 2003 to 2014, expenditure on alcohol and tobacco increased within 10km of an artisanal gold deposit in years of higher gold prices with 41%, which is much larger than the 14% increase in total household expenditure in the same period. The increase in temptation good expenditure is almost four times larger than general household expenditure from 2003 to 2014 when considering the impact of an operating artisanal mine (37% vs 10%).

However, we do not find evidence of other reported harmful effects of artisanal mining. Despite many qualitative studies describing the many children leaving school in order to take up mining, we find that artisanal mining actually has a positive, although small, impact on school enrolment (about 2%). This does not exclude the possibility that children work on the mine, since many children could mine part-time in order to pay for school fees (Hilson, 2010). This effect is however, smaller and less strongly correlated when we compare children less than 10km of an artisanal mine with children who live 10 to 20km from a mine. Since physical distance probably has a large influence on a child's decision to work on the mine, children within 10km of the artisanal mine are more likely to take up mining than children in similar areas that are slightly farther away (10 to 20km).

We also do not find that artisanal gold mining and higher gold prices have a significant impact on infant mortality compared to households farther than 10km from an artisanal mine. However, when we consider a restricted control group of households within 10 to 20km of an artisanal mine, we do find that an infant is 1 percentage point less likely to die in their first year if they were born within 10km of an artisanal mine. A limitation on our analysis on infant mortality is that we consider the location where a mother completed the survey as the location where the infant was born, meaning we cannot control for the impact of migration, which could have a downward bias on our results. We also do not find any significant impact on infant mortality when comparing siblings born before and after 2006 (threshold year for higher world gold price), as well as siblings born before and after a mine in their vicinity opened.

We, therefore, find evidence that artisanal mining has both positive and negative impacts on neighbouring households. In order to address many of the negative externalities around artisanal mines many multi-lateral and non-governmental organisation and scholar have recommended that host governments need to formalise the sector, since most artisanal miners operate informally (Hilson, Zolnikov et al., 2018). Formalisation would increase government control over the sector, allow for monitoring and oversight to address human rights abuses and environmental degradation on the mines. Licensing could allow miners to become part of the legal economy, giving them access to credit, which could allow them to make their mining operations more efficient (Hinton, 2005).

However, A. Bugmann et al. (2022) has shown that informal miners in Burkina Faso already have access to well-established informal credit channels through gold buying houses. In addition, various researchers have argued licensing cannot be separated from a broader legal framework; without the institutional, legal and political framework would not lead to more efficient mining operations and address negative externalities (Siegel & Veiga, 2009). The World Bank (2015), for example, encourages a broader definition of formalisation that also provides for governmental monitoring, oversight, and enforcement of best practices. This resulted in many governments setting high standards or requirements to formalise, often too tedious for miners to achieve. Given the burden of formalisation, many miners do not want to be part of the formal economy or cannot afford to meet the standards (Vogel et al., 2018; Echavarria, 2014; Siegel & Veiga, 2009).

Despite many advocating for formalisation, formalising such a mobile, dynamic and large informal sector is difficult in practice. In Burkina Faso, the government opted for a liberal definition of formalisation by merely registering or licensing mines. The effectiveness of formalisation to reduce negative externalities on artisanal mines would therefore depend both on artisanal miners' compliance and on the stringency of standards. On the one hand, the low barrier to formalisation would mean that more miners are able to formalise, but on the other hand, the lenient specifications would mean that miners do not necessarily adopt best practices.

In order to assess the efficacy of formalisation, we also differentiate between licensed and informal mines. We find that the positive household expenditure effect is double for formalised mines than informal mines (33% vs 16%). In Burkina Faso, traders are only able to officially purchase gold from licensed mines. This could make it easier for miners from licensed mines to have access to markets than those around informal mines, resulting in higher income for the households around the formal artisanal mines.

However, given the small number of mines next to a formal mine the effects are not significantly different. In addition, we do not find that increase expenditure result in higher asset accumulation around formal mines. We also do not find that formal artisanal mines are more beneficial for their neighbouring households in terms of infant mortality and school enrolment. Net school enrolment is even lower around formal artisanal mines than informal mines, possibly due to the potential to receive a higher income around a formal mine.

In general, we find that artisanal gold mining has a large potential to alleviate poverty. In order to fully utilise the potential of the sector, while decreasing the negative externalities, we recommend that formalisation beyond mere registration and include a broader policy framework that includes oversight and monitoring of best practices.

Appendix

3.A More information on household data

Asset Index

The DHS database include an asset index for some years (2018, 2014, 2010 and 2003) but not for earlier years (1998) and also not in the LSMS database. In addition, we would like to create an asset index pooled over all the survey years. We use the following variables as input variables of the principal component analysis, because we have information on these assets in every DHS and LSMS survey year.

Assets owned	**Water source**	**Fuel source**	**Type of toilet**	**House**
Iron	Piped/tap	Wood	Flush	Finished roof
Bicycle	Borehole	Coal	Latrine	Natural roof
Fridge	Fountain	Gas	None	Finished walls
Improved fireplace or stove	River, spring, dam			Natural walls
Radio				
Car				
Motorcycle				
TV				

Tab. 3A.1: Input variables for asset index. We used a principal component analysis to calculate an asset index for all the DHS years and the years with LSMS data.

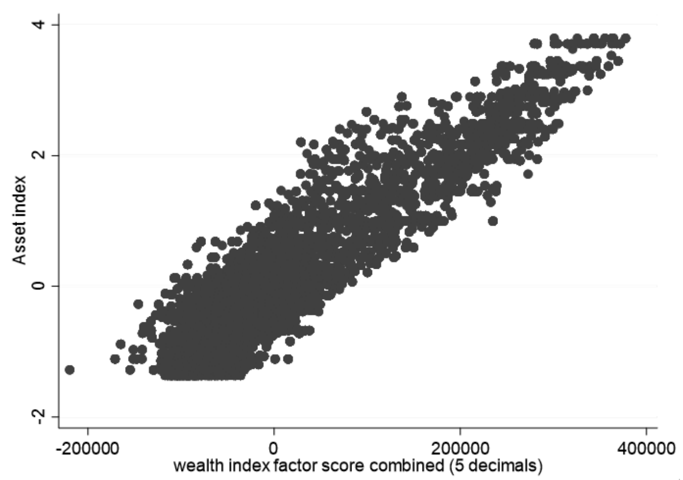


Fig. 3A.1: Comparison between wealth index constructed by DHS and results from authors' Asset Index. Calculated with a principal component analysis in 2018

Summary of data available in each year

Year	Survey Type	Sufficient satellite images	Data available on...				
			expen-diture	assets	temp. expen-diture	infant mort.	school enrol.
1998	DHS & LSMS	No	Yes	Yes	No	Yes	Yes
2003	DHS & LSMS	Yes	Yes	Yes	Yes	Yes	Yes
2005	LSMS	Yes	No	Yes	No	No	Yes
2007	LSMS	Yes	No	Yes	No	No	Yes
2009	LSMS	Yes	Yes	Yes	No	No	Yes
2010	DHS	Yes	No	Yes	No	Yes	Yes
2014	LSMS	Yes	Yes	Yes	Yes	Yes	No
2018	DHS	Yes	No	Yes	No	Yes	No

Tab. 3A.2: Summary of data available in each year.

Sample size

	Per capita expenditure	Asset Index Score	P.C. temp. good expenditure	Infant mortality	School enrolment
Initial sample size used in Eq. 1	36,145	53,153	19,318	48,008	132,276
Excluding:					
All observations before 2000	8,460	8,478	-	-	-
Municipalities not surveyed every year	8,244	6,968	3,093	22,391	39,385
HH close to mines opened in 2003 or before	4,154	3,337	1,313	1,853	6,785
Sample size used for Eq.2 (% reduction from Eq.3.1)	27,917 (40%)	34,370 (35%)	14,912 (30%)	23,764 (50%)	87,843 (34%)

Tab. 3A.3: Summary of sample restrictions for Eq.2

Temptation good expenditure

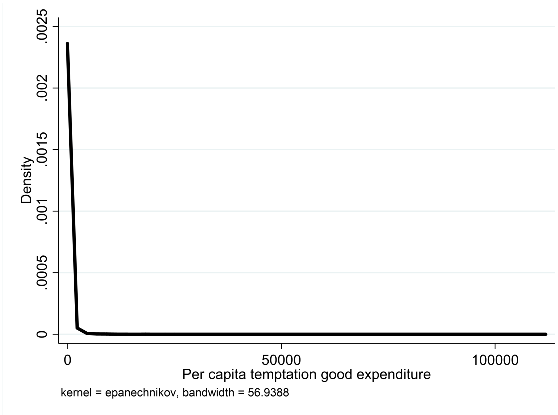


Fig. 3A.2: Density distribution of per capita expenditure on alcohol and tobacco.

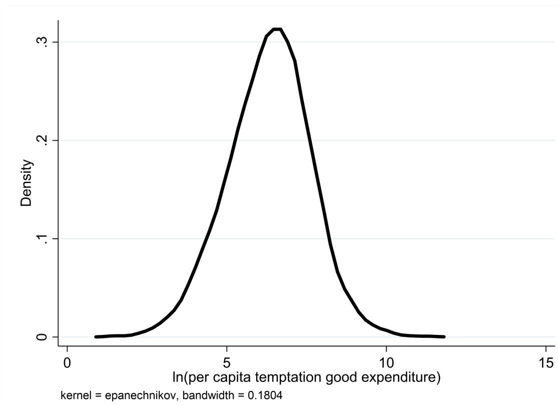


Fig. 3A.3: Natural logarithm of non-zero per capita temptation good expenditure.

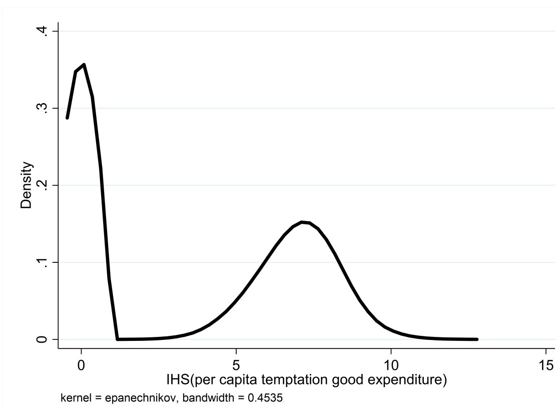


Fig. 3A.4: Inverse Hyperbolic Sine Transformation of temptation good expenditure.

School enrolment

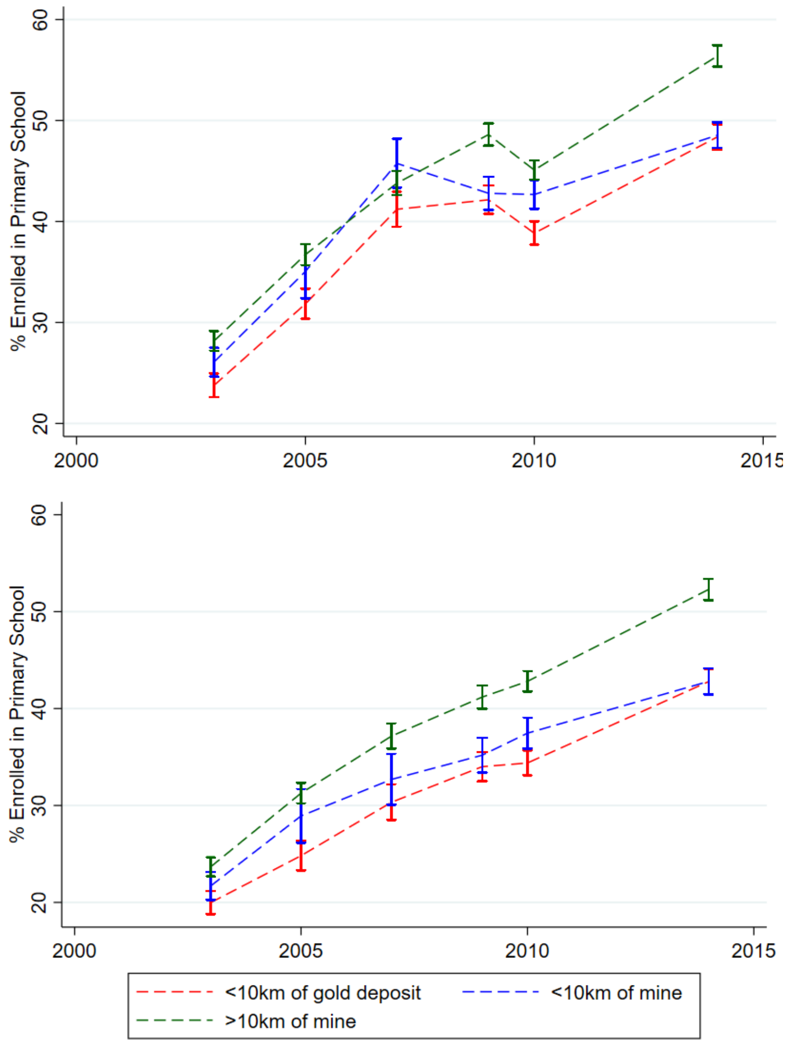


Fig. 3A.5: Additional net school enrolment. Net primary enrolment (left graph) and net secondary enrolment (right graph) of children who live close to and far from an artisanal mine, with 95% confidence intervals.

3.B Remote sensing & machine learning in artisanal mining

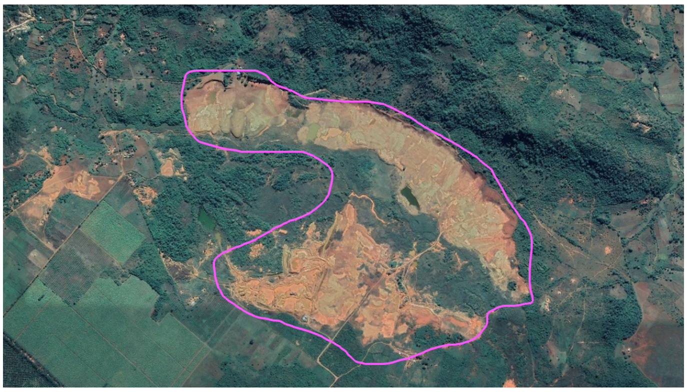
The lack of data and heterogeneous nature of artisanal mines make machine learning difficult to use. To create algorithms, machine-learning techniques require large training databases, which is often not available for artisanal mines. Saavedra & Romero (2021) used a random forest machine-learning algorithm to find mines in Peru, which they trained using data from a mining census done in neighbouring Colombia (with similar vegetation). However, very few countries have conducted similar mining censuses as done in Colombia. Guenther (2018) based his analysis on a novel database of artisanal mines that was created by using a deep learning machine-learning technique, trained on mines that he identified from looking at high-resolution satellite images from Ghana.

The problem with manually identifying mines for the training database (such as the approach taken by Guenther, 2018) is that artisanal mining activities are highly diverse, which influences the visibility of a mine on a satellite image (see Figure 3B.1). There are three main types of mining techniques: open-pit mining, underground mining, and alluvial mining, which is secondary mining, which mostly consists of mining from rivers but can also include mining from tailings or other secondary sources (see Figure 3B.1).

Manually identifying mines from training databases could create a biased database by favouring easily recognisable mines such as larger mines, alluvial or open pit mines. Alluvial mining in rivers is often the most easily recognisable on satellite images, however the percentage of alluvial gold mining depends on the country and the type of deposits. Some countries source the majority of their gold from alluvial sources, including Colombia (82%, UNODC, 2018), Côte d'Ivore and Ghana with one of the most developed alluvial gold sectors (Lassen et al., 2016). However, the majority of Burkina Faso gold deposits are in hard rock mining deposits, with only 5-10% in alluvial deposits.

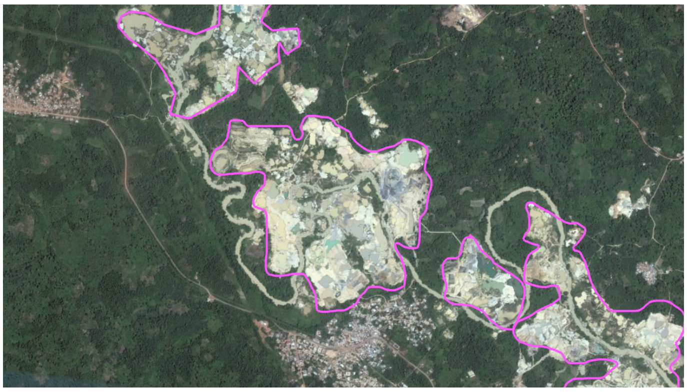
In an attempt to identify artisanal mines, the Burkina Faso government contracted the company Effigis Geo-Solutions to find artisanal mines by using satellite images (Rheault, 2018), they used a database of existing licensed artisanal mines to determine if they can successfully train an algorithm that can find other artisanal mines. They first focused on two test areas of 625km^2, one in the more arid northern region and one in the rainier southern region. In the drier northern test area, their algorithm identified 78 of 95 (82%) known gold mining sites, with a cumulative area of 6.53km^2. However, the algorithm also falsely identified 37.54km^2 as gold mining sites, which is equal to a false positive rate of 88%. Saavedra & Romero (2021) encountered similarly high false positive identification rates in Peru.

If the goal is for a government to find possible illegal mines, an algorithm with a high false positive can still be useful because it still narrows the search range for officials, provided that the true positive identification rate is high. However, the algorithm only identified 17% of mines in the wetter southern area and had a false positive rate of 81%. The high false-positive rate in the south was accredited to the difference in identification rates to the fact that inactive gold panning sites in the south are more rapidly oxidized and re-vegetated (Rheault, 2018).



Open-pit artisanal gold mine in Mozambique (2019) -18.867°; 32.836°

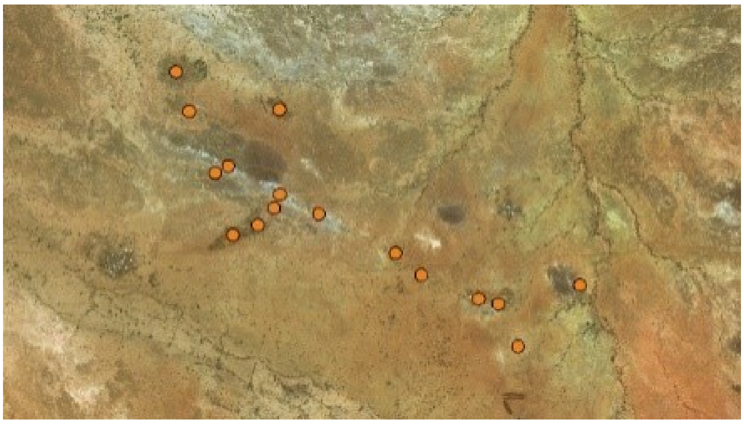
Artisanal underground gold mine in Burkina Faso (2019) 13.736°; -2.622°



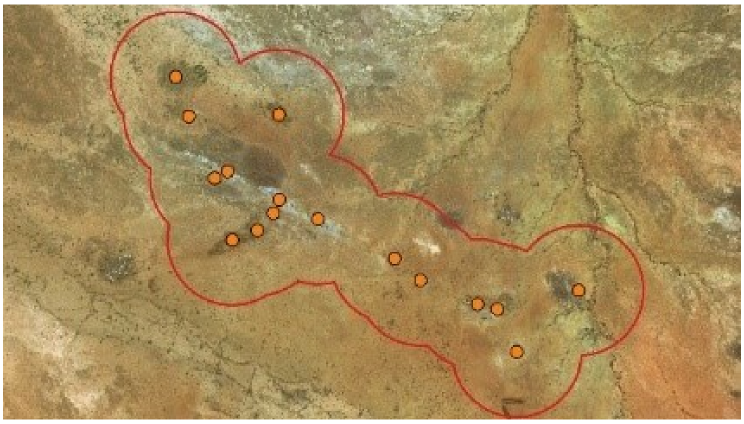
Artisanal alluvial gold mine in a river in Ghana (2020) 6.06°;-1.966°

Fig. 3B.1: Different types of artisanal mines. The mining technique used in artisanal mines, such as open-pit, underground and alluvial mines, influence the visibility of the mine on satellite images. Manually identifying mines from satellite images will include more easily recognised operations. Source: Google Earth Pro (2020)

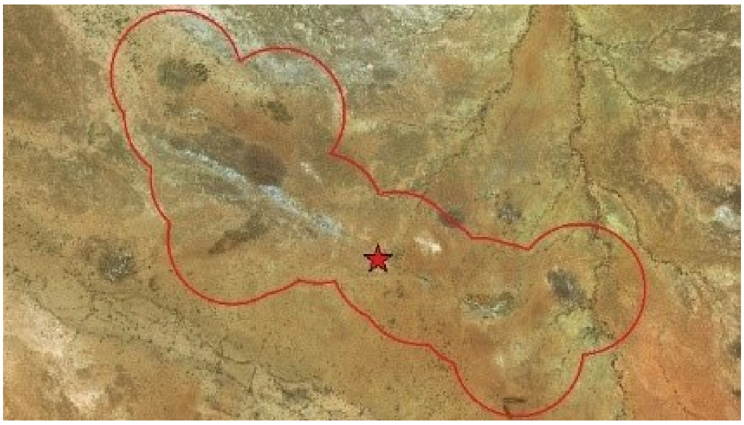
The difference in the true positive rates in the two areas highlights the difficulty with using machine learning and satellite images to identify a diverse range of artisanal mines (open-pit, underground and alluvial) in a wide range of environments, from rivers, dense forests to deserts. The commission concluded that the method is not feasible to identify mines (Rheault, 2018).



Picture 1: all possible artisanal mining activities are identified on satellite images and marked with an orange dot



Picture 2: a 250m buffer is drawn around each point, and the total area is considered the artisanal mine site



Picture 3: the centroid of each mine is exported as the coordinates of each mine.

Fig. 3B.2: Marking artisanal mines. Source: Rheault (2018)

As an alternative, they decided to investigate high-resolution satellite images manually to identify artisanal mining areas by systematically scanning images of Burkina Faso and supplement it with governmental records of artisanal mines. Manually identifying artisanal mines from satellite images (similar to Guenther, 2018) could create a biased database by favouring mines easily recognisable on satellite images. However, this bias should be minimal, since the database was supplemented with government records of existing mines and subject to remote verification.

The location of more than 700 sites was verified, of which 15% were subsequently excluded, and an extra 25% previously unidentified sites were added. Given the size of the area that needed to be scanned, they prioritised certain areas, such as areas registered as an artisanal mine with a mining license, sites listed in previous projects identified by the ANEEMAS, and areas overlapping with the geographical area that is known to host gold deposits, the Greenbelt volcano-sedimentary rock basin (Rheault, 2018). They then identified about 17'000 points with potential artisanal mining activities (as shown in picture 1, Figure 3B.2), a buffer of 250m was drawn around each point with the total area considered as a single mine (red border in picture 2, Figure 3B.2) and only a centroid (shown by a red star in the third picture, Figure 3B.2) was published as the location of an artisanal mine.

3.C Data on artisanal and industrial mines

Classification of high-resolution satellite images

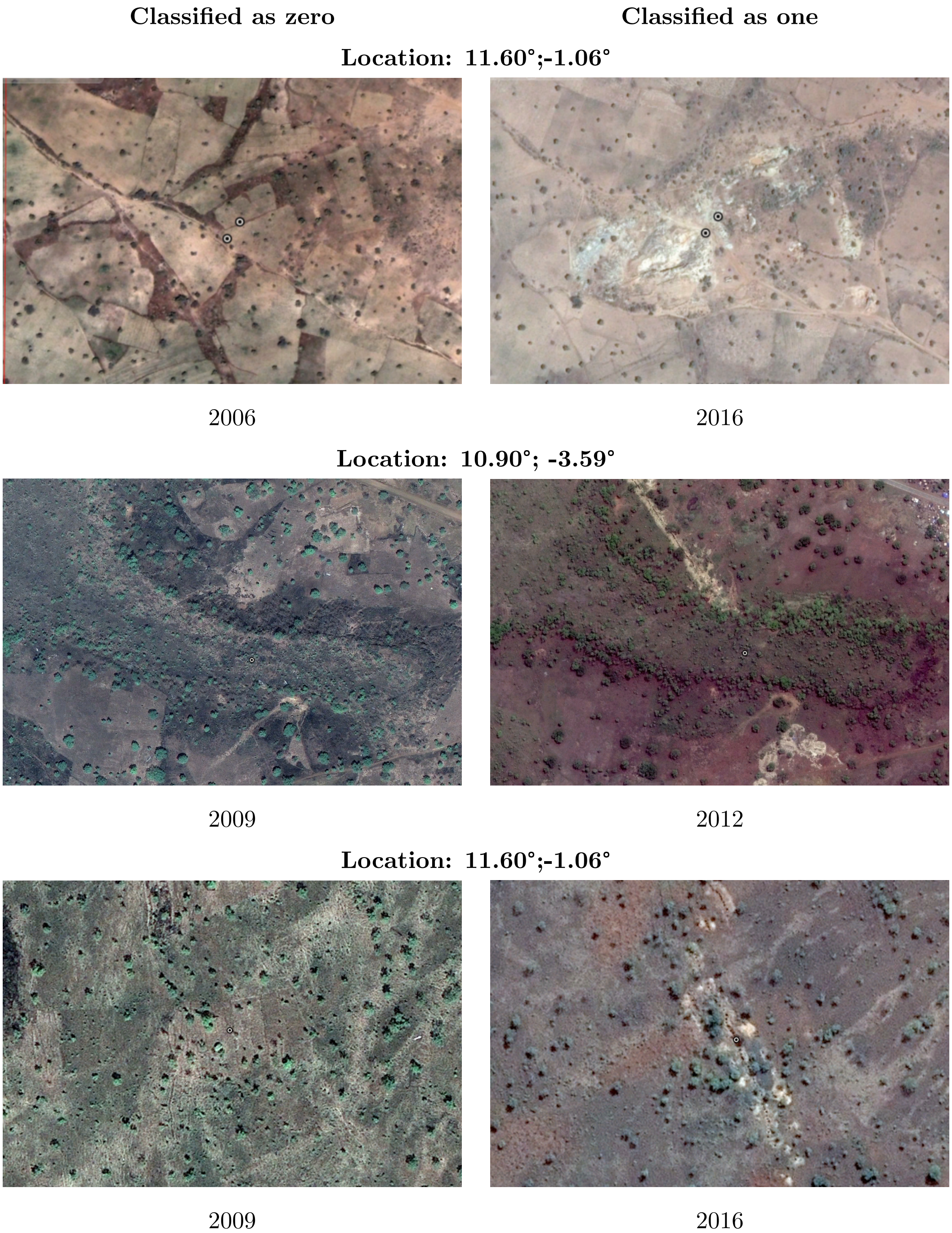


Fig. 3C.1: Example of artisanal mine classification. Each high-resolution picture was classified with one if we could see an artisanal mine and zero if not. The pictures show examples of three different locations, each initially classified as zero (images on the left) and classified as one in later years (images on the right).

	2003	2005	2007	2009	2010	2014	2018
Correctly identified	77.8%	66.7%	63.2%	80.6%	87.5%	93.3%	100%
False positive (non-mine identified as mine)	5.6%	11.1%	15.8%	9.7%	6.3%	3.3%	0%
False negative (mine identified as non-mine)	16.7%	22.2%	21.1%	9.7%	6.5%	3.3%	0%
Able to identify (images available)	18	18	19	31	32	60	63
Unable to identify	45	45	44	32	31	3	0

Tab. 3C.1: Testing accuracy of the method. To test the accuracy of the method used to determine if mine was operational or not in each period, we compared results of the method to known starting dates and found a high accuracy, but that missing values increase significantly going back in time due to low availability of satellite images in earlier years.

Artisanal mines in each period

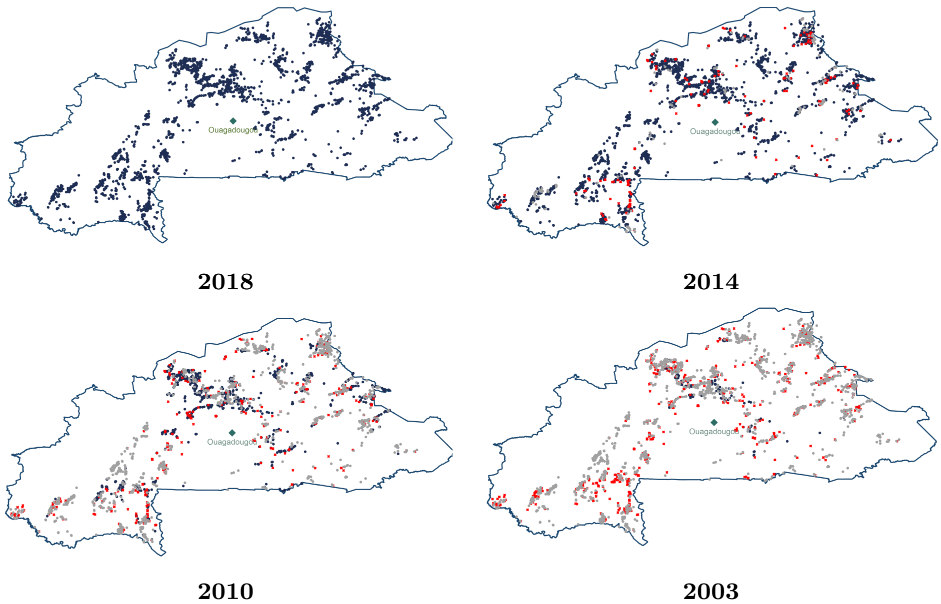


Fig. 3C.2: Location of artisanal mines. The above maps show the location of all artisanal mines that we could identify as operational (dark blue point), that we could identify as not operational (grey point) and artisanal mines that we cannot determine as operational or not (due to availability of high-resolution satellite pictures) shown by a red cross.

Data on artisanal mining licenses

We received information on 367 AEA licenses from 2005 to 2018. We excluded 13 licenses that were not related to gold but other commodities such as granite mining. A further six licenses had to be removed due to double entries. In order to have only one license per area, renewal licenses were deleted.

To determine which potential artisanal mines are licensed, we overlapped polygons showing the licensed areas with data points showing artisanal mines used in the main analysis, as identified by Rheault (2018). If a data point fell inside the license polygon or within 250m of the border of the polygon, we considered the artisanal mine licensed. We also included mines within 250m of the border of a license due to the method Rheault (2018) used to determine the potential mines, at least an area within 250m of the centroid could be a possible mine.

We assumed that any mining activity within the license polygon is the mining activity authorised by the specific license. Of the 367 licenses in the database, 281 overlapped with artisanal mines. Although we do have some information on the starting and expiry dates of licenses, the information is incomplete and often has discrepancies. We, therefore, do not differentiate if a mine was licensed in a specific year, but if an operational mine has ever or will ever be licensed. This would control for the possibility of mines that are able to formalise being fundamentally different to other mines, such as a higher financial or technical capacity to meet formalisation requirements, or political connectivity that allows for easier formalisation. Determining if a mine is licensed in a specific year is therefore less important than differentiating between the types of mine that were able to secure licensing any time in its lifespan.

Coordinates of industrial gold mines in Burkina Faso

We extracted all information on mining activities in Burkina Faso, which gave 187 recorded mine related operations, of which only four were not related to gold (one zinc mine, one nickel and two manganese projects). Of these, 166 have not commenced operations and were not considered further, these included early phase development before production, such as exploration, grass-roots operations or target outlines. Two mines started operations after the timeline of the study (2019 and 2020) and were also not considered further. Of the remaining 19 operations, 13 mines were operating, two are satellite operations, four were closed. Except for one zinc mine, all the rest are gold mining operations.

We check the coordinates given on the SNL database on Google Earth Pro (see Table 3C.2). We were unable to locate one mine on the satellite images, even within a 20km radius of the provided latitude and longitude coordinates, this mine has not reported any production and was excluded from the analysis. Of the remaining 18 mines, 12 mines' coordinates were correct, the coordinates of four mines needed to be changed slightly (within 7.5km of the coordinate) and for two mines that started operations in 2018 and 2017 there are no available images after operations started, and the coordinates could not be confirmed, for these mines we used the S&P coordinates exactly.

Mine name	Coordinates	SNL coordinates		Correction coordinates	
		Latitude	Longitude	Latitude	Longitude
Balogo	No images available since mining started	11.397390	(1.497620)		
Bissa	Correct	13.167000	(1.509000)		
Bouly	Correct	13.152160	(1.420020)		
Boungou	No images available since mining started	12.007220	1.402220		
Bouroum	Correct	13.605260	(0.706630)		
Essakane	Correct	14.381760	0.076820		
Hounde	Correct	11.416000	(3.531000)		
Inata	Correct	14.365000	(1.304000)		
Kalsaka/Sega	Correct	13.190090	(1.990680)		
Karma	Slightly changed (7.3km)	13.664280	(2.349540)	13.613925	(2.295832)
Mana	Slightly changed (5.4km)	11.855650	(3.413150)	11.957261	(3.275263)
Poura	Correct	11.083330	(2.816670)		
Sassa	Correct				
Sega	Slightly changed (4.6km)	13.385560	(1.984080)	13.408395	(1.951453)
Taparko	Correct	13.531000	(0.346000)		
Yaramoko	Slightly changed (6.9km)	11.794770	(3.333430)	11.756087	(3.283170)
Youga	Correct	11.093470	(0.459770)		
Perkoa (zinc)	Correct	12.37222	(2.60361)		

Tab. 3C.2: Name and coordinates of industrial mines in Burkina Faso

3.D Replication of Bazillier and Girard

We first replicated Bazillier & Girard (2020) results to a reasonable degree (see Table 3D.1). Differences in the coefficients could be due to various assumptions and decisions taken during data cleaning. For example, the coordinates of the clusters from the LSMS data were defined manually and independently in both articles, which could cause some discrepancies in the location of households. In addition, we corrected various spelling errors, which caused some municipalities to be listed more than once under various names. Correcting this errors in the municipalities' names decrease the number of municipalities from 398 to 340. Since we use municipal fixed effects, this had a significant effect on some of the coefficients of interest.

Dep.var.: ln pc expenditure	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	Bazillier & Girard (2020)			**Our replication**		
Reference group: (Within 10km of an ASM license) × (1998)						
< 10km of an ASM license × 2003	0.037			0.062		
	0.056			0.046		
< 10km of an ASM license × 2009	0.224***			0.323***		
	0.093			0.081		
< 10km of an ASM license × 2014	0.153**			0.164***		
	0.064			0.054		
< 10km of an ASM license × gold boom		0.163***			0.202***	
		0.058			0.054	
< 10km of an ASM license × ln(gold price)			0.122*			0.145***
			0.043			0.040
< 10km of an ASM license	-0.11*	-0.088*	-0.79***	-0.09*	-0.06	-0.88***
	0.06	0.05	0.28	0.05	0.05	0.26
Observations	30,502	30,502	30,502	36,133	36,133	36,133
R-squared	0.380	0.380	0.379	0.606	0.605	0.605
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Municipal fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	Yes	Yes	Yes	Yes	Yes	Yes

Tab. 3D.1: Replication of Bazillier and Girard. Household controls include a binary variable if the household is in an urban area, the household size, and the literacy, sex and age of the household head. Households that are in the vicinity of an artisanal mine are within 10km of a known artisanal mine.

Lastly, both researchers received data on artisanal mining licenses directly from the Ministry of Mines in Ouagadougou. However, we do not know whether the data matches exactly, as it is not dated. In addition, we excluded data on non-gold mining license (such as granite), but Bazillier & Girard (2020) do not mention if they received information on the type of mining licenses or whether they included it in the analysis. The largest difference between our results and that of Bazillier and Girard is that we get a significantly higher R-square.

3.E Full results

	(1)	(2)	(3)	(4)	(5)	(6)
Dep variable	**ln(total asset index)**			**IHS(pc temptation exp.)**		
Model	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.1**	**Eq.1**	**Eq.2**
<10km of an ASM deposit	0.036	-0.638***	0.080**	-0.357***	-2.311***	-0.250*
	0.031	0.153	0.034	0.125	0.601	0.133
<10km deposit×goldboom	0.093***			0.414***		
	0.024			0.113		
<10km deposit×ln(goldprice)		0.112***			0.332***	
		0.023			0.090	
<10km of operating ASM			0.061*			0.366***
			0.031			0.127
Reference year: 2003						
2005	0.271***	0.259***	0.195***	-	-	-
	0.016	0.016	0.020			
2007	0.408***	0.411***	0.359***	-	-	-
	0.017	0.016	0.019			
2009	0.240***	0.229***	0.188***	-	-	-
	0.020	0.020	0.021			
2014	0.367***	0.344***	0.304***	0.550***	0.550***	0.651***
	0.018	0.019	0.021	0.074	0.074	0.067
Constant	0.555***	0.567***	0.791***	6.394***	6.394***	6.312***
	0.156	0.156	0.172	0.429	0.429	0.433
Observations	52,018	52,018	36,944	19,306	19,306	14,900
R-squared	0.473	0.474	0.468	0.171	0.171	0.143
Database used	Full	Full	Restricted	Full	Full	Restricted

Tab. 3E.1: World gold prices and artisanal mining on asset index score and temptation good expenditure. Dependant variables are the natural logarithm of an asset index score and the inverse hyperbolic sine transformation of temptation good expenditure. An ASM (artisanal and small-scale mine) deposit is a gold deposit that will be an artisanal mine in the final year of the database. An operating artisanal mine is an active mine. For Eq. 3.1 we use all household data, for Eq.3.2 we restrict the data to municipalities sampled in every year, exclude observations in 1998 and households close to an artisanal mine that was already operational in 2003 (see Section 3.4). All regression includes municipal fixed effects and household controls (household size, literacy, sex, and age of household head) and urban area. Table 3F.3 in Appendix 3.F show all results considering a control group of 10 to 20km from an artisanal deposit. Standard errors below coefficients. ***p <0.01, **p <0.05, *p <0.1.

Dep. variable: infant mortality	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Model	**Eq.1**	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.2**	**Eq.2**
Born <10km of an ASM deposit	-0.003	-0.002		0.005	0.004	
	0.005	0.005		0.005	0.005	
Born <10km deposit × goldboom	0.001	0.000	-0.033			-0.070
	0.004	0.004	0.039			0.045
Born <10km of operating ASM				-0.010	-0.009	
				0.006	0.006	
Reference wealth group: poorest						
Poorer		-0.004			-0.000	
		0.004			0.006	
Neutral		-0.003			0.001	
		0.004			0.006	
Richer		-0.007*			-0.012**	
		0.004			0.005	
Richest		-0.023***			-0.025***	
		-0.004			0.005	
Observations	40,101	27,934	3,388	19,100	18,799	1,574
Comparison	>10km	>10km	10-20km	>10km	>10km	10-20km
Mother fixed effects	No	No	Yes	No	No	Yes

Tab. 3E.2: Gold prices and artisanal mining on infant mortality. An ASM (artisanal and small-scale mine) deposit is a gold deposit that will be an artisanal mine in the final year of the database. An operating artisanal mine is an active mine. For Eq.3.1 we use all household data. In Eq.3.2 we restrict the data to municipalities sampled in every year, we exclude observations in 1998 due to limited satellite images to determine if a mine was already active and to allow for more temporal variation, we omit households close to an artisanal mine that was already operational in 2003. When we include mother fixed effects, we consider all mothers who live 20km from an artisanal deposit and had at least one child before the gold boom and at least one after (Eq.3.1) or at least one child before the specific mine in their area opened and one after(Eq.3.2). All analyses control for the child's sex and birth year, as well as urban areas when not controlling for mother fixed effects. All analysis with a 10-20km comparison group is shown in Table 3F.4. Standard errors below coefficients. ***p <0.01, **p <0.05, *p <0.1.

Dep variable: net school enrolment	**(1)**	**(2)**	**(3)**	**(4)**
Model	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.2**
Within 10km of an artisanal deposit	0.026***	0.029***	0.002	0.005
	0.008	0.008	0.009	0.009
Within 10km artisanal deposit × goldboom	-0.007	-0.009		
	0.007	0.007		
Within 10km of operating artisanal mine			0.022***	0.020**
			0.008	0.008
Reference wealth group: poorest				
Poorer		0.027***		0.032***
		0.004		0.006
Middle		0.070***		0.078***
		0.005		0.006
Rich		0.144***		0.155***
		0.005		0.006
Richest		0.270***		0.281***
		0.006		0.007
Observations	130,751	130,162	86,813	86,460

Tab. 3E.3: Marginal effects of gold price and artisanal mining on net school enrolment. An artisanal deposit is a gold deposit that will be an artisanal mine in the final year of the database. An operating artisanal mine is an active artisanal mine as determined by satellite images. For Eq. 1 we use all household data, for Eq.2 we restrict the data to households that are in municipalities sampled in every year and we exclude observations in 1998 due to limited satellite images to determine if a mine was already active and households close to an artisanal mine that was already operational in 2003, to allow for more temporal variation. Basic controls include child's sex, age, urban areas and birth year. Standard errors below coefficients. ***p <0.01, **p <0.05, *p <0.1.

3.F Robustness checks

Dep var: pc expenditure	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
Model:	**Eq.1**	**Eq.1**	**Eq.1**	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.2**	**Eq.2**	**Eq.2**	**Eq.2**
Comparison group (distance from ASM deposit):	**10-20km**	**10-30km**	**10-40km**	**10-50km**	**>10km**	**10-20km**	**10-30km**	**10-40km**	**10-50km**	**>10km**
< 10km of artisanal deposit	-0.005	-0.016	-0.013	-0.056	-0.060	0.080***	0.051**	0.056**	0.032	0.029
	0.049	0.043	0.041	0.042	0.040	0.025	0.024	0.023	0.023	0.023
< 10km of operating artisanal mine						-0.019	0.002	-0.004	0.037*	0.039*
						0.023	0.022	0.022	0.022	0.022
< 10km of ASM deposit X gold boom	0.111	0.115*	0.111**	0.186***	0.192***					
	0.068	0.059	0.055	0.056	0.052					
Constant	8.807***	8.824***	8.832***	8.854***	8.845***	8.903***	8.948***	8.952***	8.972***	8.962***
	0.061	0.053	0.050	0.048	0.046	0.072	0.072	0.072	0.072	0.072
Observations	23,628	27,043	29,048	33,256	36,133	15,355	17,630	18,831	21,830	23,227
R-squared	0.629	0.622	0.622	0.611	0.606	0.603	0.594	0.595	0.585	0.583

Tab. 3F.1: Comparison groups at various distances. An artisanal gold deposit, is a gold deposit that will be an artisanal mine in the final year of the database. An operating artisanal mine, is a deposit that is currently being exploited, meaning, the mine is operational in the specific year. The gold boom is all year after 2006, when the world gold prices increased significantly. All regression include household controls, including size of the household, literacy, sex and age of household head, and a binary variable to control for households in an urban area, year and municipality fixed effects. The treatment group are considered all households within 10km of an artisanal gold deposit. Standard errors below coefficients. ***p <0.01, **p <0.05, *p <0.1

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Model:	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.1**	**Eq.1**	**Eq.2**
Dependant variable:	**ln(per capita expenditure)**			**ln(total asset index score)**			**IHS(per capita temptation good exp)**		
Within 20km of ASM deposit	-0.166**	-1.116***	-0.109***	-0.143***	-0.701***	-0.039	-1.091***	-3.692***	-0.986***
	0.074	0.260	0.032	0.039	0.142	0.046	0.167	0.631	0.178
Within 20km of operating artisanal mine			0.056***			0.018			0.317***
			0.020			0.027			0.114
Within 20km of ASM deposit X gold boom	0.209***			0.084***			0.551***		
	0.051			0.022			0.117		
Within 20km of ASM deposit X ln(gold price)		0.165***			0.093***			0.441***	
		0.038			0.021			0.094	
Observations	36,133	36,133	21,534	52,018	52,018	33,692	19,306	19,306	14,900
R-squared	0.606	0.606	0.577	0.473	0.473	0.475	0.172	0.172	0.144

Tab. 3F.2: Treatment group at 20km threshold for all expenditure and assets. An artisanal gold deposit, is a gold deposit that will be an artisanal mine in the final year of the database. An operating artisanal mine, is a deposit that is currently being exploited, meaning, the mine is operational in the specific year. The gold boom is all year after 2006, when the world gold prices increased significantly. All regression include household controls, including size of the household, literacy, sex and age of household head, and a binary variable to control for households in an urban area and municipality and year fixed effects. The control group are considered all households farther than 20km from an artisanal gold deposit. Standard errors below coefficients. ***p <0.01, **p <0.05, *p <0.1

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Eq.1	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.1**	**Eq.1**	**Eq.2**
Dependent variables:	**ln(total asset index)**				**ln(pc expenditure)**			**IHS(pc temp. exp.)**		
<10km of an gold deposit	0.06	0.05	-0.56***	0.08**	-0.08***	-0.73***	-0.05**	-0.07	-0.24	-0.04
	0.04	0.03	0.20	0.04	0.02	0.12	0.03	0.14	0.78	0.15
<10km of an operating ASM				0.07*			0.10***			-0.06
				0.04			0.02			0.07
Gold boom X <10km of an ASM deposit	0.080**	0.07**			0.14***			0.04		
	0.03	0.03			0.02			0.15		
ln(gold price) X <10km of an ASM deposit			0.10***			0.11***			0.03	
			0.03			0.02			0.12	
Constant	0.45**	0.44***	0.46***	0.73***	9.03***	9.03***	9.00***	6.11***	6.11***	6.07***
	0.20	0.16	0.16	0.18	0.06	0.06	0.06	0.44	0.44	0.45
Observations	35,500	33,330	33,330	20,258	19,304	19,304	14,898	12,728	12,728	9,270
R-squared	0.47	0.42	0.42	0.40	0.72	0.72	0.71	0.21	0.21	0.19
Control group (distance from ASM deposit)	>10km	10-20km	10-20km	10-20km	>10km	>10km	>10km	10-20km	10-20km	10-20km
Dataset	Full	Full	Full	Restricted	Full	Full	Full	Full	Full	Restricted

Tab. 3F.3: Additional asset and temptation good expenditure analyses, including 10-20km control group. All regression include municipal and year fixed effects, and household controls. Column 1 allows for comparison with total household expenditure that does not have data on 2005 and 2007 (see column 4 in Table 3.1). Column 5-7 shows the impact on total household expenditure when excluding 1998 and 2009, to allow for comparison with the analysis on temptation good expenditure. In Eq.3.1 we use the full household dataset, for Eq.3.2 we restrict the data to households that are in municipalities sampled in every year and we exclude observations in 1998 and we exclude households close to an artisanal mine that was already operational in 2003 (see Section 3.4). Standard errors below coefficients ***p <0.01, **p <0.05, *p <0.1

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable	**Infant mortality**				**Net school enrolment**			
Model	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.2**	**Eq.1**	**Eq.1**	**Eq.2**	**Eq.2**
Within 10km of an artisanal deposit	0.001	0.001	0.005	0.004	0.042***	0.045***	0.000	0.003
	0.005	0.005	0.005	0.005	0.008	0.008	0.009	0.009
Within 10km artisanal deposit×goldboom	-0.006	-0.005			-0.031***	-0.034***		
	0.006	0.006			0.008	0.009		
Within 10km of operating ASM			-0.011*	-0.010			0.016*	0.014*
			0.007	0.007			0.008	0.009
Reference wealth group: poorest								
Poorer		-0.005		0.001		0.031***		0.036***
		0.004		0.006		0.005		0.007
Middle		-0.003		0.002		0.070***		0.078***
		0.004		0.006		0.005		0.007
Rich		-0.008*		-0.013**		0.150***		0.159***
		0.005		0.006		0.006		0.007
Richest		-0.026***		-0.029***		0.281***		0.294***
		0.005		0.006		0.007		0.009
Observations	27,934	27,546	13,079	12,877	90,677	90,249	59,735	59,492

Tab. 3F.4: Infant mortality and net school enrolment with 10-20km control group. All regression include municipal and year fixed effects (birth year for infant mortality and survey year for school enrolment), controlling for urban area and child's sex and age (school enrolment only). In Eq.3.1 we use the full household dataset, for Eq.3.2 we restrict the data to municipalities sampled in every year, exclude observations in 1998 and households close to an artisanal mine that was already operational in 2003 (see Section 3.4). Standard errors below coefficients ***p <0.01, **p <0.05, *p <0.1

Chapter 4

Assessing constraints to adopt protective behaviour against mercury on artisanal gold mines: knowledge, risk perception and access

Joint work with Désirée Ruppen, Bernhard Wehrli and Fritz Brugger

Abstract: Many artisanal miners use mercury, a toxic metal, to extract gold from ore. Despite severe health implications, miners seldom use personal protective equipment. In this study, we analyse artisanal miners' use of personal protection equipment and behaviour against mercury. We study the role of knowledge, perception of danger, and improved access to protection material on protective behaviour. We combine a survey with 276 miners with a field experiment on 209 miners on uptake of personal protective equipment and analysis of hair samples (to detect mercury exposure) from 179 miners. While many participants know mercury is dangerous, their general knowledge about mercury is relatively low; almost no participants mentioned the critical symptoms of mercury poisoning or how to protect themselves against mercury. Even though most miners believe mercury is dangerous to them personally, they do not assess their risk of mercury accurately; we find no significant correlation between actual contamination (measured by hair samples) and perceived dangers of mercury. Receiving gloves for free had a large and positive impact on usage five months and one year later, which have significant health benefits for individual miners. Traders could especially benefit from free protective equipment since they at higher risk of exposure.

4.1 Introduction

Artisanal miners, who usually operate informally, use labour-intensive methods, with little capital invest and work in extremely dangerous environments. While various studies have regarded the many hazards on an artisanal mine – such as health effects of cyanide (Knoblauch et al., 2020), dust inhalation (Gottesfeld et al., 2019), accidents and injuries (Long et al., 2015) – in a meta-analysis of health studies, Cossa et al. (2021) found most studies consider the health impacts of mercury. Artisanal gold miners use mercury to separate gold and other metals from ore. Not only is mercury readily available and affordable in many artisanal mining communities, but the method is also easy to use, requires little capital investment, and can be done anywhere.[1]

Given the popularity of using mercury, the estimated 16 million artisanal gold miners in the world are collectively the largest anthropogenic source of global mercury pollution (Fritz et al., 2018; Travnikov et al., 2015). Mercury is highly toxic and can cause a wide range of health issues, such as congenital disorders, liver damage, and deter neurological development. Children, women of reproductive age, breastfeeding, or pregnant are especially vulnerable to mercury poisoning (O'Neill & Telmer, 2017; Fritz et al., 2018). Steckling et al. (2017) estimated that the global disease burden of mercury exposure in artisanal mining alone is 1.2 to 2.4 million life-years lost due to ill health, disability, or early death, which was similar to the global disease burden of both hepatitis B and Parkinson's disease in 2015. Mercury is also harmful to the global environment because it can move great distances through waterways and the atmosphere, bio-accumulating in ecosystems (Travnikov et al., 2015).

The United Nations Environmental Program (UNEP) set up an agreement called the Minamata Convention in 2017 to protect people and the environment against anthropogenic mercury pollution (Federal Office for the Environment, 2017). One of the core elements of the Minamata Convention is that countries with artisanal gold mines should work towards the elimination of mercury in the sector by creating National Action Plans focused on technical support and formalisation (Federal Office for the Environment, 2017). Formalisation would allow governments to monitor sites and enforce best practices, as well as give miners access to formal credit sources, allowing them to invest in more effective or mercury-free extraction tech-

[1]Miners work mercury into ore, which allows the mercury and gold particles to bind together (or "amalgamate"), forming a clay-like gold and mercury alloy (or "gold amalgam") that is easy to remove, which miners then burn to evaporate the mercury. Mercury vapours are considered the most dangerous form of mercury, as the lungs absorb about 70 to 80% of the vapours, which are then transferred to the bloodstream, as opposed to only 2% of liquid mercury that is absorbed through the skin (Caravati et al., 2008). Mercury is released into the environmental either as liquid mercury when miners work it into the ore and especially as vapour when the gold amalgam is burnt (O'Neill & Telmer, 2017).

niques (such as chemical leaching) and machinery (such as ball mills, centrifugal or gravity separators) that could extract a higher percentage of the gold from ore and generate less waste (Hinton, 2005).

However, moving to a mercury-free artisanal mining sector is extremely difficult. On the one hand, miners face many constraints; for example, mercury-free methods require high capital investments and expertise. Large machinery could fix miners to one location while they are currently very mobile, e.g. miners continually move to new mines (Jønsson & Bryceson, 2009; Brugger & Zanetti, 2020). Unlike other methods — such as cyanide leaching, which involves a longer process that require bulk input of ore — using mercury to extract gold is a very transparent process. A recent study in Burkina Faso has shown that the transparency in the extraction process allows the person that financed the construction of a shaft to immediately access the gold at the moment of recovery, which allows them more control to secure their return on investment (A. Bugmann et al., 2022).

Meanwhile, miners are still using mercury daily, risking serious health problems to themselves and others. However, using the same techniques with mercury, miners could practice various cheap or free methods to protect themselves by using personal protective equipment (PPE) and numerous best-practice behaviour. PPE includes masks, gloves, and retorts[2]. Best practices include burning gold amalgams in the open away from people and houses, and storing equipment and clothes outside of the house. Although using proper protective equipment and following best practices would not necessarily reduce anthropogenic mercury pollution, it could have a significant effect on miners' health.

Despite mercury's substantial health impacts, miners in Burkina Faso and other countries seldom use PPE, such as masks, gloves, or retorts. Studying 192 miners on two artisanal mines in Burkina Faso, Sana et al. (2017) found 4.5%, 2.5%, and 0.5% of participants used gloves, dust masks, and goggles, respectively. Tomicic et al. (2011) conducted a large study on 1,090 miners on eight artisanal mine sites in Burkina Faso and found that PPE usage was very rare, 2% used gloves, and 12% used dust masks. In other countries, low levels of PPE were also observed among 211 miners in Sudan (Fadlallah et al., 2020), 110 to 500 miners in Ghana (Long et al., 2015; Afrifa et al., 2017; Aram et al., 2021), and 200 mines in Bolivia (Pavilonis et al., 2017).

Some studies hypothesise that miners' lack of knowledge about mercury reduces protective behaviour. Charles et al. (2013) show that the knowledge of mercury exposure is low in Tanzania; 41% of study participants were unaware of any health risks concerning mercury and the authors suggest that educational programs could improve protective behaviour. Researchers have also described various educational

[2]Retorts are devices used to capture the mercury vapour, which protects the burner and enable them to use mercury multiple times.

programs on mines: Ottenbros et al. (2019) quantified miners' knowledge of mercury and related health risks before and after a health education program in Suriname, and Veiga & Marshall (2017) and Metcalf & Veiga (2012) describe training courses or educational theatre productions on mines in Zimbabwe. However, none of these studies estimated the impact of changes in knowledge on protection behaviour.

Even miners who have high knowledge of mercury do not necessarily believe that mercury is dangerous to them personally. Using the psychometric paradigm – a psychological theory that systematically evaluates the biases when calculating personal risk (Fischhoff et al., 1978; Slovic, 1988) – Fadlallah et al. (2020) found that artisanal miners in Sudan perceived the mine as riskier if they were educated or had a higher income. Miners with more experience in artisanal mining perceived higher control and, therefore, lower perceived risk. However, even thought the authors also note low levels of PPE usage on the mines, they do not estimate the correlation between risk perception and protective behaviour.

Other studies suggest that miners know mercury is dangerous, also to them personally but miners do not have any other choice due to the lack of access to proper equipment (Aram et al., 2021; Fadlallah et al., 2020; Hilson & Pardie, 2006). The only study we are aware of that study determinants of protective behaviour on artisanal mines, is a cross-sectional study (n=500) by Aram et al. (2021) that found more educated miners in Ghana are less likely to do dangerous jobs, such as going down galleries or shafts. And that more educated and experienced miners and those in more efficient operations were more likely to have higher knowledge of the environmental and health impact of mercury. However, they found that miners in more effective operations still conducted unsafe mercury practices. Although the authors analysed which miners were more likely to be involved in safer jobs, they did not consider protective behaviour when involved in more dangerous jobs.

Although studies on personal protection on artisanal mines are scarce, literature on PPE usage and pesticides, also in low-income settings, is more common. This literature also show the importance of knowledge, risk perception and access to protective behaviour when using pesticides. Zapata Diomedi & Nauges (2016) in Papa New Guinea, Boadi-Kusi et al. (2016) and Okoffo et al. (2016) in Ghana and Memon et al. (2019) in Paksitan, found positive correlations between PPE usage and farmers' literacy or education. Similarly, researchers found that training had a positive impact on PPE usage in Greece (Damalas & Abdollahzadeh, 2016), Papa New Guinea (Zapata Diomedi & Nauges, 2016), and Pakistan (Memon et al., 2019). In Cameroon, knowing how to use pesticides correctly was correlated to higher PPE use (Oyekale, 2018). Studies had shown that farmers in Iran and Ghana were more likely to wear PPE when handling pesticides when they perceived the consequences of pesticides as severe (Rezaei et al., 2019; Okoffo et al., 2016). Levesque et al. (2012b) and Strong et al. (2008) found farm workers in the US were more likely to use PPE if the farmer provided it. Levesque et al. (2012a) also found workers were more likely to wash their hands after using pesticides if soap was available. Of course with all these studies on PPE and pesticides, causation could go in both directions or could be caused by a confounding factor.

We are not aware of any studies the evaluated the impact of knowledge, risk perception and specifically access to PPE on protective behaviour (such as reported preferences and usage of masks or gloves) in an artisanal mining setting. We believe this is a critical gap in the literature, since evaluating the impact of knowledge, risk perception and access to PPE on protective behaviour is vital for miners' health, at least in the short to medium term, while countries are still working towards a mercury-free artisanal mining sector.

In this study, we use survey data, a field experiment and biological sampling to analyse the impact of knowledge, risk perception and access to PPE of protective behaviour and exposure to mercury. We visited four artisanal mines in the Centre-Nord of Burkina Faso, where we conducted surveys with 276 miners, field experiment with 209 miners and collected hair samples from 179. We found that miners know that mercury is quite dangerous to their health, but critical knowledge of mercury, symptoms related to mercury poisoning and ways to avoid exposure are low. Although they take various preventive measures to protect themselves, many measures are not sufficient, such as covering the mouth and nose with a t-shirt when burning a gold amalgam. While we do not find a significant correlation between risk perception and reported PPE usage, knowledge about mercury and receiving PPE has a positive impact on reported usage. We find that gold and mercury traders were more likely than other participants to show high exposure to mercury and we recommend that traders need to be targeted first in any interventions to increase protective behaviour. Our results could help governments and other organisations to disseminate protective behaviour on artisanal mines more effectively.

4.2 Research design

4.2.1 Research design and data collection

From December 2018, terrorist activities have increased in the north of Burkina Faso bordering the Sahel. Considering the security situation and that we wanted to interview miners who use mercury (as opposed to digging-only or cyanide-leaching sites), our local partners (Sagrasy Consulting and Orcade) recommended we visit four relatively safe mine sites where mercury is commonly used and to which they have access to: Sandouré and Ronguin near Kongoussi, Zomnkalga near Séguénéga and Galong-Tenga near Tikaré (Figure 4.1). According to enumerators, there are about 150 miners on Galong-Tenga, 250 on Zomnkalga and between 300 and 500 miners on Sandouré and Ronguin. These sites are small compared to sites such as Alga, which hosts several thousand gold miners (Brugger & Zanetti, 2020). Due to the security situation, only Burkinabe enumerators were allowed to visit artisanal gold mines. Researchers from ETH Zürich were remotely managing the project from Ouagadougou and Zürich.

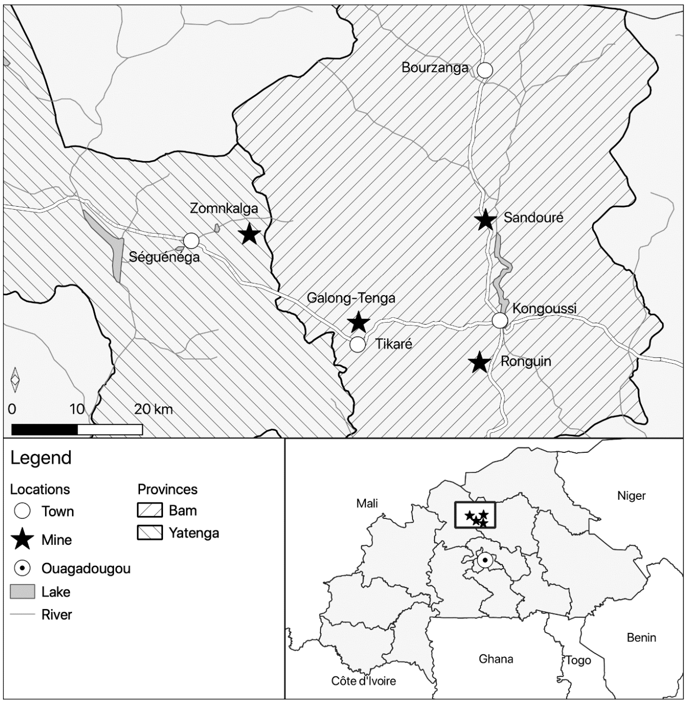


Fig. 4.1: Fieldwork study area. Location of four mining sites where we conducted fieldwork, Sandouré and Ronguin near Kongoussi, Galong-Tenga near Tikaré and Zomnkalga near Séguénéga

The first phase of the project took place between December 2019 and January 2020 and included a survey, a small field experiment, and the collection of hair samples (see Figure 4.2). The in-person survey included questions on, amongst others, participants' socio-demographics; how participants use mercury and PPE; participants' knowledge of and attitude towards mercury; and contact details (see Appendix 4.A).

After the survey, miners could participate in a lucky draw and either win a pair of gloves or a mask. Of all participants that took part in the field experiment, 54% received a pair of gloves, and 46% received a mask. Due to requirements from the ethical commissions, we did not have a strict control group of miners who did not receive anything and we needed to distribute PPE to all participants.[3] To ensure

[3]Two review boards, *Comité d'éthique institutionnel pour la recherche en sciences de la sante* (IRSS) in Burkina Faso (N/Ref. A38-2019/CEIRES) and the Ethics Commission at the ETH Zurich, Switzerland (2019-N-141) reviewed and approved the project.

that the lucky draw was truly random, we also conduct balance checks (see Table 4C.1 in Appendix 4.C). We do not find any significant difference between people who received the masks and gloves. We also asked participants if they plan to keep the gift or if they would give it away: almost all (98%) said they would use the gear themselves.

Participants were then informed of the hair sampling, which gives us an indication of mercury exposure and allows us to define a risk group of miners who have experienced unsafe exposure to mercury from all sources. Hair is a biological sample that is easy to sample, store, and transport, which are important in difficult and remote conditions. However hair also has two important limitations as an indicator of mercury exposure. First, it is not possible to differentiate between mercury that attaches to the hair externally and mercury that has entered the bloodstream through ingestion, inhalation or skin contact and is consequently incorporated into the structure of the hair as it grows (Esteban & Castaño, 2009; Laffont et al., 2011, see discussion in Appendix 4.D).

Second, hair more accurately indicates mercury contamination from organic sources such as fish consumption than inorganic sources such as mercury vapours released during the burning of a gold amalgam. However, Compaore et al. (2020) did not find that any significant difference in fish consumption in six villages in Burkina Faso. The authors also confirm their data on fish consumption is similar to previous studies. A study by Ouédraogo & Amyot (2013) analysed commonly consumed fish in Burkina Faso, and found that although certain fish species (specifically fish that mainly eat other fish), were more likely to have mercury above safe limits, most fish had relatively low levels of mercury. We therefore believe that the majority of the variation in the levels of mercury in the hair would be caused by occupational exposure from artisanal mining. We assume other pathways of exposure are minimal, including dermal contact with mercury iodide- containing soaps, shampoos and skin-lightening creams (Glahder et al., 1999), mercury in pesticides or dental amalgam fillings (CONTAM, 2012).

Due to the cultural sensitivities with biological samples, we consulted with our local partners if they prefer to take hair or fingernail samples and how the samples should be collected. Our local partner preferred hair samples and advised that we should collect the samples in a similar way to how people usually cut their hair. We, therefore, acquired the help of a local hairdresser on each site. A Burkinabe medical student was trained in how to collect the hair samples in order to avoid contamination between samples and assisted the local hairdresser. A Burkinabe toxicologist was also present for two days to verify that the hair samples were collected correctly. Samples were conserved in sealable plastic bags and sent to ETH Zürich for analysis (see Appendix 4.D for sampling procedures and analytical methods).

We conducted two rounds of follow-up phone surveys five months and one year after the baseline survey. The primary goal of the follow-up phone surveys was to monitor reported mask and gloves usage. Meaning, we recorded reported ownership and usage of masks and gloves three times: at baseline, five months later and one year later. In the first follow-up survey, we also told miners that we would return to the mines in a few months and give them another gift and that they could choose if they prefer a mask, gloves or a bar of soap. We recorded their stated gift preferences. As required by the ethical commission, directly after recording their gift preference we gave them information that emphasised the dangers of mercury vapour and the importance of wearing masks (all miners received the same information) and participants were then given the option to change their choice. For more information on the follow-up surveys, see Appendix 4.A.

During the final visit to the mines, a team of three enumerators gave miners more information about the study, individual feedback on the hair analysis, and a short training session on mercury and how to avoid exposure (see Appendix 4.E). During the final field visit, we also gave out gifts (masks, gloves or soap); unlike the first round when masks and gloves were randomly allocated by lucky draw, miners could choose the gift they preferred, and we recorded their preferences.

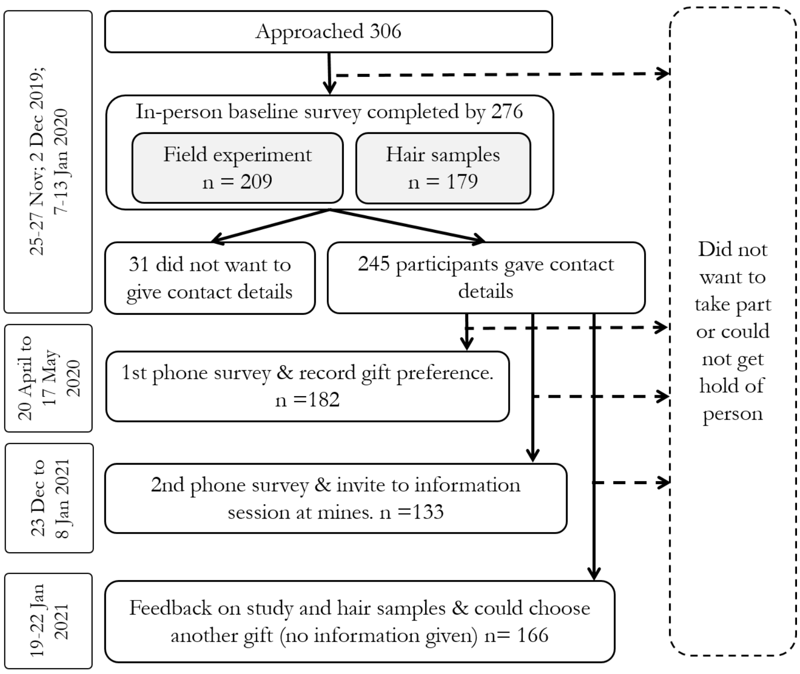


Fig. 4.2: Research design and sampling details

4.2.2 Sampling and sample size

Given the informality of artisanal mines, no formal structure on the mine or record of workers exist. Moreover, artisanal miners are sceptical of visitors, fearing that they are from the government trying to stop their activities or from an industrial mine exploring the area for possible expansion of mining activities, which meant that enumerators' movements were restricted. This made a pure random sampling impossible.

We, therefore, needed to resort to a combination of a geographic systematic sampling technique and snow-ball sampling technique. All enumerators identified a central point on the mine that the local partner considered a safe point from which enumerators can spread out. From this central point, enumerators would then split up into four perpendicular directions. An enumerator would walk in their dedicated direction until they cross paths with a miner, they would then introduced himself to the participant, give a short description of the study, and ask if the participant is willing to take part in the survey. Since miners often work in groups, the enumerator would also ask the first miners to suggest other members of their group that want to take part in the survey. If no more miners in the group wanted to take part in the surveys, the enumerator continued on the original axis that he walked on to approach the next participant.

Due to security concerns, and our local partners' availability, we could only spend about four days per mine site. In the available time, the team approached 302 miners on four mines, of whom 26 (8.6%) did not want to take part in the study. Enumerators surveyed 52 people at Galong-Tenga, which enumerators estimate is about 30% of the total mining population, 64 people at Sandouré (estimated 10-25% of mine population), 88 people at Ronguin (estimated 20-30% of mine population), and 72 people at Zomnkalga (estimated 30% of mine population). Although our purpose was not to identify a representative sample of all artisanal miners in Burkina Faso, sampling about 300 miners from four different sites gave us some heterogeneity and variation to study the knowledge, risk perception and practices regarding PPE and mercury.[4]

All participants that were willing to participate in the baseline survey (n=276) completed the entire survey. After completing the survey, participants could take part in the field experiment and win a pair of gloves or mask by drawing a ticket from a bag. Due to discussions with the local partner and logistical issues, we only conducted the field experiment on three of the four sites, with a sample size of 209. Given that we have two groups in the field experiment (no pure control group because of ethical reasons), and that initial mask and gloves ownership was low with about 10% and 5% respectively, we estimated that with a minimum detectable effect size of 20 percentage points increase in mask and glove ownership, with 80% power

[4]Other studies that collected primary data on artisanal gold mines in Burkina Faso had similar sample sizes, including 237 miners from four mines (Brugger & Zanetti, 2020), 200 miners from two mines (Sana et al., 2017), 162 miners on one mine (Black et al., 2017), and 153 miners from three mines (Ouédraogo & Amyot, 2013). However, Tomicic et al. (2011) and Pokorny et al. (2019) recorded much larger sample sizes of 1090 and 600, respectively.

and at 5% significance level, we would need a sample size of 124.

Participants were informed of the hair sampling after the survey; of the 276 people that took part in the survey, 179 were willing to give a hair sample.

Of the 276 that completed the survey, 245 gave their contact details (phone numbers; see Figure 4.2). After giving their contact details, enumerators immediately dialled the number to confirm that it works before capturing it on the survey. Of the 245 that gave contact details, we reached 182 people on the phone for the first follow-up, of which four did not want to participate, and the other 59 could not be reached. During the second round of follow-up phone surveys, we reached 133 people (of 245 who gave their contact details) of which four did not want to participate.

We had a high attrition rate between survey rounds of about 25.7% to the second survey round of which 11.0% of numbers were invalid, and 14.7% of participants could not be reached (voicemail or rang without answer). From baseline to the third survey round we had an attrition rate of 46.3% of which 12.2% were invalid numbers and 33.5% could not be reached.

A meta-analysis of phone surveys found that computer-assisted telephone interviews with multiple waves, similar to our survey, had on average an attrition rate of about 25% from baseline to the first survey round (Gibson et al., 2017). This ranged from surveys with 98% completion rate over 14 waves for a phone survey in Tanzania (Dillon, 2012) to 70% attrition over two survey waves during a phone survey in Liberia (Himelein & Kastelic, 2021). According to the enumerator who conducted the phone survey in our study, the high attrition rate in our sample could be due to various reasons, including that people work long hours on the mines and are difficult to get hold of; problems with mobile coverage in rural areas; and changing contact details due to migration.

We used an inverse probability weight to reduce a potential attrition bias between rounds. We conducted two logit regression analyses to determine the correlation between working on a specific mine site, age of participant, gender, literacy, years' experience and having children younger than 15 and the likelihood to complete the second or third survey rounds, as well as attend the final fieldwork session (see Table 4B.1 in Appendix 4.B). For the second survey round, we find that people from Zomnkalga (compared to participants from Sandouré), and those with children younger than 15 were less likely to take part in the second round. In the third survey round, we only found that people from Ronguin were less likely to take part in the survey (compared to participants from Sandouré). While participants from Ronguin (compared to Sandouré) were less likely to attend the final feedback session, older participants and those with children were more likely to attend. To address potential attrition bias, we use the inverse of these fitted probabilities as weights in the all regression analyses.

4.2.3 Analytical approach

In order to understand why miners do not use the necessary PPE when handling mercury, we evaluated the following three hypotheses. Miners do not use PPE when handling mercury due to:

1. lack of knowledge, i.e. miners do not know how dangerous mercury is or how to properly protect themselves;
2. personal risk perceptions, i.e. miners do not believe they are personally at risk of being exposed to harmful levels of mercury; and
3. low access to equipment or budget constraints, i.e. miners do not have the ability or opportunity to acquire PPE.

First, to quantify knowledge of mercury, we conduct a principal component analysis with the data from six factual questions asked in the survey to create an index that shows the knowledge of mercury expressed as a single composite variable.

Second, we use various survey questions to understand miners' perceptions of various hazards on the mine, including mercury. In order to determine if miners accurately internalise their personal risks, we correlate personal risk perception to actual levels of exposure (measured by the mercury content in hair samples). And we determine miners' biases when evaluating their personal risk by regressing miners' perception of the dangers with various covariates.

Third, we ask miners about the availability of PPE for purchase on the mine, and their willingness to pay for it. We then use the baseline survey and two follow-up phone surveys to create a panel dataset with three periods to determine the impact of receiving masks and gloves in the field experiment on reported ownership and usage.

Finally, we identify determinants – including knowledge, risk perception and access – of miners' preferences for PPE (both stated and revealed) and miners' reported usage of PPE and best practices. With a multinomial logistic regression, we determine the likelihood that miners said they preferred masks or gloves (compared to soap), and the likelihood that miners chose masks and gloves (compared to soap) when given an actual choice. With a multiple logistic regression, we show the correlation between reported use of PPE (masks and gloves) and best practices, and various covariates, including and knowledge, risk perception and access.

After evaluating which factors inhibit PPE usage by testing the three hypotheses, we use the hair samples to identify the group particularly at risk of mercury exposure, in order to design targeted interventions.

4.2.4 Characteristics of miners

Although miners of all ages work on the mines, 92% of miners are younger than 50, with an average age of 32 years, while the median age on the mine is 33, the median age in the country is 17 years (Ritchie & Roser, 2019). The majority are male (91%). Although a third of all artisanal miners in Burkina Faso are female (DeJong, 2019; ANEEMAS & Effigis Geo-Solutions Inc., 2018), the percentage of women is site-dependent. Some sites have no women or as little as 5%; other sites with less lucrative low-grade ore (such as mining in tailings) consist primarily of women and children. In general, the physically demanding work on the mines favour young men, even actively forbidding women to do certain jobs such as going down in mineshafts. The women in our study were involved in various activities on the mine, including using mercury, crushing rocks, and selling items on the mine (see Table 4.1). Of the 24 women in the sample, five reported that they are pregnant, another six were breastfeeding, and of all the participants, 73% reported that they have children younger than 15 years.

Most of the miners are not literate and have very low levels of schooling; 71% did not attend any schooling, while only 1% completed secondary school (the highest reported level of education). Although schooling is similar to national averages as identified in the Demographics and Health Surveys in 2010 (INSD and ICF International, 2012b), literacy rates in our sample are almost half of the national average of people older than 15 in 2018 (World Bank, 2021). This could indicate that artisanal mining activities disproportionately attract illiterate workers.

The UN Economic Commission for Africa's report on mineral regimes in Africa (UNECA, 2011) reports an average of five people dependant on the income of one miner. We find that this is slightly higher in our study area, with 36% of miners stating that one to five people depend on their income and 64% reporting that six or more people are dependent on their income.

Many miners (44.6%) started working on the specific artisanal mine in 2015, and 23.9% started working before 2005. About 75% of participants have worked on other artisanal mine sites, of whom 27% have worked on five to nine and 15% on ten or more other artisanal mines. There is some spillover from industrial mines to artisanal mining; 15% of participants said they previously worked on an industrial mine. The length of a working day on the mine differs significantly: ranging from one hour to more than 12 hours. If the participants who reported working "more than 12 hours per day" were assumed as 13 hours, on their previous working day, participants worked on average 8.2 hours, and the median is eight hours.

Of all participants, 65.9% said they used mercury in the last month, of which 41.3% said they use mercury at least once per week. Of all participants, 55 (20.0%) reported that they felt sick during the last week. Of these participants, 74.5%

	Study participants	Burkina Faso
Median age	33	17
Gender (percentage male)	91.3%	49.9%
Schooling		
No schooling	71.0%	69.8%
Primary education incomplete	10.9%	20.2%
Primary education completed	6.5%	2.7%
Secondary education incomplete	10.5%	6.3%
Secondary education completed	1.1%	0.3%
Any tertiary education	0%	0.5%
Literacy rate	24.7%	41.2%
Used mercury in the last month	65.9%	-
Job description		
Activities that include contact with mercury	39.7%	-
Making mercury and gold ball	*38.8%*	-
Burn gold amalgama	*19.9%*	-
Mercury and gold trader	*5.4%*	-
Other mining jobs	85.9%	-
Other non-mining jobs	42.0%	-

Tab. 4.1: Characteristics of participants, reported jobs and national statistics for Burkina Faso. National data of gender is from 2019, literacy is from 2018 (World Bank, 2021), median age is from 2015 (Ritchie & Roser, 2019) and all schooling data is based on the large-scale representative DHS study for the year 2010 (INSD and ICF International, 2012b). Participants were involved in multiple jobs on the mine. The most common mining job (not involving mercury) involved digging, crushing, milling and grinding ore and cyanide leaching. The most common non-mining jobs on the mine involve pit owners and various merchants

attributed their illness due to something in the mine: dust (46.2%) and heavy work (35.9%). Three participants (7.7%) said they were sick due to mercury.

Participants reported doing the jobs listed in Table 4.1. The average participant reported to be involved in 3.1 jobs, 39.7% of participants are involved in at least one job where they have direct contact with mercury, about 19.9% are involved in heating the gold amalgam. Different jobs cause different levels of mercury exposure: burning amalgamation is considered very high risk (De Barros Santos et al., 2017; Black et al., 2017), and working mercury into ore has lower exposure risk than burning the gold amalgam (Caravati et al., 2008). Local gold traders are individuals that buy gold from miners on a few mines, and then sell the gold to larger regional traders (Grätz, 2004). In Burkina Faso, gold traders are often present at the burning of the gold amalgam, to oversee the process, weigh the gold and make the miners an offer.

Gold traders are therefore also at risk of mercury exposure.

Gold traders are also important in the mercury trade; the majority (91%) of miners get mercury from their gold trader. Gold traders use mercury as a promotional item to ensure they increase the number of miners that would sell gold to them by giving mercury out for free if a miner promises to sell their gold to them later (A. Bugmann et al., 2022; Hilson & Pardie, 2006). About half of the participants that used mercury in the last month reported that they got mercury for free.

4.3 Results

4.3.1 Lack of protective behaviour

We asked miners about their current protective behaviour; 13% of participants said they do not do anything to protect themselves from mercury (see Figure 4.3). While the best would be never to attend mercury burnings, as mercury fumes are considered the most dangerous form of mercury, only 3% said that they never attend the burning of the gold amalgam. The most common way people protect themselves is by standing clear from the burning, putting a t-shirt over their mouth and nose, or standing in the opposite wind direction (see Figure 4.3). However, all of these measures are considered insufficient protection against mercury vapours (Black et al., 2017). Many people use dust or cloth masks when burning mercury, which would also not give sufficient protection (Tomicic et al., 2011).

We also find low levels of PPE usage, reported usage in the last month of masks, gloves, goggles, and helmets were 10.2%, 4.6%, 6.9% and 0.9%, respectively. Even before COVID-19, masks are the most commonly owned and used PPE, since it can also be used against dust. However, cloth or dust masks will not give adequate protection against mercury vapour. While we did not ask miners exactly what type of mask they have available, the recommended masks for protection against mercury vapour (masks with activated carbon filters) are expensive and not commonly available for purchase in Burkina Faso.

The second highest reported used and owned PPE is goggles, which are also used for protection when using dynamite. Participants that reported using gloves in the last month (2%) used it mainly when handling mercury (41%), ore (40%), and cyanide (36%; multiple answers possible). Although various previous studies have reported that miners do not like using retorts (Jønsson et al., 2013; Childs, 2010, 2008; Hilson & Pardie, 2006), most participants in our study (97%) have never heard of a retort. Similar to other studies (Sana et al., 2017; Tomicic et al., 2011; Fadlallah et al., 2020; Aram et al., 2021), we find low level of PPE usage and personal protective behaviour on the mines. In the following sections we evaluate possible reasons for the low levels of protective behaviour, specifically, the role of knowledge, risk perception and access to equipment.

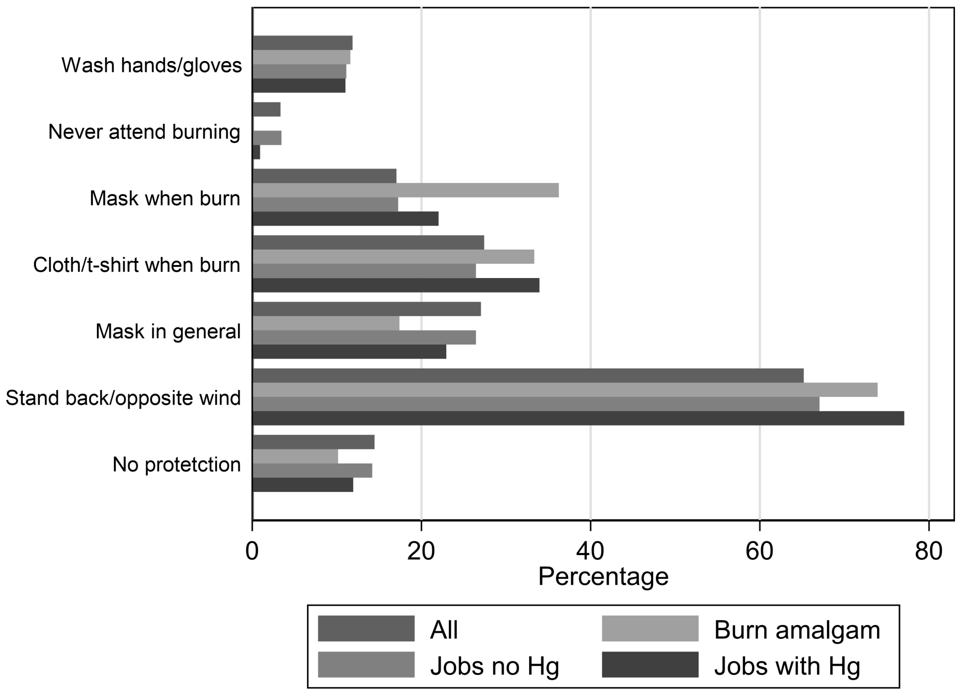


Fig. 4.3: Percentage of participants mentioning various protective measures against mercury. Multiple answers were possible.

4.3.2 Lack of knowledge

While knowledge of mercury and protection strategies alone probably do not lead to improved behaviour, it is a necessary step toward safer practices (Aram et al., 2021). Many miners said that they attended training or educational theatres about mine safety, or heard of mine safety on the radio in the past. More than half of participants (58.6%) said they have heard about mine safety on local radio, 52.7% attended an educational theatre, and 19.9% attended safety training on the mine. Of all participants, 14.3% received information from all these sources, and 25.5% have not received any information or training on mining safety.

Despite many miners reportedly attending training or educational theatre on mine safety, we found that general knowledge of mercury is low, similar to miners in Tanzania (Charles et al., 2013) but lower than miners in Suriname (Ottenbros et al., 2019). Only 35% of participants said they have ever heard of mercury poisoning. Although some symptoms of mercury poisoning could be managed with medication, mercury poisoning cannot be cured. Of all the participants that have ever heard of mercury poisoning, only 21% said that it can definitely not be treated. Participants mentioned treatments such as medication from the health clinic, or a milky drink, called *lait bonnet rouge*.

Miners were also not well informed of the symptoms; 73% of miners could not name any symptoms related to mercury poisoning. The most commonly named symptoms of mercury poisoning were respiratory issues such as coughing (mentioned by 15%), tightness in the chest (14%), as well as fatigue (11%). Very few people identified the symptoms that are identified by the World Health Organisation (World Health Organisation, 2017): tremors (mentioned by 3%), insomnia (mentioned by 0.7%, although 11% mentioned fatigue), headaches (mentioned by 9%), and no participants mentioned memory loss, neuromuscular effects, motor dysfunction, neurological and behavioural disorders, or congenital disorders (health effects for foetuses), or any development issues in children.

Most participants knew that mercury is not biodegradable when thrown into water (79%) or on the ground (77%). Fewer participants realised that this is also the case when burning mercury: 80% of participants said mercury disappears when it is burnt.

We also find relatively low levels of knowledge on protective behaviour. Only 33.0% of participants correctly said that the safest place to burn mercury is outside away from other people. Other participants said the safest place is outside anywhere on the mine site (25.7%), 33.7% said inside, which is considered the worst practice (although some specified that the house needs to be well-ventilated), and 7.6% did not know.

Although cyanide leaching is more effective than mercury to extract gold (cyanide can extract up to 90% of gold and mercury typically extracts 30-40%; DeJong, 2019), 27.1% of participants thought that mercury is a more efficient method to extract ore and 13.7% did not know. Although most participants knew cyanide is more effective, 75% of participants still believe that mercury is efficient enough to extract almost all or a lot of the gold out of the ore.

Using the six factual questions that we asked miners about mercury (see Table 4.2), we used a principal component analysis (PCA) to create a composite variable to indicate miners' knowledge about mercury. Since a PCA is sensitive to the range of input variables, we made all the input variables binary, except total symptoms identified, which we standardised on a scale from zero to one by dividing the variable by seven, the maximum number of symptoms any one participant identified.

In Appendix 4.F, we show the factor loading on the composite variable on the knowledge of mercury (see Table 4F.1). The first three factor analyses have Eigenvalues larger than one and explain 58% of the data's variance. We also show the density distribution of the index scores of the first three factor loadings with Eigenvalues larger than one. We use the second factor analysis that has a relatively normal distribution (see Figure 4F.1) and has a similar Eigenvalue to the first factor loading. We use the index score again to determine the impact of knowledge on perceived risk and reported usage of PPE (Sections 4.3.3 and 4.3.5).

Question	Correct answer	Percentage answered correctly
True or false: Mercury never disappears	True	25.7%
When is mercury most dangerous?	When burnt (mercury vapour)	89.5%
Where is the safest place to burn mercury	Outdoors, away from other people	33.0%
What is the cure for mercury poisoning?	There is no cure	7.3%
Do mercury or cyanide extracts the most gold?	Cyanide	59.2%
What are the symptoms of mercury poisoning?	WHO lists at least 14 symptoms	0.86 symptoms named on average

Tab. 4.2: Factual questions asked to miners in baseline survey.

4.3.3 Risk perception

Merely knowing facts about mercury would not lead to increase protective behaviour, if miners do not believe those risks apply to them personally. Artisanal mines are high-risk working environments, when we asked the miners what they think is the most dangerous thing on the mine, 23.6% said landslides, followed by shaft collapses (16.7%), dust (10.9%), cyanide (9.5%), digging (7.3%) and mercury (7.3%). Unlike landslides, shaft collapses, and other accidents, mercury exposure often does not have immediate consequence.

In order to determine perceived personal risk of mercury contamination, miners need to consider various parameters, including the number of times they have been exposed to mercury, the severity, and type of exposure (liquid mercury or mercury vapour), and the potential consequences for them personally. However, this is very difficult, since mercury vapour is a colourless and odourless gas and not observable in the surrounding environment, as opposed to other heavy metal pollution that can change the watercolour in rivers, kill fish and livestock. Despite the difficulties to assess mercury's danger, the majority of miners (63.9%) said that mercury is quite or very dangerous to their health.

We also asked respondents how likely they are to be contaminated by mercury, as well as, how likely it is that the people around them will be contaminated by mercury. People could answer on a five-point Likert scale, from extremely unlikely to extremely likely. On average, people thought they had a neutral to moderate likelihood of contamination and the average person had a neutral to moderate unlikelihood of contaminated. Figure 4.4 shows the difference between participants' perception of their personal risk of contamination and the contamination risk other people on the mine, called general risk (Sjöberg, 2003). A difference of zero means they access their personal risk similar to everyone else's. Positive values means that they think they are more likely to be contaminated than the average person on the mine, and less than zero means that they think their risk of contamination is less than the average person's. In general, we find that people thought they were personally at more risk than the average person on the mine.

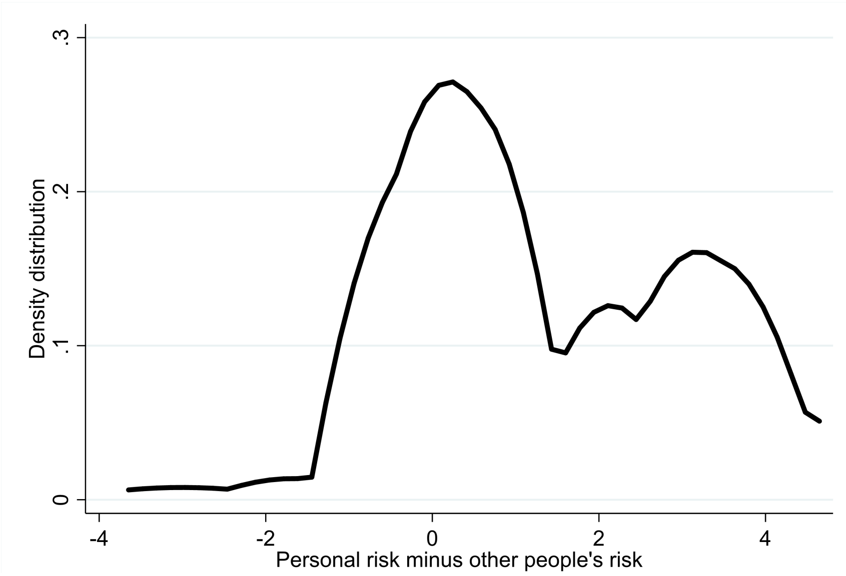


Fig. 4.4: Difference between perception of personal and general risk of mercury contamination. We asked participants on a five-point scale both what their person risk of mercury contamination is and what the contamination risk is of other people on the mine. The graph shows the difference between personal risk and other people's risk.

Personal risk perception and actual contamination of mercury are not significantly correlated (as measured with the hair samples).[5] Meaning, we do not find any indication that miners have accurately internalised their risks of mercury contamination; those who are more exposed to mercury are not significantly more likely to believe that mercury is dangerous to them personally. In order to understand what drives personal risk perception we conduct a multiple logistic regression model with a dependant variable that is equal to one if the participant said mercury is very or quite dangerous to them personally (top two points of a five-point Likert scale) against various independent variables as identified by the psychometric paradigm. According to the psychometric paradigm, miners should perceive mercury as more dangerous if they have higher knowledge, less familiar with mercury or do not receive

[5]Correlation between binary variable, thinking mercury is very or quite dangerous to them personally, and binary variable if mercury in hair above 1ppm, (1ppm is considered low exposure) is 0.05 (p-value 0.504). For more information on measuring mercury in hair, see Section 4.3.6 and Appendix 4.D.

a lot of benefits from using mercury.

To quantify knowledge, we use the index of mercury's knowledge calculated in Section 4.3.2. To quantify familiarity with using mercury, we include years' experience in artisanal mining and how often miners reportedly used mercury. We also include the type of job the miners are involved in. To quantify possible benefits from mercury, we add two binary variables, one if the miners think mercury remove a lot or almost all of the gold from ore and another if miners receive mercury for free.

Table 4.3 show the marginal effects at the means of the likelihood that miners thought mercury is very or quite dangerous to them personally. We do not find that knowledge or literacy has any significant impact on perceived dangers of mercury. Contrary to psychometric paradigm and results from Fadlallah et al. (2020), we find that miners with more years' experience in mining, are 1.2% more likely to think mercury is dangerous to them personally (significant on the 5%-level). However, years' experience refer to artisanal mining in general and not using mercury specifically, which could explain the difference to Fadlallah et al. (2020) and the psychometric paradigm, who narrowly referred to the experience and risk perception in the same activity. In line with the psychometric paradigm, we find that people more familiar with mercury (using mercury almost every day), is 18% less likely to perceive it as dangerous to them personally. Interestingly, getting mercury for free is associated with an almost 30% higher likelihood of perceiving it as dangerous. Although receiving mercury for free is an additional benefit of using mercury, which according to the psychometric paradigm should lead to lower perceive risk, it could be that miners feel they have less choice in what chemical to use and therefore less control, leading to higher perceived risk.

Lastly, our results suggest that miners underestimate some of the risks of mercury. Many do not believe mercury's biggest negative impact is on people; when we asked participants what they think is mercury's most significant negative impact, 52.2% said air pollution, 34.4% said poisoning people, 4.0% said water pollution, 3.6% said polluting food and 5.8% did not know. We showed participants a picture of an artisanal mine with a men sitting burning a gold amalgam, with children, a pregnant woman and other people in the vicinity (see Figure 4G.2 in Appendix 4.G). We first asked the participants who on the picture can be exposed to mercury (multiple answers possible), and as a follow-up question, we asked for whom on the picture mercury is most dangerous (only one answer option possible). While almost everybody identified that the people at the burning could be exposed to mercury (96%, Figure 4G.2), only half of the participants identified another group. In principle, all groups on the picture are at risk, even if not directly involved in the burning process. Most participants said mercury is the most dangerous to people at the burning. This corresponds to what is considered the most hazardous mercury-

Dependent binary variable:	**Mercury is very or quite dangerous to me personally**
Female	0.052
	(0.094)
Age in years	0.001
	(0.003)
Can read or write	-0.065
	(0.069)
Index score: knowledge of mercury	0.017
	(0.034)
Years' experience in artisanal mining	0.012**
	(0.006)
Use mercury almost every day	-0.180**
	(0.078)
Get mercury for free	0.295***
	(0.050)
Mercury extract a lot or almost all the gold	-0.093
	(0.089)
Job that involves mercury	
Burn gold amalgams	0.097
	(0.082)
Work mercury into ore	0.004
	(0.085)
Sell gold and/or mercury	0.108
	(0.092)
Observations	219

Tab. 4.3: Drivers of personal risk perception. Logistic regression analysis that shows the marginal effects of various variables on likelihood that miners think mercury is very of quite dangerous to them personally. Standard errors in brackets, *** $p<0.001$ ** $p<0.05$ * $p<0.1$

related activity. Participants also identified that mercury is most dangerous to pregnant women, who are considered one of the most vulnerable groups (46.7%; see Figure 4G.2 in Appendix 4.G). However, few people mentioned children (4.7%), who are also considered vulnerable to mercury poisoning since they are still developing.

Therefore, most miners know mercury is dangerous to them personally, even more so than the average person on the mine, which is interesting since people tend to underestimate their own personal risk compared to the risk of others (Sjöberg, 2003). However, miners do not accurately predict their own risks, miners who thought mercury was more dangerous to them personally, were not more likely to have experienced high exposure to mercury (as measured in the hair samples). Instead, we find some biases when estimated personal risk, specifically miners who use mercury frequently are more likely to think it is not dangerous to them personally. And miners who receive mercury for free, perceive it as more dangerous, possibly because they experience lower perceived control. We also find evidence that miners underestimate children as high-risk group.

4.3.4 Access to protective equipment

Miners can only sufficiently protect themselves against mercury if, in addition to sufficient knowledge of mercury and perceiving it as dangerous to them personally, they also have access to the proper equipment. When we asked miners what is available for them to purchase on the mine, the most common items available for purchase on the mine are extractive equipment, specifically pickaxes and shovels, followed by PPE (masks and gloves). Larger equipment like sluice boxes and crushing machines are not commonly available. Only 2% of participants said retorts are available for purchase (Figure 4.5).

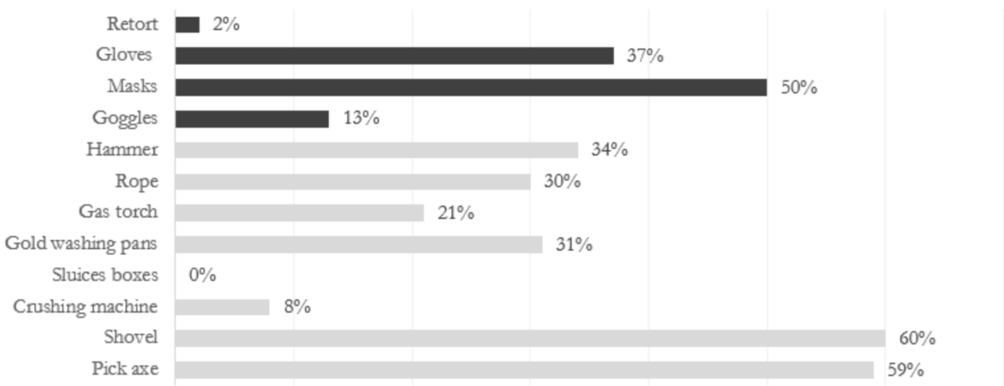


Fig. 4.5: Equipment available to purchase on the mine. Darker grey bars indicate various PPE, lighter grey bars are general extractive equipment.

Miners face budget constraints; while 97% said they are willing to buy a mask for XOF 300 (0.5 USD), only 15% were still willing to buy a mask for XOF 500 (0.9 USD). However, even for XOF 500, miners would only be able to purchase a disposable dust or cloth mask that would not give protection against mercury vapour. The proper activated carbon masks, which is at least 50 times more expensive, is not readily for sale in Burkina Faso.

Miners were willing to pay a bit more for gloves; for XOF 400 (0.70 USD) 97% of miners said they will buy gloves but this decreased to 50% if gloves are XOF 800 (1.4 USD). It would probably be easier for miners to find the proper gloves; any plastic glove would give adequate protection against liquid mercury, but thicker gloves are preferable when working with coarse material like ore.

During the experiment, participants could randomly win a pair of gloves or masks by drawing a ticket from a bag. We find glove recipients were 1.7 to 2.1 times more likely to report that they own gloves in the second and third rounds than mask recipients (1% significance level; columns 1 and 2, Table 4.4). This is an indication that giving out PPE increases ownership, even a year after distribution. However, due to mandatory mask usage during the COVID-19 pandemic, ownership of masks increased from 8% to 98%. Therefore, mask recipients were not more likely to own a mask in subsequent rounds than participants that received gloves (columns 3 and 4, Table 4.4).

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
	Own gloves		**Own a mask**		**Used gloves in last month**		**Used a mask in the last month**	
Gloves recipient	1.727***	2.082***			1.712***	2.220***		
	(0.354)	(0.384)			(0.357)	(0.386)		
Mask recipient			-0.0402	0.0489			0.00481	0.0533
			(0.263)	(0.294)			(0.263)	(0.294)
Observations	311	394	311	394	311	394	311	394
Number of people	179	179	179	179	179	179	179	179
Period	5 mths	1 year	5 mths	1 year	5 mths	1 year	5 mths	1 year

Tab. 4.4: Receiving PPE on reported ownership and usage. Marginal effects of receiving PPE and owning the same equipment five months and one year later, columns 1 to 4. The marginal effects of receiving PPE and reportedly using it in the last months, columns 5 to 8. Standard errors in brackets, *** p<0.001 ** p<0.05 * p<0.1

Although receiving gloves leads to higher ownership, owning PPE does not necessarily mean miners use it. In the baseline survey and both the follow-up surveys, we asked miners if they used the specific equipment in the previous month (binary variable equal to one if miners reportedly use the PPE). A logistic regression analysis showed that people who received gloves were 1.7 to 2.2 more likely to report using it in the last month (significant on the 1% level; columns 5 and 6, Table 4.4). Of those who did not use gloves, 57% said that they do not own gloves, 8% said their gloves broke, 4% said they do not currently do a job that requires gloves, 3% do not know why and one person said the gloves are uncomfortable (they are too big). However, receiving a mask did not have a significant impact on the likelihood that it was used in the last month (columns 7 and 8, Table 4.4). Again, we believe this is due to COVID-19 regulations that made mask usage mandatory. The people who did not use masks said they did not own one, or the mask broke. We find similar results without using the inverse probability weights.

We also asked miners about their preferred PPE during the follow-up phone survey in April and May 2020. We told miners that we would return to the mines in a few months, and we would give them another gift. However, this time they could choose what gift they would like (mask, gloves, or bar of soap) and we recorded their gift preference (see Figure 4.6). In this time, Burkina Faso was under a state of sanitary emergency and mask usages were mandatory. Despite most participants reporting that they owned a mask in April 2020, 56% of miners preferred a mask as a gift.

However, when we visited participants again in January 2021, we immediately gave them the option to choose between masks, gloves, or soap (see Figure 4.6). During this time, the numbers of COVID-19 case numbers have not increased significantly, and while many restrictions on public life have been relaxed, masks were still mandatory. We find some evidence that their stated preference did not translate into a revealed preference.

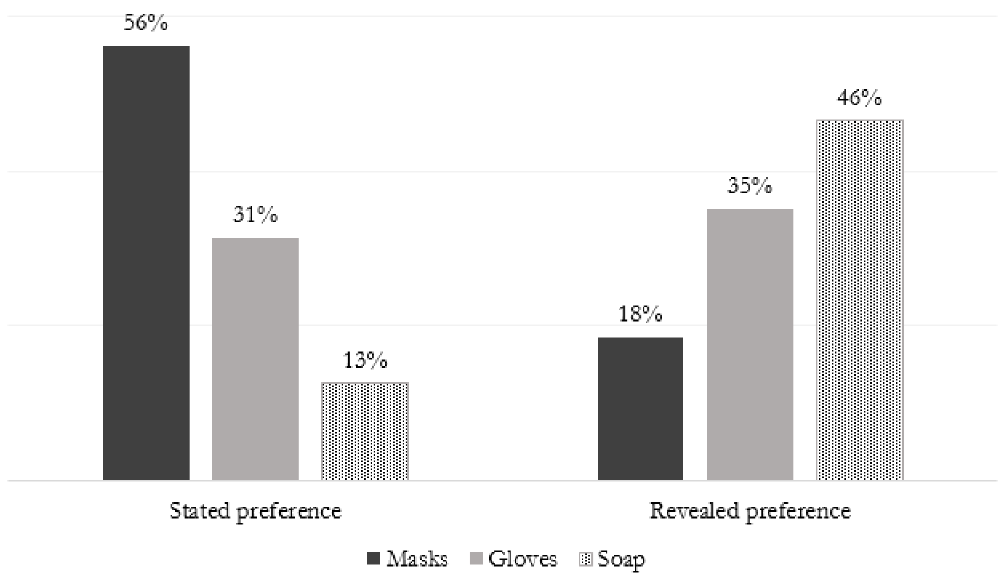


Fig. 4.6: Stated vs. revealed preferences. Stated choice in gift before and after information and revealed choice made at debriefing.

4.3.5 Combining knowledge, risk perception and access: determinants of PPE preferences and usage

In order to identify which determinants — knowledge, perception of risk and access — are significantly correlated to participants' preference for masks, gloves and soap, as well as miners' reported usage of gloves and masks, and best practices we conduct various multinomial and multiple logistic regressions.

To measure miners' preference for PPE, we use a multinomial logistic regression to determine the likelihood that miners' stated gift preference during a follow-up survey (see Figure 4.6) is a mask or gloves compared to soap. To measure miners' revealed preference for mask and gloves, we use a multinomial logistic regression to determine the likelihood that miners chose a mask or gloves (compared to soap) during the final in-person fieldwork in January 2021 (see Figure 4.6). We use miners' reported usage of masks and gloves in two periods, first at baseline and then at the first follow-up phone survey after miners received a masks or gloves from us in the experiment. We also consider if miners who reported they are involved in any job involving mercury (working mercury into ore, burning gold amalgams, or trading gold or mercury) practice any safety measures, including reportedly washing their hands after using mercury, wearing gloves when handling mercury, wearing a mask when burning, or not attending mercury burnings.

We use determinants of PPE usage from literature on pesticides as covariates (Zapata Diomedi & Nauges, 2016; Boadi-Kusi et al., 2016; Okoffo et al., 2016; Memon et al., 2019; Rezaei et al., 2019; Levesque et al., 2012a,b; Strong et al., 2008), including a continuous variable on age, and a binary variable if they read or write. We also include their index score on their knowledge about mercury (see Table 4H.1 in Appendix 4.H for the regression results if we separately add a variable for each knowledge question instead of the index score). For their perception on mercury's risks, we include a binary variable if they consider mercury the most dangerous thing on the mine and another binary variable if they think mercury is quite or very dangerous. To quantify access to PPE, we include two binary variables if they said that masks and gloves are currently available for purchase on the mine site and a binary variable if they received gloves in the lucky draw. Lastly, we include binary variables for two jobs on the mine, burning the gold amalgam and concentrating mercury in ore, which would require the use of masks and gloves, respectively. To reduce attrition bias, we again weight all analyses done with data from follow-up surveys with the inverse probability weights.

Even though we do not find that participants with higher knowledge were significantly more likely to say that they prefer masks or gloves compared to soap, more knowledgable participants were more likely to choose a mask compared to soap during the final fieldwork. Participants with higher knowledge were also more likely to report that they used gloves and mask in the last month (significant on the 1% level). If we add each factual questions separately into the analysis, instead of the index score, we find that participants that know more symptoms, know mercury vapour is the most dangerous and know cyanide is more effective to extract gold were more likely report using a mask (see Table 4H.1 in Appendix 4.H).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Stated preferences (compared to soap)		**Revealed preferences (compared to soap)**		**Reported usage**			
	Mask	**Gloves**	**Mask**	**Gloves**	**Best practices**	**Mask**	**Gloves**	**Gloves (after gift)**
Index score: knowledge of mercury	0.890	0.771	2.269***	1.472	0.046	0.033**	0.025***	0.022
	(0.198)	(0.207)	(0.645)	(0.461)	(0.053)	(0.016)	(0.008)	(0.046)
Think mercury is the most dangerous thing on the mine	0.657	0.215	0.761	1.234	0.153	0.147	0.078	0.187
	(0.547)	(0.249)	(0.881)	(1.055)	(0.186)	(0.104)	(0.078)	(0.128)
Think mercury is quite or very dangerous to their health	0.779	1.533	0.431	3.738**	0.008	0.030	-0.003	0.090
	(0.470)	(1.088)	(0.293)	(2.361)	(0.107)	(0.040)	(0.022)	(0.155)
Masks are available for sale on the mine	2.852	6.875***	0.137*	0.797	0.174	0.056	0.004	-0.308*
	(1.828)	(4.161)	(0.147)	(0.461)	(0.117)	(0.050)	(0.025)	(0.158)
Gloves are available for sale on the mine	0.821	0.259**	1.116	1.348	0.006	-0.015	-0.010	0.180
	(0.491)	(0.165)	(1.165)	(0.846)	(0.122)	(0.047)	(0.024)	(0.169)
Received gloves as a gift in the experiment	3.461**	0.184**	1.618	0.156***	NA	NA	NA	0.775***
	(1.996)	(0.137)	(1.127)	(0.088)				(0.051)
Job: burn gold amalgam	0.312	0.288	1.029	4.003*	0.235**	0.016	-0.021	-0.130
	(0.228)	(0.249)	(1.053)	(3.349)	(0.095)	(0.059)	(0.021)	(0.193)
Job: work mercury into ore	2.341	2.121	2.213	0.329	-o-	0.007	0.000	-0.123
	(1.617)	(1.663)	(1.381)	(0.259)	-o-	(0.046)	(0.021)	(0.160)
Analysis and interpretation	Multinomial Logistic - Relative Risk Ratios				Logistic - Marginal Effects			
Observations	165	165	110	110	88	227	227	164
Sample	All	All	All	All	Miners with mercury job	All	All	All

Tab. 4.5: Gift preferences and reported behaviour. Columns 1 and 2 show the stated preferences for masks and gloves compare to soap as indicated in the first phone survey. Columns 3 and 4 show the revealed preferences for masks and gloves compared to soap when they could chose a gift. Column 5 shows results for reportedly doing best practices (including, washing their hands after using mercury, wearing gloves when handling mercury, wearing a mask when burning, or not attending mercury burnings) of miners who has mercury-related jobs. Columns 6 and 7 shows the reported usage of gloves and masks at baseline. Last column show reported glove usage at second phone-survey, meaning, after miners received gloves in the field experiment. All analysis include controls for age and literacy. Standard errors shown in brackets, *** p<0.001 ** p<0.05 * p<0.1

We do not find that higher risk perception (thinking mercury is the most dangerous thing on the mine, or thinking mercury is quite or very dangerous to your personal health) is associated with higher reported mask or glove usage (also after receiving gloves for free) or any best practices. However, we do find that participants who think mercury is dangerous to their health are about 3.7 times as likely to choose gloves instead of soap. We probably do not find the same effect for masks, since most miners already owned a mask at this time due to COVID-19.

Access to PPE had a significant impact on stated preference and revealed preferences for PPE. Participants who received gloves were more about 3.46 times as likely to say they prefer a mask compared to soap and about 18% less likely to say they prefer gloves compared to soap (columns 1 and 2 in Table 4.5 showing the relative risk ratios). Meaning, miners were more likely to choose a gift that they did not previously receive. We observe the same trend in the revealed preferences, participants who received gloves were about 16% less likely to choose gloves again compared to soap (column 4 in Table 4.5 showing the relative risk ratios). Although participants who received gloves were more likely to choose mask, the effect is not significant. Importantly, our results suggest that miners who received gloves were 77.5% more likely to report using gloves after five months (column 8 in Table 4.5 showing the marginal effect at the mean). Due to COVID-19, we do not show the impact of receiving a mask on reported mask usages, during the follow-up survey almost all participants said they owned and used a mask in the last month.

Finally, we do not find that knowledge, perception of risk or access has a significant impact on reported best practices for miners involved in mercury-related jobs. However, we do find that miners who are involved in the burning of the gold amalgam, which is considered the most dangerous mercury-related activity, are almost 25% more likely to report best-practices. Interestingly, when considering a logistics regression with each knowledge question added separately (as opposed to the index score), we do not find that knowing mercury vapour is the most dangerous form, is significantly correlated to reported best practices (see Table 4H.1 in Appendix 4.H).

4.3.6 Determining group at risk of exposure for targeted interventions

Since giving miners free access to PPE had a large and significant likelihood that miners reported using PPE, we recommend giving miners free access to PPE. Although giving miners free access to PPE would not reduce the mercury pollution, it could have a significant health benefits for miners. Since mercury vapour is the most dangerous form of mercury, such an intervention would need to include gas masks with activated carbon filters. These activated carbon masks can cost at least 50 USD[6]. We use the hair samples to determine which miners are most at risk of

[6]For example Dräger half mask with activated carbon filters: `https://www.draeger.com/en-us_us/Productselector/Respiratory-Protection/Respiratory-Masks/Half-Masks?page=1`

exposure in order to design targetted and more cost-effective interventions.

To identify a group at higher risk of exposure, we measure the total mercury concentration in hair samples. The mercury concentrations measured in hair samples do not only reflect occupational burden but total mercury exposure through various roads of exposure.

We measure mercury concentration in the hair in parts per million (ppm), which would be the same as milligrams of mercury found in one kilogram of hair. A threshold value below 1ppm is considered low exposure, below which we do not expect any adverse health effects (CONTAM, 2012; WHO and UNEP, 2008; Bose-O'Reilly et al., 2020; Drasch et al., 2001). In our study in Burkina Faso, total mercury concentrations ranged between 0.085 ppm and 30.66 ppm with a median of 0.446 ppm and an average of 0.910 ppm. A large majority of the participants (84.4% or 151 participants) had mercury concentration less than 1 ppm in their hair and are classified as low risk (for details on results see Appendix 4.D). A share of 15.6% of the participants show mercury concentrations above 1 ppm, which indicate unsafe levels of mercury exposure.

Even people in high-income urban contexts, who are not exposed to any artisanal mining, can have unsafe levels of mercury exposure, primarily due to fish consumption. For example, researchers have found mercury concentrations in hair ranging from 0.261 and 1.89 ppm in France (Laffont et al., 2011) and 0.04 to 2.53 ppm in Germany (Drasch et al., 1997). However, similar to our study, other studies that measured mercury in hair from artisanal miners found much larger ranges than those in high-income countries in which the diet is not mainly based on fish and seafood. Total mercury burden in artisanal gold mining communities in Philippines ranged from 0.03 to 37.76 ppm (Drasch et al., 2001), in Zimbabwe it ranged from 0.02 to 112.18ppm (Boese-O´Reilly et al., 2004).

Despite similar ranges, a smaller percentage of miners in our sample had unsafe levels of mercury in their hair (above 1 ppm safety threshold) compared to over 30% of miners in the Philippines and in Zimbabwe that exceeded an even lower safety threshold of 5 ppm (Drasch et al., 2001; Boese-O´Reilly et al., 2004). However, these studies were conducted in different circumstances, with large artisanal gold mines in the midst of a gold rush (Boese-O´Reilly et al., 2004). Larger booming sites have higher gold productions than the smaller sites in our study and therefore also higher mercury use.

Controlling for the various jobs that involve mercury use (working mercury into the ore, burning gold amalgam, or trading in gold or mercury), we find gold buyers are significantly more likely to show higher levels of exposure (significant on the 1% level; see Table 4.6). Based on clinical data and urinary mercury concentrations, Tomicic et al. (2011) also found that gold buyers in Burkina Faso have significantly higher levels of contamination because they are often present in burning the gold amalgam or burn the amalgam more frequently than others on the mine. People who reported that they were involved in burning gold amalgams were more likely to have higher levels of exposure, but it was not significant (see Table 4.6).

Dependant binary variable:	**Mercury in hair above 1 ppm**
Job on mine	
No control group, multiple options possible	
burn gold amalgam	0.064
	(0.073)
trade in gold and/or mercury	0.378**
	(0.163)
work mercury into ore	-0.006
	(0.039)
Any education	-0.009
	(0.033)
Year experience working in artisanal mining	-0.003
	(0.004)
Hours spent on the mine om the previous day	0.012*
	(0.006)
Age in years	-0.001
	(0.002)
Used mercury in the last month	0.121***
	(0.037)
Protect from mercury by...	
(no control group, multiple options possible)	
Wear mask when burning gold amalgams	0.023
	(0.031)
Wear cloth around nose while burning amalgam	0.084
	(0.056)
Observations	178

Tab. 4.6: Determinants of mercury exposure. Logistic regression analysis showing the marginal effects between mercury above 1ppm in hair samples and reported jobs, protection strategies and other characteristics. Standard errors shown in brackets, *** $p<0.001$ ** $p<0.05$ * $p<0.1$

Miners who reported working longer hours on their previous work day and who confirmed that they used mercury in the last month, were more likely to show unsafe exposure to mercury, which could be an indication of more opportunity for exposure.

Lastly, we did not find any significant effect on the reported protection strategies;

some of the strategies, such as standing clear from the burning, we know is ineffective from previous literature (Tomicic et al., 2011). Notably, we do not find a significant correlation between reportedly wearing a mask when burning the gold amalgam and low mercury exposure, which could be because miners did not use the proper masks or that the mercury attached to the external structure of the hair in which case a mask could have given protection against inhaling mercury fumes but that it still showed high levels of mercury in the hair sample (see Section 4.2 and Appendix 4.D).

We find that miners with a higher occupational mercury burden, such as gold and mercury traders, and people who reported any mercury use in the last month are more likely to have higher levels of mercury concentration in their hair, making them a group more at risk of mercury contamination. We recommend that interventions that give free access to PPE first target groups with the highest occupational burden, notably gold and mercury traders, as they would be the easiest to identify and then miners who use mercury frequently.

4.4 Conclusion and discussion

Most artisanal miners in Burkina Faso use mercury, a toxic metal that could cause significant adverse health impacts, such as tremors, memory loss, depression in adults, congenital disabilities and deterred development in babies and children. Despite the potential severe health impacts of mercury exposure, similar to other studies, we find low levels of PPE usage. Using a survey, field experiment and biological sampling, we evaluate the impact of knowledge, personal risk assessment and access to PPE on low PPE usage and protective behaviour in Burkina Faso.

Although miners say they know mercury is dangerous for their health, we find that they have insufficient knowledge of mercury and how to best avoid exposure. Participants could only mentioned a few respiratory-related symptoms of mercury contamination, and nobody mentioned more serious neurological symptoms and underestimated children as high-risk group. Only three participants know what a retort is, a device that could protect them from dangerous mercury fumes and allow them to reuse mercury multiple times. Only a third of miners know that the safest place to burn gold amalgams is outside, away from other people. Miners with more knowledge of mercury are slightly more likely to report that they used a mask or gloves in the month.

A majority of participants say they think mercury a quite or very dangerous to them personally. Participants are on average more likely think they are more at risk of contamination than other people on the mine. However, miners do not accurately assess their risk of mercury contamination; miners who think mercury is more dangerous to them personally are not more likely to show high levels of exposure to mercury (as measured by the mercury content in miners' hair samples). In addition, higher knowledge of mercury is not significantly correlated to perceiving mercury as riskier for them personally.

Instead miners have some significant biases when assessing the danger of mercury for them personally. For example, participants are more likely to perceive mercury as more dangerous if they do not use it often or if they receive mercury for free. Higher familiarity with an activity, increases perceived control and lowers perceived risk (Fischhoff et al., 1978; Slovic, 1988; Fadlallah et al., 2020). If miners receive mercury for free, they have less of a choice in what method to use, therefore lower perceived control, which leads to a higher personal risk assessment of mercury. More importantly, higher personal risk perception of mercury are not significantly correlated to higher reported usage of PPE or other best practices.

Although PPE, such as masks and gloves, are relatively available for purchase on the mines compared to small mining equipment, such as ropes, and hammers. Most miners are not willing to pay more than 1 USD for a mask. Given the low willingness to pay for cheap masks, miners would not be willing to invest in masks that give adequate protection against mercury vapour, such as reusable masks with activated carbon filters that cost at least 50 USD. We also find that miners' stated preference for PPE (masks, gloves and soap) are influenced by what they already had available to them; e.g. miners who received gloves mask from us for free, are less likely to say that they want another pair of gloves five months later and also less likely to actually choose gloves as another gift one year later (compared to soap in both instances).

We find that giving miners free access to PPE increase protective behaviour. During the field experiment, we randomly distributed masks and gloves, and find that glove-recipients are significantly more likely to report using gloves up to one year later. Due to COVID-19, mask ownership increased independently from our experiment and we did not find the same significant effect. A shortcoming of our project is that we only considered participants' reported usage of PPE, which could be subject to a social desirability bias, i.e. participants would be more likely to report using PPE because they believe that it is the correct answer, or a recall bias, i.e. when participants do no accurately remember their usage in the last month. In addition, we only consider if participants used any PPE and not if they use the correct equipment in the correct way, which is an avenue for future research.

Although giving PPE would not decrease anthropogenic mercury pollution from the artisanal mining sector, it has significant health benefits for miners. We therefore recommend increasing miners' access to PPE. Given that proper PPE can be expensive and that estimations of the number of artisanal miners in Burkina Faso range up to one million people (Mondlane, 2017), we recommend targeting miners at risk of high exposure to ensure cost-effective interventions. Using hair samples collected on four artisanal mines, we find that mercury and gold traders are more at risk of high mercury exposure (same as Tomicic et al., 2011). Local traders are usually informal gold collectors who visit a few mines to purchase gold and then sell the gold to larger regional traders in nearby towns or cities (Grätz, 2004). Tomicic et al. (2011) also found that traders in Burkina Faso show high exposure to mercury, since they are often present at the burning of the gold amalgam or would burn it again later to make sure they evaporate all the mercury. In addition, we find miners that reportedly used mercury in the last month are also more likely to have unsafe levels of mercury in their hair. However, this group might be more difficult to identify than traders.

We recommend that targeted interventions that give groups with high-risk of exposure, such as gold traders, free access to PPE would have a large and significant impact on miners' health and well-being. However, given the low levels of knowledge, and evidence that higher knowledge is correlated with higher reported protective behaviour, we recommend that technical interventions needs to be combined with training or information campaigns that inform miners of mercury poisoning, related symptoms and best practices to avoid exposure.

Appendix

4.A Survey

Although all surveys were conducted in French, it was also translated into the local language Mooré for training purposes. During training, enumerators used the Mooré translation to standardise the questions if a participant wanted to be interviewed Mooré. Although all reference made to the survey in this article is given in English, no participant answered the survey in English.

The in-person survey included 121 questions on participants' socio-demographics; how participants use mercury, PPE, specifically masks and gloves, and other mining equipment; participants' general health and well-being; participants' knowledge of mercury; participants' attitude towards mercury, cyanide and technology; and participants' contact details, which allows us to understand miners' knowledge, use, attitudes, and perception of danger of mercury.

The first phone survey took on average 36 minutes to complete and included 22 questions overlapped with the baseline survey, including questions on demographics to check if we surveyed the same person, equipment use and perceptions of dangers of mercury. We included an additional 20 detailed questions on the use of masks and gloves, in order to measure changes in reported usage after receiving masks and gloves in the field experiment. Lastly, we included 18 questions on local gold markets and the COVID-19 pandemic for a separate research project.

The second phone survey took, on average, 22 minutes to complete and included 23 questions. Five questions that overlapped with the baseline survey was used to check that we surveyed the same individual, including questions on demographics and the gift they received. Another 10 questions that overlapped with previous surveys focused on reported usage of masks and gloves, and the perception of mercury's health risks. We gave participants information about when and where we will visit the mines to give feedback on the study and hair samples. We also included two question about their availability to attend the feedback sessions. Lastly, we included six questions on local gold markets and COVID-19 for a separate research project.

Baseline questionnaire

Section A: Introduction and consent

A1 Welcome to our study and thank you for showing interest in our project. We are a group of researchers and health workers working with ORCADE and the Swiss NGO Action de Carême and the Swiss university ETH Zurich. We are very interested to learn more about your work on the gold mine. By participating in this survey, you are contributing to a better understanding of the situation working on a mine in

Burkina Faso and improving the lives of miners. We guarantee that your identities will be treated in strict confidentiality. If you are willing, we would like you to take part in our survey. The survey should take about 30 minutes. You are free not to take part in our survey or stop the survey at any time; you do not have to give a reason why. We will be at the mining site for a couple of days, and we will return to inform you of some of the results of the study next year in March. If you will not be here next year March or you have any other questions regarding our study, you can contact us the numbers on the business card. (*GIVE BUSINESS CARD*). The Swiss NGO Action de Carême and the Swiss university ETH Zurich fund this study.

A2. Are you willing to take part in our study?

A3. How old are you?

Section B: Demographics

B1 What is your gender?

B2 Are you expecting a child?

B3 Are you currently breastfeeding?

B4 What is your ethnicity?

- Mossi
- Fulani
- Gurma
- Bobo
- Gurunsi
- Other

B5 Can you read and write (any language)?

- I can write
- I can read
- I can read and write
- I cannot read and write

B6 On how many days did you listen to the radio in the last week?

B7 On how many days did you read the newspaper in the last week?

B8 What is the highest level of education?

- None / Did not attend school
- Primary education incomplete
- Primary education complete

- Secondary education incomplete
- Secondary education complete
- Technical school
- University incomplete
- University complete
- Other

B9 Where do you currently live?

- On the mine
- less than 1 hour from the mine
- 1 hour from the mine
- 2-5 hours from the mine
- more than 5 hours from the mine

B10 Do you have children younger than 15 years old?

B10.1 Do your children live with you?

- All of my children live with me
- Some of my children live with me
- None of my children live with me
- Rather not say

B11 Where are your children currently living?

- On the mine
- less than 1 hour from the mine
- 1 hour from the mine
- 2-5 hours from the mine
- more than 5 hours from the mine

B12 How many people - including you and children - live from the income you earn on this mine?

- Only me
- Two
- Three
- Four
- Five
- 6-10
- 11-15
- More than 20 people

Section C: Health

C1 How do you feel today?

- I feel extremely well
- I feel very well

- I feel moderately well
- I feel slightly unwell
- I feel very unwell

C2 Did you feel sick during the last week?

C3 What symptoms have you had? Multiple options possible

- Chest tightness
- Respiratory infections (e.g. coughing, sore throat)
- Nausea
- Vomiting
- Headache
- Fever
- Diarrhoea
- Stomach cramps
- Fatigue
- Insomnia
- Difficulty remembering things
- Problems with breathing
- Problems with my eyes
- Other

C4 What do you think caused these symptoms? Multiple options possible

- Not enough food
- Dirty water
- Cold or flu
- Malaria
- Yellow fever
- The cold
- The heat
- Work on the mine
- Other

C5 What on the mine made you sick?

- Dust
- Cyanide
- Mercury
- Heavy work
- Bad air
- Humidity/moisture in the shafts
- Noise
- Other

Section D1: Daily activities

D1 What year did you start working on THIS mining site?

- before 2005

- ...
- 2019

D2 Have you worked on another mine before?

D2.1 Is this the primary mine you work on?

D3 On how many other mines have you worked before?

- 10 or more
- 9
- 8
- ...
- 3
- 2
- 1

D4 What year did you start working on artisanal gold mines?

- 2000 or before
- ...
- 2019

D4.1 Have you ever worked on large-scale mines?

D5 How often do you work on THIS mine?

- Almost every day
- 4-5 days a week
- Once a week
- Once every month
- Only once or twice before
- Rather not say

D5.1 Not considering today, when was the last day you worked on this mine?

- yesterday
- the day before yesterday
- 3 days ago
- last week
- last month
- can't remember

D6 How many hours did you spend on the mine on that day?

- 1
- ...
- 12 or more hours

D7 Which of the following tasks do you perform on the mine? Please name all you are engaged in. Surveyor: READ out options - multiple option possible.

- Stabilise shafts
- Dynamite expert
- Excavating/digging
- Crushing
- Milling
- Cyanide leaching
- Concentrating
- Squeezing amalgamation
- Burning amalgamation
- Selling mercury
- Selling cyanide
- Selling gold
- Buying gold
- Selling mining equipment
- Selling water and food
- Coiffeur
- Transportation services
- Pit owner
- I do not perform any tasks on the mine
- Other

D8 How do you get paid for your main work on the mine? (Multiple option possible)

- In cash, daily salary
- In cash, weekly salary
- In cash, monthly salary
- In cash, per task
- In gold
- In ore
- Other
- Rather not say

Section D0: Gold

D0.1 Have you sold gold to a trader during the last month?

D0.4 Where did you sell the gold?

- At home
- On the mine
- Nearby processing center
- In the nearest village
- In the next town
- In another larger city
- in Ouagadougou
- Do not know
- Don't want to say

D0.5 How many gold traders do you know to whom you can sell gold to?

- Only one
- 2
- ...
- 5
- More than 6

D0.6 Do you usually sell gold to the same person?

- Yes
- Most of the time
- Sometimes
- I always sell to someone else

D0.7 How much XOF did you get per gram for the gold the last time you sold gold?

- Less than XOF 20 000 per gram
- XOF 20,000-24,999 per gram
- XOF 25,000-29,999 per gram
- XOF 30,000-34,999 per gram
- XOF 35,000-39,999 per gram
- more than XOF 40,000 per gram
- Can't remember

D0.8 How does the trader pay for the gold? Multiple options possible

- In cash
- Loan/credit
- Mercury
- I don't know
- Rather not say

Sections D1: Cyanide /D2: Mercury /D3: Borax *(Only showing questions regarding mercury, same questions asked about cyanide and borax)*

D2.1 Have you used mercury during the last month?

D2.2 How often do you use mercury?

- Almost everyday
- At least once per week
- Once every two weeks
- Once a month
- Only used it once or twice
- Don't know
- Don't want to say

D2.3 Where do you store mercury?

- On your person
- At home

- With the mercury trader
- At the site
- With a friend
- With the patron
- I do not store any mercury
- Don't want to say
- Other

D2.4 The last time you got mercury, where did you get it?

- On the mine from a gold buyer
- On the mine from a friend
- On the mine from the patron
- On the mine from the mercury seller
- In the nearest village
- In the next town
- In a larger city
- A nearby processing center
- Do not know
- Don't want to say
- Other

D2.5 How many mercury dealers do you know that you can get mercury from?

- Only one
- ...
- More than 6

D2.5.1 Do you always buy mercury from the same trader?

- Yes
- Most of the time
- Sometimes
- I always buy from someone else

D2.6 How much per ball did the mercury cost the last time you got it? *(price ranges differ for mercury, cyanide and borax)*

- It was for free
- ...
- Can't remember

D2.6.1 How big is the ball of mercury?

- In grams:
- I do not know
- I do not want to say

D2.6.1 How do you get mercury?

D2.7 Is the person you get mercury from the same person that buys your gold?

D2.8 How much of the gold can you get out of ore using mercury? (one answer - READ answers)

- Almost all of the gold
- A lot of the gold
- About half
- Very little
- Don't know
- Don't want to say

Section E: Equipment

E0 What method do you think extract the most gold, mercury or cyanide?

- Mercury
- Cyanide
- I don't know
- Rather not say

E1 Which of the following equipment have you used last month and/or own personally? Surveyor: Please READ out. Have you used one in the last month? Do you own one ?

- Shovel
- Pick axe
- Mill/Grinder
- Sluices boxes
- Shaking tables
- Gold washing pans
- Gas torch
- Goggles
- Masks
- Gloves
- Rope
- Retort
- Hammer
- Helmet
- Bags
- Crushing machine
- Scale
- None of the above

E2 Which of the following equipments would buy if you had 100.000 XOF right now? Surveyor: Please READ out answers. Multiple choice possible

- Shovel (XOF 10 000)
- Pick axe (XOF 10 000)
- Sluices boxes (XOF 100 000)

- Gold washing pans (XOF 2000)
- Gas torch (XOF 5 000)
- Goggles (XOF 500)
- Masks (XOF 500)
- Gloves (XOF 2000)
- Retort (XOF 100 000)
- Rope (XOF 5 000)
- Hammer (XOF 10 000)
- Scale (XOF 15 000)
- Helmet (XOF 1 000)
- None of the above
- Other

E2.1 Which of those items can you currently purchase on the mine from a trader or the patron? Surveyor: Please READ out answers. Multiple choice possible

- Shovel
- Pick axe
- Crushing machine
- Sluices boxes
- Shaking tables
- Gold washing pans
- Gas torch
- Goggles
- Masks
- Gloves
- Retort
- Rope
- Hammer
- None of the above
- Other

E3 Is there anybody on the mine who manufactures or repairs his own equipment for mining?

- I make my own equipment
- I repair my own equipment
- Others make equipment
- Others repair equipment
- Nobody manufactures or repair equipment on the mine

E4 Which type of equipment is repaired or manufactured on the mine? Multiple choice possible

- Shovel
- Pick axe
- Mill/Grinder
- Sluices boxes
- Shaking tables

- Gold washing pans
- Gas torch
- Goggles
- Masks
- Gloves
- Retort
- None of the above

Sections F: Mask /G: Gloves /H: Retorts. *(Only showing questions regarding masks, same questions asked about gloves and retorts)*

F1 Where can you buy a mask?

- On the mine
- In the nearest village
- In the next town
- In larger cities
- I do not know
- Other

F2 How much does a mask cost in XOF? *(price ranges differ for question regarding gloves and retort)*

- Less than XOF 300
- XOF 300- 390
- XOF 400-490
- XOF 500-590
- XOF 600-690
- XOF 700-790
- XOF 800 or more
- Do not know

F3 Do you or have you ever owned a mask?

- Yes, I currently own a mask
- Yes, I owned a mask in the past
- No, I do not and have never owned a mask

F3.1 Do you still use it?

F4 Why did you stop using the mask?

- I lost it
- It was stolen
- It broke
- It belonged to my previous patron
- It was not comfortable
- It did not work
- It was difficult to use

- It was not safe
- I borrowed it to somebody else
- My job changes
- Don't know
- Don't want to say
- Other

Additional question regarding retort: H1 Do you know what a retort is used for?

Section J: Mercury knowledge and perception

J1 What is the most dangerous thing on a mine site for you?

- Digging
- Mercury
- Cyanide
- Blasting
- Dust
- Landslides
- Machinery
- Shaft collapse
- Terrorists
- Contaminated water
- Crushing ore
- Other

J2 How dangerous is mercury on this mine to your health?

- Not at all dangerous
- Barely dangerous
- Somewhat dangerous
- Quite dangerous
- Very dangerous
- Don't know

J2.1 What do you do to protect yourself from mercury? Multiple choice possible

- Stand clear from burning mercury
- Stand in opposite wind direction when burning mercury
- Do not attend mercury burning
- Never suck mercury out of ore
- I wear a mask on the mine
- I put my T-Shirt over my mouth on the mine
- I tie a piece of cloth around my nose and mouth
- I wear a mask when burning
- I use gloves when burning
- I put my T-Shirt over my mouth when burning
- I wash my hands after using mercury
- Nothing

- Other

J3 Which answers are true? (READ answers)

- If mercury is thrown into the water, it disappears
- If mercury is discarded in soil, it disappears
- If mercury is burnt, it disappears
- Mercury never disappears

J4 When is mercury the most dangerous? (one answer - READ answers)

- When touching it
- When washing it into ore
- When burning it
- Mercury is always equally dangerous
- Mercury is never dangerous
- Do not know

J5 Where is the safest place to burn mercury?

- Indoors
- Well-ventilated house
- Outdoors anywhere on the mine site
- Outdoors, away from other people
- Do not know
- Other

J6 What is in your opinion the biggest negative impact of mercury? (one answer - READ answers)

- Polluting the water
- Polluting the soil
- Polluting the air
- Polluting food
- Poisoning people
- Don't know

J7 Show picture to participant. Who on this picture can be contaminated by mercury? Multiple choice possible

- People at burning
- People sitting under the tree
- Children on mine
- Pregnant woman
- Women fetching water

J8 Look at the picture again. How can someone not present at the mercury burning be contaminated? Multiple choice possible

- The wind blows the mercury to people
- Vapour attached to the houses and walls, and people living there breathes it

- Vapour attaches to the trees and leaves, and people gathering under a tree breathes it
- Vapour attaches to the fruit on the tree that people eat
- Other

J9 For whom on the picture is mercury the most dangerous?

- People at the burning
- Children
- Pregnant woman
- Everybody on the mine

J10 Have you ever heard of mercury poisoning?

J11 What are the symptoms? Multiple choice possible

- Chest tightness
- Rapid heart beat
- Respiratory issues (such as coughing)
- Kidney failure
- Madness
- Nausea
- Vomiting
- Headache
- Fever
- Diarrhoea
- Stomach cramps
- Fatigue
- Insomnia
- Difficulty remembering things
- Impotence
- Excessive saliva
- Bleeding gums
- Metal taste
- Difficulty moving
- Tremors
- Numbness
- Weight loss
- Skin rash
- Hair fall out
- Mood swings
- Other

J12 How can it be treated?

- With medication from health center
- Traditional healer
- Sleeping and resting
- It can not be treated
- Don't know

- Other

J13 How do you estimate your risk of getting mercury poisoning?

- Almost definitely be contaminated
- Somewhat likely
- Neither likely nor unlikely
- Somewhat unlikely
- Almost certainly not contaminated
- Do not know

J14 Do you personally know somebody that had mercury poisining over the last year?

Section L: Education and training

L1 Have you ever attended a training about safety on the mines?

L2 Was the educational talk by ORCADE?

L3 Have you ever attended a theatre about safety on the mines?

L4 Was the theatre by ORCADE?

L5 Have you ever heard information about safety on mines in the radio?

Sectoin M: Thank you, contact details and gift

M1 Thank you for taking part in our survey. To thank you, you can win a small gift. Let participant draw a number from the lucky draw. What did you get?

- Mask
- Gloves

M1.1 What is the number on the ticket you drew from the lucky draw?

M1.2 This mask will only give you some protection against mercury fumes. The most important thing is that you still need to take the necessary precautions when using mercury: do not attend mercury burning if you do not have to, a retort when burning mercury, burn mercury away from other people in an open area, store your safety gear away from other people. If you use the mask when burning mercury, you need to replace the mask often. If you do not personally burn mercury, the mask can help you with other problems, such as dust.
M1.3 You should always wear plastic gloves when using mercury or cyanide. But this pair of gloves will only give you some protection against mercury, you still need to take the necessary precautions when working with mercury. Do not attend mercury

burning if you do not have to, use a retort when burning mercury, burn mercury far away from other people in an open area, store your safety gear away from other people.
M2 Do you plan to use this mask/gloves yourself or will you give it to somebody else, and to whom? Surveyors: READ out options.

- Will use it myself
- Will give it to my children
- Will give it to a female adult in my family
- Will give it to a male adult in my family
- Will give it to somebody on the mine (but not family)
- Don't want it and give it back to the surveyor
- Don't know yet.

M3 We will visit this mine again next year and want to contact you to talk to you again. Would you give us your contact details? Be assured that anything answered in this survey, and also your contact details, will only be shared with the researchers of this project.

M4 What is your mobile phone number? (Or number where we can reach you.)

M5 Whose number is this?

- My number
- Male relative
- Female relative
- Friend
- Colleague
- Other

M6 Fieldworker, call the number to see if it works.

Section Q: Hair sampling

Q1 Mercury is a dangerous chemical that can make you very sick. When you work with mercury, it can be absorbed into your body, maybe when you wash into ore or often when it is burned. Once mercury is in your body, it can spread in your body and some of it can even be found in your hair. We like to test the amount of mercury that has spread in every miners' and workers' body by taking a little bit of hair. The hair will be put in small bags and will then be taken to Switzerland to analyse, to see how much mercury is in it. The bags will be sealed in front of you and only opened again in Switzerland. If you want to see how much mercury you have in your body, you can give us a small sample of your hair. If you are not comfortable with giving a hair sample, you do not have to. Nobody will know if you choose not to take part.

Q2 Are you willing to give us a sample?

Q4 After we have analysed it, we will visit the mine again next year March and tell you the results. Nobody will know your results because we will only give the results according to your case number. Only you will know your results. It is very important that you remember this number, to help you remember, we will put the number on the back of the card we gave you. Surveyor: take sticker and put it on the back of the card you gave in the beginning. We will send you an sms with the number.

Q5 Surveyor: Send unique number via sms. Did you receive the sms?

Q6 Take this bag to the hairdresser in the tent. There is a medical student that will take the bag from you and help the hairdresser to take a hair sample.

4.B Inverse probability weighting

	(1) Did not complete round 2	(2) Did not complete round 3	(3) Did not attend feedback
Reference mine site: Sandouré			
Ronguin	-0.042	-0.496***	-0.217**
	(0.075)	(0.072)	(0.087)
Galoun-Tenga	0.067	-0.078	0.128
	(0.085)	(0.113)	(0.112)
Zomnkalga	0.193***	-0.060	0.099
	(0.064)	(0.101)	(0.091)
Age in years	-0.003	0.001	0.007*
	(0.003)	(0.005)	(0.004)
Participant is female	-0.088	-0.194	0.015
	(0.166)	(0.151)	(0.173)
Can read and write	0.094	0.046	0.129
	(0.063)	(0.088)	(0.083)
Years experience in artisanal mining	0.001	0.005	-0.007
	(0.007)	(0.008)	(0.007)
Have children younger 15	0.256***	0.113	0.168*
	(0.095)	(0.105)	(0.092)
Observations	240	240	240

Tab. 4B.1: Balance table for attrition between rounds. Mean of selected baseline variables to determine possible attrition bias.

4.C Balance table for randomisation in experiment

Variable	Masks (1)	Gloves (2)	p-value
Age in years	33.724	31.760	0.174
Received any education (binary)	0.284	0.344	0.358
Listen to the radio (days per week)	3.190	2.969	0.502
Know that mercury is not biodegradable (binary)	0.233	0.260	0.644
Total symptoms of mercury poisoning known	0.733	0.781	0.826
Years working in artisanal mining	11.450	11.028	0.657
Use mercury at least once per week (binary)	0.414	0.490	0.272
Have job that involves mercury (binary)	0.500	0.542	0.548
Think mercury poisoning has treatment (binary)	0.571	0.800	0.245
Exercise protection against mercury (binary)	0.836	0.865	0.565
Children live with them, pregnant (binary)	0.759	0.667	0.144
Know someone with mercury poisoning (binary)	0.114	0.167	0.583
More than five dependants (binary)	0.603	0.521	0.230
Get mercury for free (binary)	0.319	0.313	0.920
Mercury is effective to extract gold (binary)	0.845	0.833	0.822

Tab. 4C.1: Differences in samples receiving gloves and masks. P-values show if the mean of the sample who received masks and the sample who received gloves are significantly different.

4.D Method and discussion of hair sampling

Laboratory analysis

For each hair specimen, 0.05 to 1 g of unwashed terminal hair was cut from the scalp. The length of the hair in the samples ranged from several millimeters to 5 cm. Assuming that hair close to the scalp shows exposure of the previous one to three weeks (Nuttall 2006) and that African hair grows at a rate of around 0.8 cm per month (Loussouarn 2001), hair specimens collected at the mine sites cover an exposure period of several weeks to up to 5 months preceding sampling.

The hair samples were conserved in sealable plastic zip bags and analysed at the ETH Zurich, Switzerland. We assessed the total mercury content in the human hair using the cold vapour mercury Analyzer AMA 245 of LECO Corporation (AMA-254, Altec Ltd., Prague, Czech Republic). The atomic absorption spectrometer was specifically developed to analyse mercury in solid and liquid samples and does not need prior sample digestion. AMA Mercury Analyzer has two different detector cells with different sensitivities that are calibrated individually. We started each day's measurement series with a drift correction of both calibrations (LECO Corporation 2005).

To validate the accuracy of the mercury measurements, we used standard reference material IAEA-086 (International Atomic Energy Agency) and NIES No. 13 Human Hair (National Institute for Environmental Studies Japan) for the lower and upper calibration window, respectively. After a cycle of ten sample measurements, we crosscheck the validity of the results measuring the reference standard of the respective detector cell. After a measurement with a mercury concentration of more than 0.5 ppm, we ran a cleaning cycle to remove mercury from the amalgamator. We corrected the measurements of the reference standards and the hair samples for moisture. We evaluated the moisture by heating approximately 100 mg of the hair material in an oven with 80°C for four hours. After cooling down in a desiccator for 30 minutes, we compared weights before and after the heating. For the hair samples, we used a mix of hair from eight different hair samples.

For analysis with the AMA Mercury Analyzer we transferred around 20 mg of hair sample to a nickel boat. We took aliquots from each hair sample and measured the same sample two to five times depending on the deviation between the measurements. We accepted duplicates if the observational error between two measurements was below 10%. For some hair samples, we only could perform a single measurement due to the small amount of hair available (n=6). For data treatment and statistical analysis, we calculated mean concentrations of total mercury (μg/g) between the aliquots of each sample. We used the average of the daily observational error of the reference standards to calculate the error of each measurement. The measurement error was on average $\pm$ 5.85%. Detection limits of the AMA Mercury Analyzer were low as 0.5 ppb Hall & Pelchat (1997); Salvato & Pirola (1996).

We did not wash hair prior to analysis. Numerous studies have shown the inefficiency of washing procedures to remove exogenous mercury (Morton et al., 2002; Li et al., 2008). Comparable recent studies on mercury contamination in hair have consequently renounced to any prior washing procedure (Bose-O'Reilly et al., 2020; Drasch et al., 2001; Reuben et al., 2020; Abad et al., 2016). We rinsed some of the hair sample three times with acetone and milliQ water to remove a large amount of dust (n=1) or mould (n=2).

Limitation of method

The amount of mercury in the hair is determined by the mercury circulating in the blood of a human body. During the formation of a hair in the hair follicle, mercury is bound to the amino-acid cysteine and incorporated in the hair structure (Phelps et al., 1980; Nuttall, 2006). Mercury is concentrated around 250-fold in the hair with respect to the mercury concentrations in blood at the time of formation, but the ratio shows high inter-individual variations (CONTAM, 2012). Some mercury species are incorporated more efficiently into the hair then others. The organic form of mercury, methylmercury, which humans take up through fish consumption, is incorporated most efficiently. Other inorganic mercury species are bound much less efficiently (Nuttall, 2006). Laffont et al. (2011) demonstrated through the analysis of isotopic mercury signatures that the methylmercury fraction highly varies between individuals, making up 4% to 86% of the total mercury concentration in hair of gold miners in Bolivia depending on the type of gold mining and living and working conditions.

Overall, mercury exposure levels in human bodies can be monitored via different human specimen such as blood, urine, hair, nails, also indicating different periods of exposure (Risher, 1999). Major studies have combined different biomonitors, mainly hair, urine and blood, to evaluate total mercury exposure levels (Ye et al., 2016). Urine is most frequently used as a biomonitor for assessing exposure to inorganic mercury vapour (WHO, 2000). However, head hair is the human specimen that is most easy to sample, transport and store which is especially relevant for remote and challenging sampling conditions. The main inconvenience of hair for biomonitoring is the impossibility to distinguish between the exogenous contamination by adsorption to the external hair structure, and the internal dose incorporated via the human body (Laffont et al., 2011; Esteban & Castaño, 2009). Washing treatments of hair samples with detergents, complexing agent or acids have proven to be ineffective to remove adsorbed mercury (Nuttall, 2006; Morton et al., 2002). In a detailed analysis of hair from workers after an occupational exposure to mercury vapour, Abad et al. (2016) proved direct adsorption of mercury in human hair and showed that mercury concentrations in exposed hair can be up to 1000 times higher than mercury concentrations incorporated into the hair via ingestion or lung absorption.

Considering the discussion above, results of the mercury content in the hair of the Burkinabe gold miners presented in this study do therefore not only reflect occupational exposure to inorganic mercury but rather total mercury exposure. However, a public health study in a small-scale gold mining area in Zimbabwe in 2004 clearly demonstrated that additional occupational burden with mercury vapour rose the percentage of inorganic mercury in hair of the burdened group compared to the control group. Mercury in hair in the control area was mainly methyl-mercury, whereas the mercury in the gold mining district with low fish consumption was mainly inorganic mercury (Bose-O'Reilly et al., 2020; Bose-O´Reilly et al., 2004).

In a study on the health burden of chronic mercury intoxication, Steckling et al. (2014) observed that, depending on the kind of biomonitor, 80-90% of the gold miners showed mercury concentrations above exposure limit values, whereas controls rarely exceeded exposure limit values.

4.E Information on mercury exposure given to miners

Fig. 4E.1: Information given to miners. After study, miners were given more information on mercury, mercury exposure and how to protect themselves.

4.F Knowledge of mercury index

Factor	Eigenvalue	Difference	Proportion	Cumulative
Factor 1	1.385	0.153	0.231	0.231
Factor 2	1.232	0.153	0.205	0.436
Factor 3	1.079	0.114	0.180	0.616
Factor 4	0.964	0.173	0.161	0.777
Factor 5	0.791	0.243	0.132	0.909
Factor 6	0.548	.	0.091	1.000

Tab. 4F.1: Factor loadings for principal component analysis on knowledge of mercury

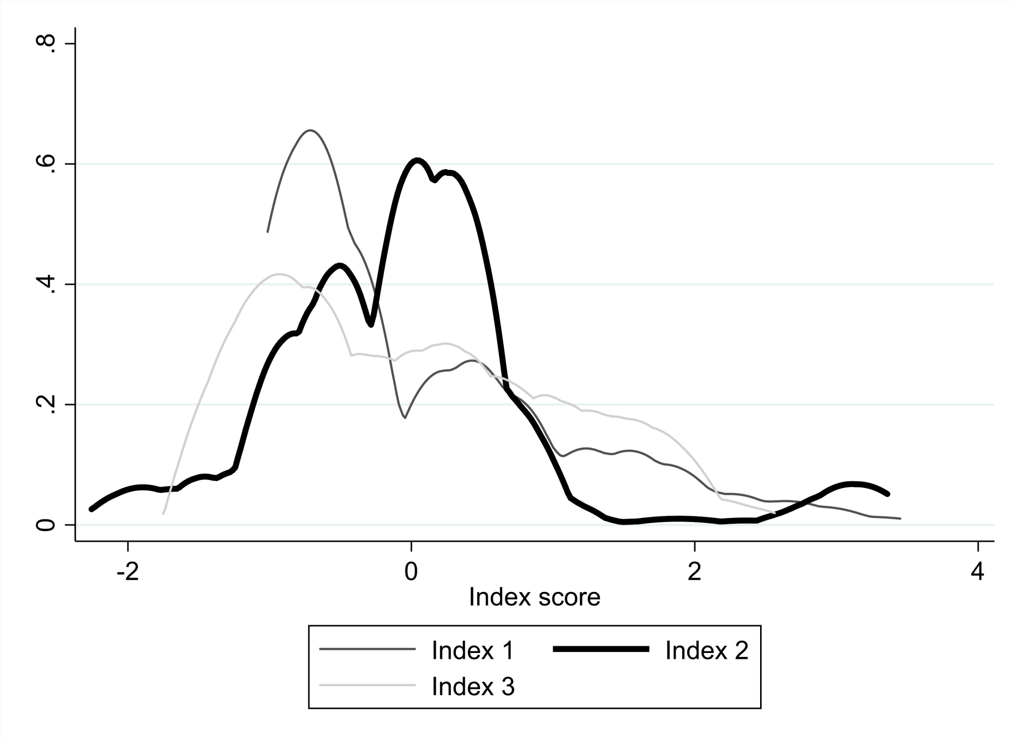


Fig. 4F.1: Distribution of Index Scores. Density distribution of the index scores of the first three factor analyses, with Eigenvalues larger than one.

4.G Testing mercury's perceived danger

Fig. 4G.1: Picture to determine risk perception. Picture showed to participants with the questions: (1) "Who on this picture can be contaminated by mercury? Multiple answers to the question were possible." And then (2): "For who on the picture is mercury the most dangerous?"

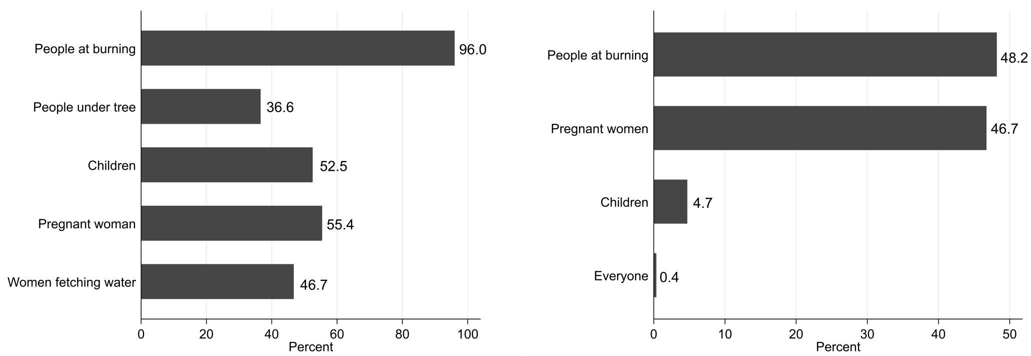


Fig. 4G.2: Who can be exposed and to whom is mercury the most dangerous? We showed participants a large print-out of the picture of a mine. The first panel shows the answers to "Who on this picture can be contaminated by mercury? Multiple answers to the question were possible." And the second panel shows the answers to the question: "For who on the picture is mercury the most dangerous?"

4.H Determinants of PPE usage

	(1)	(2)	(3)
Reported usage in the last month of:	**Gloves**	**Mask**	**Best practices**
Input variables to mercury index:			
Number of symptoms identified (standardised from 0 to 1)	0.069	0.176**	0.291
	(0.045)	(0.081)	(0.218)
Mercury is not biodegradable	-0.021	-0.017	0.103
	(0.017)	(0.037)	(0.132)
Safest place to burn mercury is outside, away from others	0.053	0.032	-0.002
	(0.034)	(0.041)	(0.100)
Mercury do not have a cure	0.070	-0.049	0.126
	(0.073)	(0.038)	(0.240)
Cyanide is the most effective method of extract gold	0.022	0.089***	0.013
	(0.020)	(0.036)	(0.099)
Mercury vapour is the most dangerous form		0.069*	0.057
		(0.038)	(0.166)
Think mercury is the most dangerous thing on the mine	0.070	0.113	0.071
	(0.083)	(0.099)	(0.172)
Think mercury is quiet or very dangerous to their health	-0.011	0.033	0.002
	(0.027)	(0.036)	(0.116)
Gloves are available for purchase on mine	-0.006	-0.025	0.054
	(0.025)	(0.041)	(0.130)
Masks are available for purchase on mine	-0.011	0.062	0.164
	(0.026)	(0.048)	(0.120)
Job: burn gold amalgam	-0.020	0.036	0.285***
	(0.024)	(0.063)	(0.102)
Job: concentrate mercury in ore	-0.010	-0.024	
	(0.023)	(0.043)	
Age	0.000	0.000	0.004
	(0.001)	(0.002)	(0.005)
Can write or read	0.031	-0.027	-0.008
	(0.030)	(0.036)	(0.112)
Observations	236	261	104

Tab. 4H.1: Impact of factual questions. Determinants of reported PPE usage, knowledge questions input separately. Standard errors in brackets, *** p<0.01, ** p<0.05, * p<0.1

Chapter 5

Blockchain is only as strong as its weakest link: transparency and artisanal gold

Single author, research brief published on ETH Research Collection

Abstract: To ensure responsible gold sourcing, accredited refiners often obtain gold directly from a few industrial mines, building up trust relationships and visiting these mines frequently. This approach is not feasible for artisanal mines, given their large numbers and the high-risk conditions in which they operate. Can blockchain substitute for trust relationships to support responsible sourcing from artisanal miners? The main obstacle for using blockchain is to create a link between the physical world (the traded gold) and the digital (the blockchain). Linking the physical and digital worlds can be done either by uniquely identifying the physical object by its chemical composition or by adding a unique mark or tag to the product. For the case of artisanal gold, both these methods are limited. Geochemical analysis requires large and expensive reference databases and can only be done before smelting and refinement. Tags need to be added by a central authority, which weakens the power and trust of the blockchain in fragile areas. While blockchain could contribute to a more transparent gold supply chain, it has a limited ability to ensure responsible sourcing from artisanal miners.

5.1 Introduction

We all use gold every day: to show our commitment, to celebrate, to communicate, to show we care, to invest, and much more. The question is; how do we know if the gold in our mobile phones, wedding rings and bank vaults were not mined by children or in ways that caused irreparable harm to the environment?

The gold supply chain can be divided into two parts, the upstream part from miner to refiner and the downstream part from refiner to retailer. While the downstream part of the supply chain is very complex, transforming the gold into its various final forms, the upstream part is the critical part to ensure responsible sourcing (Interviewee B).

Various due diligence initiatives, such as the OECD (Organisation for Economic Co-operation and Development) guidelines and LBMA (London Bullion Market Association) accreditation, have aimed to increase the transparency in the gold supply chain. Refiners are a critical point in the supply chain, with only six major gold refineries in the world - four of which are located in Switzerland. Given refineries' position in the supply chain, responsible sourcing initiatives often have had implications for them, specifically refiners accredited by the LBMA and those following the OECD requirements. One way in which refiners handle the cost of due diligence is by shortening the supply chain. Refiners reduce uncertainty by buying primarily from a few industrial mines, allowing them more control over the source and origin of the gold. They build up personal relationships and perform risk-based site visits at these mines (Interviewee B).

Although industrial mines extract about 80% of the gold, the other 20% is produced by a myriad of artisanal miners, often working alone or in small groups or cooperatives (Fritz et al., 2018). Artisanal mining creates a livelihood for millions of poor individuals, but at a high cost, as these artisanal miners work in extremely dangerous conditions and are often informal or involved in illicit trades. The sector has also been characterised by various human right abuses, such as child or forced labour, mining in protected areas, and mercury pollution. Sourcing gold from artisanal mines is often considered high risk in terms of due diligence requirements (LBMA, 2018).

The supply chain for artisanal gold can be very complex and long, especially at the level of individual artisanal miners, each of whom extract only a very small amount of gold that is subsequently accumulated by many local and regional traders and passed on to local gold shops (Interviewee C). Worldwide, an estimated 50'000 gold shops buy from artisanal miners (Telmer, 2020). These local gold shops or traders smelt gold from various sources together to create a form of unrefined gold, called doré, which, depending on the area, consists of a varying percentage of gold, plus secondary minerals such as silver and copper and other impurities.

Given these long and complex supply chains, it is costly for refiners to meet the necessary due diligence requirements when they buy from artisanal miners. Accredited large refiners, therefore, avoid buying artisanal gold on a large scale. This makes it more difficult for responsible artisanal mines to make a livelihood. Can blockchain cut the due diligence cost of buying from artisanal miners and bring responsible artisanal miners into the formal market?

5.2 Using blockchain in the gold supply chain

Blockchain, also known as distributed ledger technology, is a system that does not need a central regulating body to oversee or build a trust relationship; instead, trust is integrated into the mechanics of the blockchain system design (Nakamoto, 2008). When a new transaction is completed, it is broadcasted to all actors in the network, who record the transaction in their database. Each blockchain system defines its own set of rules of how new transactions are accepted or rejected.

A blockchain can be designed to fit its required purpose. This includes stipulating who can participate in the blockchain, for example a select group or the public; and defining the appropriate consensus mechanism, which specifies the requirements for accepting a new transaction (Interviewee F). For example, lowering the number of participants required to accept a new transaction could push a large volume of transactions through but could be more error prone, leading to issues such as "forking" (when two versions of the ledger emerge). Alternatively, a high acceptance rate could create a more accurate dataset but be slower in validating new transactions (Interviewee F).

Two advantages of using blockchain include (a) lower vulnerability to data tampering, as blockchain lists are decentralised and not kept on one verifying list, making the entire network less susceptible to hacking or tampering; and (b) the ability of users to share information more effectively. In order to use a blockchain system, users have to standardise the way they represent data. This prerequisite, in itself, is often a valuable contribution to increasing transparency in the supply chain, one that could allow companies to more easily manage vast amount of data and avoid data overload (Interviewee F).

I conducted interviews with experts in blockchain, tagging and geochemical analysis who are working in gold extraction, trading and logistics, refinery, and product development, to investigate the feasibility of using blockchain as a low-cost mechanism to verify due diligence requirements on artisanal gold. The aim was to interview experts on all aspects of the upstream part of supply chain related to responsible sourcing, as well as experts related to blockchain. We conducted five semi-structured phone interviews, one unstructured in-person interview and due to a unreliable internet connection, one e-mail correspondence. Two interviewees were experienced in blockchain, two in tagging and one in geochemical analysis. Only one expert, who is an expert on blockchain, did not have specific experience in the gold industry. The experts were distributed over the entire gold supply chain: two of the interviewees worked in extraction, one in trading and logistics, one worked for a large Swiss refiner, one worked in product development and one worked for a certification schemes. All interviews, except the e-mail correspondence, lasted between 30 minutes and an hour. Half of the experts were approached for interviews at the "Small-Scale and Artisanal Mining for Sustainable Development" event held by the Swiss Development Cooperation (SDC) in Geneva in July 2018, the other experts were identified ad hoc or by reference. All experts agreed to take part in an interview. I gave all experts the opportunity to comment on the final research brief, of which four responded (see Appendix 5.A for more information).

We find the main issue with applying a digital system such as blockchain to a physical system like gold is the need for a link between the two systems. This means that every gram of gold that is traced needs to be uniquely identifiable in the digital system; the blockchain needs to be able to follow every gram of gold from a responsible source, and be able to differentiate it from other gold. Linking the physical world to the digital one can be done in two ways: (1) as with DNA in humans, by developing a way to analyse the physical product in a way that would allow us to uniquely identify it anywhere in the supply chain; or (2) similarly to a passport issued to an individual, we can add a unique, tamperproof mark or tag to the product (Interviewee F). Although using blockchain could marginally contribute to more transparent gold supply chains, evidence suggests that using geochemical analysis and tagging to link artisanal gold to the digital system are restricted.

5.3 Unique link: Geochemical analysis

Mineral ores have unique morphological, mineralogical and chemical properties that are linked to the specific geological processes through which they were formed. Geochemical provenance analysis can describe ore mined from a specific deposit by analysing these unique properties, similar to how DNA analysis can identify specific individuals. Refiners, who usually do the geochemical analysis, can then estimate where the gold is from by matching its composition to a reference database of the geochemical composition of gold deposits around the world.

Although geochemical provenance analysis or "fingerprinting" of primary gold is scientifically possible, its application is limited due to gold's physical and chemical properties, only the composition and presence of trace and secondary minerals in the ore can be used to create a unique geochemical signature (Melcher et al., 2008; Hruschka et al., 2016).

Secondary and trace minerals are only present in ore concentrates before refining and smelting. While gold shops remove many of the secondary and trace minerals, high-end refiners can remove any remaining impurities to create up to 99.99% pure gold. Geochemical provenance analysis can therefore only be applied before refinement (Epstein & Yuthas, 2011). This implies that the feasibility of using geochemical analysis depends on whether or not refiners consistently analyse the isotopes in impurities of the gold they buy (Interviewee A).

In addition, this method is not feasible when gold ore from different sources is smelted together, as is invariably the case with artisanal mining. For refiners it will be extremely costly to create a reference database, which would involve taking samples of all known gold deposits. This is especially problematic when there are many artisanal miners who continuously move to new gold deposits (Interviewee B). Moreover, even if geochemical analysis could give a unique signature for gold from a specific ore, this might not be detailed enough if one wants to differentiate between multiple miners who mine from the same deposit.

Other advantages of using geochemical analysis

Despite these difficulties with using geochemical provenance analysis as a link between the blockchain system and the real world, this method could mitigate some other issues in the gold supply chain.

Firstly, Roberts et al. (2016) have shown that the processes used by many artisanal operations, such as mercury amalgamation and low-temperature smelting processes, create unique characteristics in the gold, such as traces of mercury, tin and lead.

These metals are not found in gold extracted and processed by industrial mines. Gold from artisanal mines is often traded under wrong origin and declared as scrap gold. The presence of these metals could indicate that at least one of the sources was from an artisanal mine, although the absence of any of these metals is not necessarily proof that gold has been sourced responsibly.

Secondly, geochemical analysis could also be used as a verification tool by confirming that the gold is indeed from the area that the traders claim. In this case a refiner only needs a sample of the ore from where the gold allegedly originates from, instead of a reference database showing the chemical composition of all gold ore deposits in the world.

5.4 Unique link: Tagging

Tagging involves fixing a physical tag to a given quantity of a mineral, much like an individual uses a passport to verify their identity. Tags, or automatic identification devices, include a wide range of technologies used to identify a specific item and track it through the supply chain. Gold is highly recyclable and any tag or marking could easily be removed by smelting the gold, without diminishing its value. However, tags are usually fixed not to the actually mineral but to a tamperproof bag containing the gold.

Similar to issuing passports, tags need to be assigned by a central authority. This weakens the blockchain's trust mechanism, which can reduce the power of using blockchain (Brugger, 2019). A blockchain is a system that does not need a central authority's input; meaning, if a central authority administers tags, the system could resemble a normal ledger instead of a distributed ledger or blockchain.

During bagging-and-tagging projects done in the DRC by the iTSCi (ITRI Tin Supply Chain Initiative), conflict-free tin and tantalum mines received bar codes which were added to the bagged ore, updating information on the bar code manually through the supply chain, and cross-checking with logbooks. Many technical problems hindered the capabilities of these projects. The iTSCi reported instances of untagged bags being smuggled or corruption compromising the operation (Gerritsen, 2013). Many reported that government fieldworkers solicited miners for bribes, a situation which, in the end, closely resembled the one that the project aimed to curb (Vogel et al., 2018). Other issues included a lack of electricity and internet connection impacting information uploads, and logbooks being lost or damaged by bad weather (Bray, 2012; Evans-Pughe, 2010). In addition, the cost of running such a large operation could make it unsustainable (Evans-Pughe, 2010).

A pilot project in the DRC by the German Federal Institute for Geosciences and Natural Resources (BGR) assessing the feasibility of bagging-and-tagging to track gold from conflict-free artisanal mines showed that an automated system could address some of these issues. Four conflict-free artisanal mines were identified and supplied with tamperproof plastic bags with near field communication (NFC) tags. Government fieldworkers were responsible for bagging and tagging the gold at the mines. Various checkpoints in the supply chain were identified and supplied with biometric cards, which automatically updated information when connected to the NFC tag in the bagged gold. All information was stored in the chip and did not have to be recorded manually. The automated nature of the system significantly reduced the cost of tracing the gold (Neumann et al., 2019, Interviewees D and E).

Using tags to link the real world and the blockchain is feasible, but its success still depends on the security and trust in the point of human intervention needed to tag the gold (Brugger, 2019). For such a system to be successful, the country of extraction needs to have certain systems in place. In the BGR pilot study, existing governmental fieldworkers were responsible for bagging the gold, which reduced the cost but could still include a risk of exploitation during tagging. Other important prerequisites include legislation for legal procedures about artisanal mining rights and duties, royalty schemes and governmental structures to enforce the law (Interviewee E).

5.5 Conclusion

Given the numerous difficulties with creating a unique link between the blockchain and the physical gold, it is not feasible to use blockchain to trace the small quantities of gold mined by millions of artisanal miners for the time being. There are two possible links between the blockchain and physical gold. One is to identify gold by its chemical composition, which, like DNA in humans, is inherent to the gold. However, given the many limitations of using geochemical provenance analysis, this is not feasible. Another possible link is tagging, especially since a more automated bagging-and-tagging gold pilot project by the BGR addressed some of the technical issues usually associated with bagging-and-tagging projects. However, the fact that tags need to be added manually reduces trust in the blockchain system.

Although blockchain, and therefore geochemical analysis and tagging, is not the panacea for the problems surrounding artisanal gold mining that many have hoped for, it could be a progressive improvement towards a slightly more transparent supply chain as long as its limitations are kept in mind. For example, geochemical analysis could detect traces of mercury, which could serve as an indication that at least one sources of the gold is an artisanal mine. Alternatively, geochemical analysis could be used to confirm that the stated provenance of the gold is correct. While tagging, especially an automated tagging system, could allow downstream actors to buy from responsible miners within conflict areas, there is a risk that the tagging procedure could create new opportunities for rent seeking and solicitation from those responsible for administering tags. Therefore, while blockchain could contribute to a more transparent gold supply chain, its ability to include responsible artisanal miners in the formal supply chain on large scale is limited.

Appendix

5.A Information on interviews

Persons interviewed

Name	Area of expertise	Date of interview	Review and commented on final version
Interviewee A	Product development	January 2019	Yes, June 2020
Interviewee B	Refineries, geochemical analysis	January 2019	Yes, July 2020
Interviewee C	Logistics and trading	December 2018	Yes, July 2020
Interviewee D	Extraction, tagging and blockchain	December 2018	Yes, October 2020
Interviewee E	Extraction and tagging	January 2019 (email correspondence)	No
Interviewee F	Blockchain	December 2018	No
Interviewee G	Certification	July 2018	No

Tab. 5.1: Details of expert interviews conducted.

Interview structure
Welcome and thank interviewee.
Ask again if they are willing to take part *(already agreed via e-mail and scheduled an appointment before)*
I have a few questions, and would very much like to get your opinion on. Then, we also want to publish this as a policy brief or maybe a journal article, we do not have to name you by name, but would it be ok if we use this interview to supplement our research? I will also send you the article once we are done, you can comment or check that you are satisfied with your comments in the article.
Give background on the study

1. Which of the following methods have you used to manage minerals in a supply chain?

    - Financial auditing
    - Certified suppliers
    - Geochemical Provenance Analysis (Fingerprinting)
    - Tagging
    - Blockchain

    For each of the options chosen, the following question are asked

2. When have you used this method?
3. Why was it necessary to use this method? What issue did you want to manage?
4. For what mineral?
5. Are there any characteristics to this particular mineral that lends itself better to this method? In other words, can you also use this method for other minerals in a similar situation?
6. Did you consider using another method to address this issue?
7. Why was this method better than the other methods in addressing this issue?
8. Was there additional advantages in using this method?
9. How costly was it to use the method? (AFP – cost of expertises)
10. Was there any other disadvantages in using the method?
11. (In your opinion what do you think can the method contribute to transparency in the gold supply chain?)

Blockchain questions

1. Potential of blockchain to manage supply chains? Contribution
2. Uses of blockchain outside of cryptocurriencies – what type of problems?
3. Accept new information as correct in non-Bitcoin blockchain systems?
4. Tags – how do you know what you see is correct? Type of product (low smelting point, many miners, etc.)
5. Forking? How big a problem is it?
6. Why does blockchain allow information to be more digestible across parties?
7. Energy usage?
8. Cost?
9. Any contribution to the gold supply chain?
10. Any additional advantages?

Fingerprinting questions

1. What can fingerprinting contribute to gold supply chains
2. Cost of fingerprinting – can it be done on a large scale?
3. Commercial viability
4. Is this done automatically for all gold that comes in?
5. Databases, how costly is it to build up? Given the information that is already available
6. How many sources can be detected?
7. How useful given many ASM?
8. Manipulating chemical analysis
9. Can you differentiate between ASM and LSM on methods used?
10. Any additional advantages?
11. How can fingerprinting be used in certification schemes?

Chapter 6

Certified gold: too many schemes and not enough demand

Single author, research brief published on ETH Research Collection

Abstract: Various gold certification schemes aim to mitigate problems in the gold market, including child labour, dangerous working conditions and pollution. However, the average consumer does not often buy gold and does not understand all the complexities of the gold sector and the role of gold certification schemes. Retailers and banks still mainly drive the demand for certified gold, but they face different constraints when sourcing gold from certification schemes. Investors focus mainly on cost, while jewellers are a diverse group from small goldsmiths to large international companies, all with different motivations and incentives.

6.1 The dark side of gold

As early as the Spanish exploitation of the Americas, gold has long been associated with human rights abuses and environmental degradation. We all want to know that children did not mine the gold in our wedding rings and that the gold in the vault did not finance armed groups. Many certification schemes have aimed to alleviate the gold industry's impact at various stages of the supply chain, focusing on different issues and types of mining. The result is a highly fragmented gold certification landscape. In addition, the demand for gold is split into mainly two distinct sectors: the demand for gold jewellery and the demand for gold bars and coins for investment purposes. The different nature of the two sectors further complicates the demand for certified gold. To understand what drives the demand for certified gold I consolidated three lists of existing certification schemes identified from literature, I conducted interviews with experts working in banking, jewellery, and certification (see Appendix 6.A), and I use data from a large-scale household questionnaire (for more information on the sample and survey design and question see Section 7.2 and Appendix 7.A in Chapter 7).

6.2 Certification to the rescue?

Certification schemes are relatively new in the gold industry. I used three sources to identify 14 different certification schemes certifying gold (Fisher & Childs, 2013; Kickler & Franken, 2017; Mori Junior et al., 2015). See Table 6.1.

Most notable schemes include the Good Delivery List and Responsible Sourcing Guidance of the London Bullion Market Association (LBMA), Fairtrade Certified Gold and Fairtrade Ecological Certified Gold, and Code-of-Practices and Chain-of-Custody from the Responsible Jewellers Council (RJC). Many schemes certify multiple metals; for example, the RJC also certifies other metals and stones commonly used in jewellery, such as diamonds and silver.

Certification schemes fall into three main categories. In a product segregation scheme, certified material is kept separate from non-certified material at every step in the supply chain, which is expensive in very complex and long supply chains. In a mass-balancing system, certified and non-certified materials can be mixed, as long as the volume of certified material entering the supply chain is equal to the amount of gold eventually certified. A book-and-claim scheme uses sustainability certificates, similar to carbon credits, to offset some impact during production (Norton et al., 2014).

Name of scheme	Organisation	Metals	Location	Mine type
Conflict-Free Gold Standard (CFGS)	World Gold Council	Gold	Worldwide	Industrial mines
Conflict-Free Smelters Program (CFSP)	Conflict-free Sourcing Initiative (CFSI)	Tantalum, Tin, Tungsten and Gold	Worldwide	Smelters only
Environmental and Social Performance Standards (IFC)	International Finance Corporation (IFC)	All mineral resources		Industrial mines
Fairmined Standards for Gold and Associated Precious Metals (Fairmined)	The Alliance for Responsible Mining (ARM)	Gold, silver and platinum	Latin America, Caribbean, Africa, Asia and Oceania	Artisanal mines
Fairtrade Standard for Gold and Associated Precious Metals (Fairtrade)	Fairtrade Labelling Organisations International (FLO)	Gold, silver and platinum	Developing countries	Artisanal mines
GRI Reporting Principles and Standards Disclosure and Sector Supplement	Global Reporting Initiative (GRI)	All mineral resources		Industrial mines
International Cyanide Management Code (ICMC)	International Cyanide Management Institute	Cyanide and gold	Worldwide	Industrial mines
International Standards Organisation 14001 (ISO14000)	ISO Environmental Management System		Worldwide	
LBMA Good Delivery Refiners & The Responsible Sourcing Program	The London Bullion Market Association (LBMA)	Gold	Worldwide	Refiners only
Minerals Certification Scheme of the International Conference on the Great Lake Region (ICGLR)	Public-private coalition	Tin, tantalum, tungsten and gold	Great Lakes Region, Africa	Industrial and artisanal mines

Continued on next page

Tab. 6.1 – continued from previous page

Name of scheme	**Organisation**	**Metals**	**Location**	**Mine type**
RJC Council of Practices and RJC Chain-of-Custody Standard	Responsible Jewellery Council Code of Practices (RJC)	Diamonds, gold and platinum group metals	Worldwide	Industrial mines
Standard for Responsible Mining	Initiative for Responsible Mining Assurance (IRMA)	All mineral resources	Worldwide	Industrial mines
Standards for Certified Trading Chains (CTC)	Ministry of Mines of DRC	Tantalum, Tin, Tungsten and Gold	Democratic Republic of Congo	Artisanal mines
Sustainable Development Framework (SDF)	International Council on Mining and Metals (ICMM)	All mineral resources		Industrial mines
Towards Sustainable Mining (TSM)	Mining Association of Canada (MAC)	All mineral resources	Canada	Industrial mines

Tab. 6.1: List of certification schemes operating in the gold sector. Complied from schemes listed in Fisher & Childs (2013); Kickler & Franken (2017); Mori Junior et al. (2015)

Each certification scheme determines its own standards, methodology to verify compliance and scope of operation, including where in the world they operate, which part of the supply chain and whether they focus on industrial mines, artisanal mines or both. While the LBMA ensures gold and silver bars' assay and weight standards, Fairtrade sets and verify various environmental, social, and economic standards in the artisanal mining sector. Unlike Fairtrade Gold, most certification schemes do not advertise directly to consumers. For example, RJC certification mainly aims to verify responsible practices between businesses and is not a well-known consumer label.

The diversity and quantity of these certification schemes highlight the complexity and fragmentation of the gold certification landscape. In addition, despite the many different certification schemes, the demand for certification schemes are low. For example, the market share of Fairtrade Gold is about 0.35% in 2020.[1]

6.3 Demand for gold

Unlike other metals, gold has a sizeable direct consumer market. Although gold is used as an intermediary good, for example in electronics, gold as a final good is a considerably larger market. Since 2010 jewellery and the financial sector made up more than 77% of the global demand for gold (see Figure 6.1). The demand for jewellery includes end-user demand for newly made carat jewellery and gold watches. Gold investment demand includes exchange traded funds (ETFs) and bullion bars and coins.

Despite a large share of gold being purchased directly by consumers, the average consumer does not often buy gold. In a household survey I conducted in collaboration with researchers at Development Economics Group in 2018, 94% of respondents (n=2505) said they did not buy gold jewellery in the last year, 79% and 87% said they have never bought bullion bars or coins as a gift or investment, respectively (see Appendix 7.A in Chapter 7 for survey questions).

Moreover, certified gold is a type of credence good, which are goods with qualities that could be worthwhile to pursue, but cannot be assessed by normal consumption and is costly to verify (Darby & Karni, 1973). Labelled certified goods, such as Fairtrade, are often regarded as a type of credence good (Andorfer & Liebe, 2015; Hainmueller & Hiscox, 2015) because they include characteristics that cannot be verified during consumption, such as child-free labour conditions or certain environmental standards during production. A consumer is unable to "learn" about their preferences by merely consuming credence goods. Some researchers argued

[1] Using values from Fairtrade Annual Report 2020, selling Fairtrade gold worth CHF 8,071,213, which at the average annual gold price in 2020 (CHF 53.3 per gram) is about equal to 152kg of gold. Compared to total demand in Switzerland in 2020, which is estimated at 42.9 tonnes(World Gold Council, 2021c)

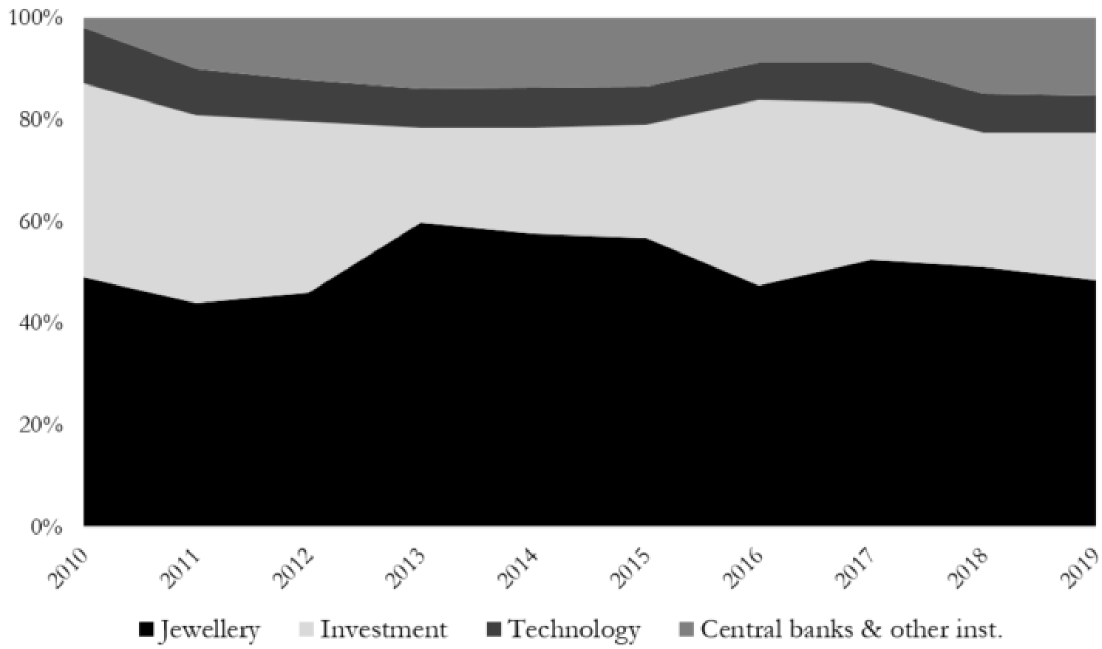


Fig. 6.1: Demand for gold from 2010 to 2019. Data: World Gold Council.

that certified goods are not strictly speaking a credence good because consumer can actually see the certification label and that certified goods are rather indeterminate goods because experts cannot agree if the certification scheme has an effective impact on the lives of workers (Balineau & Dufeu, 2010). It is therefore important for consumers to trust certification scheme to be able to meet the requirements they set (Hainmueller & Hiscox, 2015).

If consumers want to know more about a certified product, they can consult the certification scheme directly, access it online or consult the retailers at point of purchase. In the household survey on Fairtrade conducted in 2018, about 90% of respondents (n=2,951) said that they are either very familiar or somewhat familiar with the Fairtrade logo, while 91% of respondents said they have never visited the Fairtrade website (see Appendix 7.A for questions in Chapter 7). Although consumers know the Fairtrade brand, they either do not know what certification entails exactly or rely on retailers for additional information.

Retailers, such as jewellers, and banks are therefore the main drivers of demand for certified gold in two important ways. First, retailers, and not the certification schemes, are usually in direct contact with consumers, and need to address consumers' concerns about negative externalities in the supply chain and answer consumers' questions regarding certification schemes. Second, retailers are considered a critical point to increase the saturation of a certified good. For example, a major reason why bananas have one of the highest market saturation of all Fairtrade products in Switzerland is that the largest retailer in Switzerland, Coop, decided to sell only Fairtrade bananas (Fairtrade, 2018).

6.3.1 Demand for certified gold jewellery

Jewellers sourcing gold responsibly might not necessarily want to communicate this to consumers for marketing reasons. Connecting jewellery—marketed as luxurious and exclusive products with sustainability labels associated with fruit and vegetables such as Fairtrade could reduce the jewellery's perceived worth (Grünenfelder et al., 2018; Achabou & Dekhili, 2013).

However, the tide could be turning, as demand for ethical consumption is increasing in the gold industry. A small goldsmith in Switzerland mentioned that while he needed to convince consumers of the merits of Fairtrade Gold only a few years ago, customers now approach him specifically to buy certified jewellery (Interviewee X). However, these small goldsmiths probably disproportionately attract customers who care about ethical consumption. Larger retailers have not reported the same pressure from their consumers (Interviewee W). The most significant determinant of demand for certified gold is still retailer demand, which is itself influenced consumers (Interviewee Z).

Large companies' demand for certified gold is growing mainly to proactively avoid a scandal or criticism due to unethical conduct (Interviewee W). Smaller organisations, such as one-person goldsmiths, have a high demand for ethically sourced gold, as they are intimately involved in the production process and feel responsible for ensuring best practices. Medium-size retailers do not have the same risk of scandal nor close connection the product, and generally have a lower demand for certified gold. Even if medium-size retailers want to source gold more responsibly, they often use semi-finished products leaving them with less control over their production than large and small retailers who produce their products from raw materials (Interviewee X). However, the total demand for certified gold in the jewellery sector remains relatively low, since small goldsmiths who probably have the highest demand for ethical gold only account for a small percentage of the total gold used in the jewellery sector (Interviewee Z).

6.3.2 Demand for certified gold investments

The cost to operate the certification label and ensure that standards are upheld makes certified gold more expensive. The price mark-up for certified gold is more important for investors than for jewellers. Since gold is only a part of the total cost of a jewellery piece and labour and operating costs could be high, the additional cost due to certification is small for jewellery (Interviewee X). However, gold bullion bars are made of 99.999% pure gold and are directly purchased from the refiner. Therefore, the additional cost of certification is directly transferred to the price of the bar. For large investors, switching to certified gold is expensive, especially for those who would like to replace their current stock of gold with certified gold.

In addition, while there are many gold certification schemes, only a few, most notably Fairtrade Gold, have any brand recognition on the consumer level. Investors are even less willing to pay more for certified gold if they have never heard of the label (Interviewee Y). Given the limited supply of Fairtrade Gold, banks such as ZKB can only sell Fairtrade Gold in small bars (1g -10g only). In addition, due to travel restrictions of commercial and cargo air travel during the COVID-19 pandemic, many certification schemes were unable to get the gold from the mine to the market, further restricting supply.

The supply of certified gold is insufficient to meet the total demand for gold investments and replacing existing stock. Banks need to consider a mix of sources, not only certified gold with high brand recognition but also to educate investors on lesser-known certification brands (Interviewee Y). Book-and-claim certificates could be used to offset the impact of existing gold stock. Increasing transparency on the provenance of gold to the mine level will also add to investor confidence and help keep the downstream industry accountable. Banks play a pivotal role in increasing the demand for certified investment by educating investors and making a more comprehensive range of certification schemes available (Interviewee Y).

6.4 Conclusion

While consumer demand for ethical gold is increasing, retailers and banks are still the driving force for certified gold. However, jewellers and banks face different concerns when sourcing certified gold. The additional cost of certification is a more significant issue for investors than for jewellers; since gold is only a small part of the total cost of a piece of jewellery, the certification mark-up is smaller. Through different motivations, small and larger retailers are more likely to demand certified gold than medium-sized retailers. In addition, since certified gold is very costly to investors and in short supply, banks would need to diversify their sources of responsible gold.

Appendix

6.A Information on interviews

Persons interviewed

Name	**Affiliation**	**Date of interview**	**Review and commented on final version**
Interviewee W	International retailer	November 2018	No
Interviewee X	Goldsmith	February 2021	Yes, May 2021
Interviewee Y	Banking and trading	February 2021	Yes, May 2021
Interviewee Z	Certification	January 2019	Yes, May 2021

Tab. 6.2: Details of expert interviews conducted.

All experts agreed to be interviewed before and scheduled an appointment. All interviewees were given the opportunity to comment and verify the final research brief. I wanted to interview experts from various aspect covering the demand of certified gold, including various types of demand (banking, large jewellery retailers and small goldsmiths), and certification. Since few people have experience with selling certified gold, interviewees were identified by opportunity, by relying on references.

Guiding interview questions

- How did the pandemic effect all and certified gold supply?
- Do you feel any pressure from consumers to sell responsibly sourced gold? If not, any specific reason why you sell Fairtrade Gold?
- In your experience, are consumers interested to learn more about certified gold?
- Do you think if consumers know gold is certified or recycled, that they perceive it as less valuable?
- What options do you as retailer/banker have available to source gold responsibly? If many options, how did the fragmented nature influence sourcing?
- Jewellers: How your organisation differ from larger/smaller retailers?
- Banker: Is there a difference in the demand for large and small bars

Chapter 7

Viability of Urban Mining: the relevance of information, transaction costs and externalities

Joint work with Livia Cabernard and Isabel Günther
Paper submitted to Ecological Economics

Abstract: Phones are one of the most commonly owned personal electronic devices and they contain more than 15 different metals, mostly extracted with severe negative environmental externalities. Sourcing metals from retired mobile phones, i.e. urban mining, could alleviate these effects. In this study, we analyse the viability of urban mining in Switzerland using a representative survey in Switzerland with 2,500 respondents. We estimate that there are around seven million unused phones with embedded gold worth about USD 10 million in Switzerland. People do not particularly value their retired phones: 22% do not know why they keep it, and 40% said they are willing to sell their old device for USD 5 or less. Based on a follow-up experiment with 15,000 employees at one Swiss institution, we find that the high transaction cost of recycling limits return rates. While informational treatments did not change recycling rates, reducing transaction costs doubled return rates from 2.1% to 5.5%, making it more cost effective. Lastly, while urban mining is not economically viable if we only consider the market value of embedded metals, it is profitable when taking into account the total environmental cost of producing a new mobile device with metals from a primary mine.

7.1 Introduction

Mining has expanded worldwide, particularly in Africa, to supply the growing demand for metals in various sectors such as renewable energy and consumer items (Ali et al., 2017; Christensen, 2019), including mobile phones and smartphones. For example, a smartphone has, amongst others, large quantities of iron, tin, nickel, copper, aluminium, and chrome and smaller amounts of metals such as cobalt, tungsten, tantalum, silver, and gold (Williams, 2019; Rasmi, 2019). While the mining industry has had a positive effect on the economies of many resource-rich countries in Africa in recent years, it also has had significant adverse environmental and social impacts; including deforestation, heavy metal pollution, demanding large areas of land, as well as various human rights abuses such as child labour and financing of terrorist activities (Bell & Donnelly, 2006; Younger et al., 2002; Down et al., 1977; Tratschin et al., 2017; Feichtner et al., 2019; Stiglitz, 2005).[1]

Various initiatives have focused on alleviating mines' negative local environmental impacts; including, making extractive activities more transparent (such as the Extractive Industry Transparency Initiative) or certifying companies to uphold best practices (such as Fairtrade Gold or the LBMA Responsible Sourcing Guidance). However, negative upstream impacts of mining in low-income countries can also be alleviated by changing consumers' behaviour in high-income countries, such as using electronic devices longer and recycling them at the end of life.[2] Recovering metals from retired mobile phones – a form of urban mining – has a threefold positive effect; firstly, reintroducing metals back into the supply chain can alleviate pressure on primary sources and contribute to a circular economy (Hira et al., 2018; Scharnhorst et al., 2005). Secondly, avoid the negative environmental externalities linked to metal mining (Bell & Donnelly, 2006; Younger et al., 2002; Down et al., 1977). Thirdly, reduce the potential amount of e-waste, which is one of the fastest-growing waste streams in the world (Gu et al., 2019).

Increasing recycling of electronic devices requires both technical advancements to extract metals from electronic devices and altering the behaviour of people to return their old devices for recycling. While many studies have focused on the techniques and method of recovering metals' from electronic waste (Kang & Schoenung, 2005; Zeng et al., 2018; Sun et al., 2018), less research has focused on how to increase return rates of unused electronic devices in high-income countries, one of the significant obstacles to increase recycling.

[1]More literature on the environment degradation caused by mining see Razo et al. (2004); El Azhari et al. (2017); Valente & Gomes (2009); Mwaanga et al. (2019) and instances of human right abuses see Farrell et al. (2012); Bento (2017); Hilson (2010); Fritz et al. (2018).

[2]While responsible recycling practices are important to alleviate the negative externalities of the sector, the topic falls outside the scope of this study. However, all electronic devices recovered in our Urban Mining Experiment will be recycled with Immark AG who are certified recyclers and ensure data protection.

Our study consists of three parts to analyse the viability of urban mining of old mobile phones in Switzerland. First, we conducted a survey with a representative sample of 2,500 German-speaking Swiss about their mobile phone usage and recycling behaviour. Second, using the survey results, we designed a randomized controlled trial with 15,000 employees at one Swiss institution to test different mechanisms to increase the collection of hibernating devices via a mail-back envelope. Last, and linked to the high cost of any treatment to collect retired phones in our field experiment, we conducted a cost-benefit analysis to compare the cost of collecting the mobile phones against the environmental savings calculated with a life-cycle and multi-regional input-output analysis (Stadler et al., 2018; Cabernard et al., 2019).

We focus on mobile phones, as they are not only one of the most commonly owned personal electronic devices, but also the personal electronic device with one of the shortest lifespan in many high-income countries, including Switzerland (Thiébaud et al., 2018), Germany (Prakash et al., 2016), Spain (Bovea et al., 2018), and the United Kingdom (Ongondo & Williams, 2011).

Previous studies have analysed the impact of single information campaigns or available collection methods on the total number of phones collected (Litchfield et al., 2018; Ongondo & Williams, 2011; Silveira & Chang, 2010; Tanskanen & Butler, 2007). These studies lack both a control group as well as information on the total number of people in the treatment group and are, hence, unable to calculate the impact of specific campaigns on return rates. The only notable exception is Litchfield et al. (2018) who estimate the efficiency of various methods to collect phones, such as collecting phones as part of an awareness campaign, distributing mail-back envelopes to the public or advertising recycling opportunities online. For example, the method that collected the most phones (called "Courier Collect") entailed a mass email campaign, asking people to collect phones and return them for recycling using a printable voucher available online, which means the exact number who received the information is not known. Therefore, although the Courier Collect method recovered the most phones, they are not able to calculate the return rate – or efficiency – of the method.

Therefore, these studies were not able to record the number of people that were effectively treated, and relied on estimations to determine return rates. As Ongondo & Williams (2011) write: "Information about the quantities of mobile phones collected by the various schemes is very sparse... Due to data gaps, it is not possible to conclude which category of takeback scheme is most successful." Our study contributes to filling this research gap by systematically testing different collection campaigns in a randomised controlled trial (RCT) with a control group, controlling treatment exposure, and minimising spill overs across groups.

We also contribute to the existing literature by comparing the cost-effectiveness of the various urban mining methods. Many RCTs in economics focus primarily on testing the effectiveness of the intervention and not whether it is cost-effective (Evans, 2016; Barrett & Carter, 2010). While Litchfield et al. (2018) show the cost to collect a phone using various collection methods, they only consider the production cost of the satchels in which people could return their phones, but did not include other costs of the various collection methods. In addition, Litchfield et al. (2018) also mention the amount of landfill space recovered but not a comprehensive analysis of environmental savings in monetary values. We consider both the market values of metals embedded in a phone and monetise a broader range of environmental savings when calculating the benefits of urban mining.

The remainder of this paper is structured as follows: the second section outlines the method, data, and results from the representative Swiss survey. The third section describes the method and results of the RCT combining mail-back envelopes with various information treatments and transaction costs. The fourth section is a cost-benefit analysis which details the cost of collecting the mobile phones with the various methods against the environmental savings calculated with a life-cycle and multi-regional input-output analysis. The fifth section discusses the results and limitations of the study and concludes with further avenues for research.

7.2 Recycling behaviour in Switzerland

7.2.1 Method and data

To understand mobile phones' usage and disposal in Switzerland, we conducted an online survey with a representative sample of 2,500 adults in German-speaking Switzerland in October 2018.[3] The survey was administered by LINK, who has the largest and most representative online panel with more than 115,000 registered adult panellists who take part in various surveys (www.link.ch/en/). The questionnaire included, besides demographics, a wide range of questions on the current and old mobile phones of participants (see English translation of the questionnaire in Appendix 7.A). In addition, we elicited participants' opinion of the biggest problems in gold mining. The questionnaire results were used to understand phone usage and recycling behaviour in Switzerland and inform the design of the urban mining experiment.

The participants came from 22 cantons in Switzerland with a German-speaking populations of the total 26 cantons in the country. The pure French cantons Jura, Vaud and, Neuchâtel, as well as the Italian canton, Ticino, were not represented

[3]Switzerland has four official languages, Swiss German or German is the most common language; spoken by more than 62.6% of the country and the predominant language in 19 of the 26 cantons in Switzerland. The other languages are French (22.9%), Italian (8.2%) and Romansh (0.5%; Federal Statistical Office of Switzerland, 2019). The survey was conducted only in German-speaking Switzerland due to budget constraints.

in the survey. The largest shares of our survey come from the cantons of Zurich (24.4%), Bern (16.5%), and Aargau (11.8%) which are also the cantons with the largest shares of the German population in Switzerland.

Table 7.1 compares sample means to the means for the entire Swiss population and the German-speaking population using national and cantonal averages published by the Federal Statistical Office of Switzerland (2021). We calculated the German-speaking averages by weighing cantonal means with the official percentage of the German-speaking population living in that specific canton. All federal data is from 2018, the same year in which we conducted our survey. Our sample is very similar to the German-speaking Swiss population, with the exception that our sample shows somewhat higher educational levels and a higher percentage of part-time employment and slightly lower levels of unemployment.

	Sample	**Swiss national**		**German-speaking**	
	average	**Average**	**p-value**	**Average**	**p-value**
Percentage men (age >18)	49.6%	49.6%	0.973	49.5%	0.857
Average age (age >18)	50.2	49.6	0.097	49.7	0.259
Average size of household	2.4	2.2	0.000	2.2	0.000
Education (age >25)					
Compulsory secondary only	4.0%	19.2%	0.000	17.5%	0.000
Additional secondary education	56.6%	45.8%	0.000	48.1%	0.000
Tertiary education	39.4%	35.0%	0.000	34.4%	0.000
Employed					
Full-time employed	42.6%	42.3%	0.762	43.3%	0.480
Part-time employed	24.3%	19.2%	0.000	19.9%	0.000
Unemployed	1.9%	3.1%	0.001	2.5%	0.055
Inactive in education	5.5%	6.3%	0.100	5.6%	0.827
Other economic inactive	25.8%	26.9%	0.215	28.1%	0.011
Yearly household income after tax					
Less than USD 50,000	19.4%	USD119,417		USD 120,661	
USD 50,000 – USD 99,999	42.1%				
USD 100,000 – USD 149,999	24.4%				
More than USD 150,000	14.2%				

Tab. 7.1: Comparison of national and German-speaking to the sample means. Federal statistic on employment is given for individuals 15 and older, our employment averages are for participants 18 and older. Since the national averages for education are given for individuals 25 and older, we also restricted our sample to this age group for education. Other economic inactive mostly consist of pensioners, and homemakers but also include other inactivity, for example due to ill health or civil service. The p-values of the hypothesis that the difference between the sample mean and each of the national and German-speaking means are not equal to zero.

Half of the sample is female (50.4%).The average age of participants in our study is 50.2 years and average household size 2.4. Participants in our sample who are 25 and older are highly educated with almost 40% having completed tertiary education[4] and an additional 56% having completed more than compulsory secondary education. Last, only 1.9% in our sample are unemployed. Since we asked participants to report their total household income before taxes, including pension subsidies in 2017, in income brackets (see questionnaire in Appendix 7.A), we are not able to calculate the average income per household. Most participants in our sample report a total household income between USD 50,000 and USD 150,000 per year. For comparison: the Swiss mean household income is around USD 120,000 per year.[5] Majority of the sample (91.1%) were born in Switzerland, and on a political spectrum from left (zero) to right (ten), the average person political orientation is 5.11.

7.2.2 Results

The average phone in use was bought two years and two months ago for men and two years and five months for women; 16.2% of phones were bought in the last year, 40.7% in the previous two years, and 68.2% were bought in the previous three years. Only a quarter of people said they replaced their previous phone because it broke and it was not repairable (Table 7.2). About 20% said they just wanted a new or better phone, and 15% said they could not update the software and another 15% said the phone was broken, but no attempt was made to repair it. When controlling for the various parameters (size of the household, participants' sex, age, political views, education, employment and country of origin) respondents with a higher household income and younger respondents were more likely to have bought their current mobile phone more recently (see Table 7.3, column 1). We also find that about 30% more women than men replace their phone because it is broken whereas 50% more men than women buy a phone because they just want to have a new phone.

The second important question is what people do with the retired mobile phone once they replace it. We find that less than 1% of people discard their old phone in normal municipal waste (Table 7.2), similar to studies done in other high-income countries such as Australia (Islam et al., 2020), Germany (Gurita et al., 2018), Scandinavia (Baxter & Gram-Hanssen, 2016), and the United Kingdom (Speake & Yangke, 2015; Ongondo & Williams, 2011). However, only about 25% of people recycled their previous device or gave it back to the service provider. Low levels of recycling are not likely due to ignorance about where to recycle old phone: 57.8% said they know where to recycle their old phone and 29.8% reported that they

[4] Tertiary education include any degree at the Federal Institute of Technology (ETH Zurich or EPFL) or other universities, including universities of applied science and teacher training.

[5] All values in survey were asked in Swiss Francs (CHF) but converted to USD with a 1:1 exchange rate. The average exchange rate for 2018 was CHF 1: USD 1.02 (source: ofx.com)

can easily find out. We find that the higher participants think the national phone recycling rate is, the more likely they are to have recycled their previous phone. Of course, causality can go in either direction here. We also find that the age and income category of the respondent was positively correlated to reportedly recycling their previous phone. People who were born in Switzerland were 7.7% more likely (significant on 5% level) to report that they recycled their previous phone (Table 7.3, column 2).

	Total	**Men**	**Women**	**Difference**
A. Why have you replaced your previous phone? (n=2,318)				
Broken, not repairable	26.0%	22.2%	29.7%	-7.5%***
Broken, no repair attempted	14.4%	14.4%	14.3%	0.1%
Wanted new phone	20.8%	25.6%	16.3%	9.3%***
Unable to upload software updates	15.7%	15.4%	16.0%	-0.6%
Too slow	7.9%	7.7%	8.1%	-0.5%
New phone with contract	7.6%	8.7%	6.5%	2.2%**
New phone as gift	7.6%	6.1%	9.1%	-3.0%***
B. What have you done with your previous phone?(n=2,318)				
Still at home	53.1%	52.4%	53.8%	-1.3%
Recycled or returned to service provider	25.3%	25.0%	25.6%	-5.6%
Donated	15.4%	15.6%	15.2%	0.4%
Sold it	4.3%	5.0%	3.5%	1.5%*
Normal refuse	0.4%	0.4%	0.4%	0.0%
I do not know	1.5%	1.5%	1.5%	0.0%
C. If still at home: Why do you keep your old phone? (n=1,231)				
I do not know	22.1%	19.8%	24.4%	-4.6%*
As a back-up device	41.3%	45.4%	37.1%	8.3%***
Sentiment of collector	8.1%	8.2%	8.1%	0.0%
To protect data	7.5%	6.3%	8.6%	2.3%
Use with second simcard	3.6%	4.3%	2.9%	1.5%
Use without simcard	17.5%	16.0%	19.0%	-3.0%

Tab. 7.2: Reasons for replacing and keeping previous phone. Percentage of men and women who gave the following answers for three questions: (1) the reasons participants gave for replacing their previous phones, (2) what people did with their last phone; and (3) why they keep their previous phone at home; uses without a simcard include using the phone as toy, to store data, or other non-sim uses such as using old phones as an alarm clock. Questions were not open-ended; participants could choose one option per question shown in the first column (also see survey in Appendix 7.A). All participants who said they owned more than one mobile phone and their previous phone were not stolen or lost received the first and second questions (n=2,318). All participants that said they still have their phone at home received the third question (n=1,231). The last column shows the difference between men and women and whether it is significant on the 10% level (*), 5% level (**), or 1% level (***).

The majority of people (53%) still have their previous phone at home (Table

7.2). Moreover, about 70% of participants in our survey report to have at least one of their old unused mobile phones at home. Half of the households have even two or more old and unused mobile phones at home. We estimate that there are between 6.4 and 7.1 million[6] unused mobile phones in Switzerland, which includes an estimated 242kg of gold worth about USD 10.8 million.[7]

In a third step, we analyse why people keep their old phone at home (Table 7.2). About 20% of participants said that they still use their old phone, either for another sim card or without a sim card, e.g., to store data, as an alarm clock, to listen to music, or as a toy for children. Another 7.5% keep their phone because they are unsure of what will happen to their data once they recycle it. The other 70% of participants do not use it anymore: 22.1% said right away that they do not know why they keep their old phone, 8.1% said they keep it due to sentiment, and 41.3% say they keep their phone as a back-up device if their current phone breaks. However, given the estimated young age of phones in use in our sample, it is unlikely that households would reuse an old phone except for a very short time. Moreover, of this group, 15.4% were not even sure if their old phone still works. These results are largely in line with a qualitative study by Gegenbauer & Huang (2012), who conducted in-depth interviews with 17 households in Switzerland, and found that respondents mostly hold on to their old devices because they feel it might be useful in the future, because the device still has sensitive data, or because they have a personal history and sentimental attachment to the device.

To summarize, about 70% of phones lying around in Swiss drawers are not in use anymore and could be recycled without significantly reducing their owners' utility. This interpretation is confirmed by a willingness-to-sell question that we included in the survey: we asked each participant if they are willing to sell their phone for a price between USD 2 and USD 100 that we randomly assigned to each respondent. Since we estimate that the total metals' market value in an average phone is about USD 1.68 (see Appendix 7.G for details) and it costs at least USD 99.20 to buy a new smartphone,[8] we offered all participants a price higher than the metals in their phone but not higher than USD 100. Due to the randomisation of the price offered, each price was offered to around 15 to 39 people.

We find that participants have a relatively inelastic price elasticity of (stated) second-hand mobile phone supply: for every 1% increase in phones' buy-back price,

[6]We asked participants how many unused mobile phones they have at home and the size of their household, which we used to estimate the average unused phone per person in our sample. We then extrapolated it to the entire population of Switzerland (8,544,527 in 2018; Federal Statistical Office of Switzerland, 2021). We estimate on a 95% confidence interval that there is between 6,369,768 and 7,050,032 unused phones in Switzerland.

[7]Amount of gold per mobile phone is 0.036g as indicated by Williams (2019), at annual average gold price of 2019 (World Gold Council 2020).

[8]Model Blackview A80; prices taken on 22 February 2021 on digitec.ch.

participants' stated willingness-to-sell increases by only 0.2%. The variance in the willingness-to-sell old devices at a certain price is, however, also high (see Figure 7B.1 in Appendix 7.B). Already 44.4% of people said they were willing to sell their phone for USD 2 - 5. However, even though most buy-back schemes in Switzerland would pay more than USD 5 for a phone[9], only 4% of participants sold their old device. In contrast, significantly more people (15.4%, Table 7.2) just gave their old device away for free, a further indication that increased buy-back prices will not substantially impact willingness to sell in a high-income country such as Switzerland.

Our hypothesis is that people favour keeping their phone at home instead of recycling it because of inertia. One reason for inertia could be loss aversion (Thaler & Sunstein, 2017); however, we do not believe that loss aversion is the main reason for not recycling old phones. While loss aversion could explain the relatively inelastic supply curve of obsolete phones, the low intercept of the stated supply curve indicates the contrary. According to the stated supply curve, more than 40% of participants should be willing to sell their phones for as little as USD 2 - 5. An alternative explanation from psychology is that inertia could be driven by ownership; people associate the good they own with themselves and are therefore reluctant to give it up (Morewedge et al., 2009). However, if this is the case, people are not aware of it: only 8.1% of our sample said they keep their old phone for sentimental reasons.

Based on our survey results, we, hence, suggest that one of the main reasons for this inaction to recycle is due to the high transactional cost of recycling. Recycling can have a high individual transactional cost, associated with the high opportunity cost of time spent on various tasks to recycle (Berglund, 2006, pp: 561-562), such as remembering to recycle the phone, taking the initiative to do so, finding the phone, finding out where to recycle it, and sending or taking the phone to such a point. Reducing the transactional cost of recycling could significantly increase recycling rates. In addition, our results suggest (see Table 7.2, section C) that better informing people about secure data protection and reminding people about their old device in a drawer could also increase recycling rates as informing people about the recycling behaviour of others (see Table 7.3, column 2). We test all interventions in a next step conducting an RCT with 15,000 employees of a Swiss institution.

[9] Service provider Sunrise offers to buy back an old iPhone, depending on the model, for a price between USD 16 and USD 456, and an old Samsung Galaxy between USD 13 and USD 238 (prices taken on 5 November 2020; see Sunrise (2021).

	Age of phone in years	**Recycled last phone**
Estimated national phone recycling rate		0.004***
		(0.000)
Age of phone in years		0.028***
		(0.005)
People in household	0.012	0.011
	(0.034)	(0.010)
Female	0.070	0.023
	(0.097)	(0.021)
Age of respondents	0.031***	0.002***
	(0.003)	(0.001)
Born in Switzerland	0.199	0.077**
	(0.153)	(0.032)
Political views (0= left to 10= right)	-0.011	-0.004
	(0.024)	(0.005)
Reference group: income less than USD50,000		
Income: USD50,000 – 100,000	-0.383**	0.077**
	(0.150)	(0.032)
Income: USD 100,000-150,000	-0.478***	0.101**
	(0.158)	(0.039)
Income: more than USD 150,000	-0.503***	0.071
	(0.182)	(0.046)
Reference group: Compulsory education only		
Secondary education	-0.565*	0.077
	(0.318)	(0.059)
Tertiary education	-0.532	0.072
	(0.324)	(0.065)
Reference group: Unemployed		
Employed	-0.481	-0.028
	(0.467)	(0.093)
Inactive	-0.464	-0.020
	(0.476)	(0.089)
Constant	1.841***	
	(0.538)	
Observations	1,929	1,820
(Pseudo) R-squared	0.070	0.076
Regression analysis	Multi-linear	Logit

Tab. 7.3: Age of phone and recycling behaviour. Linear regression model showing coefficients of multiple control variables to age of phone in years (1) and marginal effects of logit regression model showing various correlations to people who previous recycled their phone or gave it back to the service provider. Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, and * $p<0.1$

7.3 Increasing recycling rates – RCT

7.3.1 Experimental design and data

Using the results from our own survey and based on previous literature on recycling behaviour (Czajkowski et al., 2017; Allcott, 2011; Goldstein et al., 2008; Frey & Meier, 2004; Chan & Bishop, 2013; Berglund, 2006; Ito et al., 2015; Geiger, 2020), we designed a field experiment to obtain a better understanding of the nudges that could increase the recovery rate of old phones.[10] We use a mail-back envelope method in the experiment, which involves envelopes distributed to people, which they can use to mail back their old phones for recycling. The mail-back envelope method allows us to randomly add messages to analyse the impact of different types of information and randomise the level of transaction costs by including postage for some envelopes (reducing cost and mostly time for the participant) and not for others. We used mail-back envelopes to analyse the effectiveness of various informational treatments instead of static displays or advertising campaigns for three key reasons: (1) it enables us to randomise treatments at an individual level; (2) we can control who is treated and reduce spillovers; and (3) we can reach a larger audience.

We worked together with the ETH life magazine, a magazine distributed to all employees of ETH Zurich. The magazine was interested in participating in this experiment in an effort to make ETH more sustainable by collecting unused mobile phones from ETH employees. The magazine is distributed four times a year and is sent to about 15,000 people. Employees can choose if they want to receive a magazine at their home or office address; most magazines (87.6%) are delivered to employees' home addresses. The high percentage of magazines sent to home addresses reduces the potential for spill overs. The magazine is distributed in German (about 10,500 copies or 70.9%) and English (about 4,300 copies or 29.1%). Employees can decide which language they want to receive. The percentage of Swiss people is very likely much higher among employees who opted for the German issue – but we do not have exact numbers. Employees receive the magazine for free, and they can opt-out of the magazine at any time. We included a mail-back envelope in each copy of the magazine for the October 2019 edition, which was sent out in batches during the first two weeks of October 2019. Recipients were asked to return envelopes by 31 October 2019, but we received many envelopes afterwards (see discussion below).

We developed eight different envelopes, which were translated into English and German, meaning there are 16 different types of envelopes (see Appendix 7.C). We randomly allocated envelopes across the magazines, and recipients did not know that the envelope was part of an experiment. For ethical reasons, we notified people that they were part of an experiment in the July 2020 issue of the magazine.

[10] The experiment was reviewed and approved by the ETH Ethical Commission (Number: 2019-N-109)

The first envelope (*env1_postage*) only indicated that people should recycle their phone ("recycle your old phone"). This envelope also included return postage that allowed recipients to mail the phone back through traditional mail (and with mailboxes distributed across Switzerland) without buying postage (see Appendix 7.C). The second envelope (*env2_nopostage*) was the same as the control, but postage was not included. Recipients of this envelope could either buy the postage and mail it via Swiss post or drop the envelope off at the university's Campus Info. Campus Info is a well-known location on campus, with two prominent service desks, one on each of the university's two main campuses. This treatment group had the highest transactional cost to participants; they needed to buy the correct postage, which involves both time and money, or take the phone to a collection point on campus.

The third envelope's message (*env3_social*) was based on a behavioural theory and empirical studies that suggest people tend to align their behaviour according to the perceived social norm (see for example, Czajkowski et al., 2017; Allcott, 2011; Goldstein et al., 2008; Frey & Meier, 2004). This correlation between behaviour and the perceived social norm was also evident in the survey: participants who thought the national recycling rate of phones were higher, we more likely to have recycled their previous phone (Table 7.3). In this treatment, we therefore notified participants that recycling rates in Switzerland are almost ten times higher than in the rest of the world: based on our survey, 25% of participants recycled or had returned their last retired phones to their services provider, which is high compared to the global average of 3% (SENS, SWICO Recycling & SLRS, 2011). In the survey, we also asked people what percentage of people in Switzerland they thought recycled their old phone. On average, respondents thought the recycling rate of old phones is much higher (38%) than the actual rate (25%). Given that people thought the recycling rate in Switzerland was much higher than the actual rate, we believe *env3_social* would, on average, rather be a priming treatment than an informational treatment. The message on the fourth envelope (*env4_nature*) underlined the moral obligation to recycle for the sake of the environment by asking recipients to recycle their phone for nature's sake and that it is the "right thing to do." Several previous studies on electricity use, paper cups, and kerbside recycling have suggested that pro-recycling campaigns that use moral suasion and an association with nature are effective (Chan & Bishop, 2013; Berglund, 2006; Ito et al., 2015; Geiger, 2020).

The remaining four informational treatments were chosen based on the results from our survey in Switzerland. Since gold constitutes 87% of the total value of all metals in a phone (see Table 7G.1), we asked people in the survey what they think are the biggest problems in the gold mining industry. The four most common concerns that people mentioned were related to labour conditions in the mines (health of miners, insufficient wages, lack of work security, and child labour) and not environmental issues (such as included in the fourth treatment, *env4_nature*). Therefore, the fifth treatment (*env5_labour*) asks participants if they are worried about working conditions in mines. The sixth treatment (*env6_data*) reassured people that their data would be protected given that 7.5% stated that they do not recycle because of data concerns (Table 7.2).[11] The seventh treatment (*env7_stillworks*) reminded people that they probably do not even know whether their old phone still works (responding to the 40% that said they keep their old phone as a back-up device, Table 7.2). Last, since more than 20% said they do not know why they keep their old devices (Table 7.2), the last treatment (*env8_whykeep*) simply asks people: "Why do you keep your old mobile phone?" Similar to the envelope *env1_postage*, the six informational envelopes also included postage.

Table 7.4 gives an overview of the envelopes, including whether return postage was included, the English version of the message, as well as the number of envelopes of each type and language that was randomly distributed (see Appendix 7.C for an example of German and English envelopes).

Envelope name	**Include return postage**	**Message**	**Distributed**	
			English	**German**
env1_postage	Yes	No additional message	534	1298
env2_nopostage	No	No additional message	528	1298
env3_social	Yes	In Switzerland old mobile phones are recycled almost 10 times more than in the rest of the world.	544	1311
env4_nature	Yes	Do the right thing for nature.	514	1311
env5_labour	Yes	Worried about working conditions in mines?	528	1288
env6_data	Yes	We protect your data.	544	1299
env7_stillworks	Yes	Does your mobile phone still work?	510	1285
env8_whykeep	Yes	Why do you keep your old mobile phone?	543	1290
		Total	**4'245**	**10'380**

Tab. 7.4: Summary of different envelopes' design

We included a very short article in the magazine where the envelopes were added about phone recycling (see Appendix 7.D). The article was only seven sentences and less than 100 words and referred to the envelope that has been included with the magazine. This step was requested by the magazine to collaborate on this

[11] All phones were recycled with Immark AG with confirmation of data protection and destruction of all devices.

experiment. Since it is challenging not to mention any of the information given in our informational treatments, especially with regards to data protection, we decided to mention all the treatments in the article. We also gave an additional link to a project webpage (see Appendix 7.D) that included similar information to the article, including details on our data protection policy. In the months of October and November 2019 we had only 265 and 24 unique IP-addresses visiting this website and no unique visits since.

Envelopes were shuffled manually and then added to a magazine with a machine that folds the magazine and then uses air to insert an envelope into the fold before it is covered in plastic wrapping. German envelopes were allocated randomly to the German issue of the magazine, and English envelopes were assigned randomly to the English copy of the magazine. In order to verify if the randomisation was done correctly, we counted the total received of each envelope type per day, and we did not find a clear pattern of the day or week when we received envelopes for each treatment group (see Figure 7E.1 in Appendix 7.E).

7.3.2 Results

In total, we received 826 phones in 745 official envelopes between October 2019 and February 2020, i.e. a return rate of 5.1% for all envelopes.[12] In addition, we received 77 unofficial packages or envelopes (envelopes that we did not distribute) containing 107 phones. These envelopes and phones will be disregarded from the main analysis since we do not know what message they received.

About two-thirds (65.7%) of the phones we received were smartphones. Although we received a wide variety of brands, the majority of phones were Apple iPhone (24.6%), Samsung (21.2%), Nokia (20.8%), and Sony (9.4%). Other brands included Blackberry, Siemens, LG, Huawei, Fairphone, and 32 different brands.[13] The average phone we received weighed 110.8g with a standard deviation of 28.0g. The average phone was 10.6mm thick, with a standard deviation of 4.5mm. Given the increased capabilities of a smartphone, needing more metals,[14] smartphones are, on average

[12]Most envelopes (90.9%) had only one phone (as was also requested on the envelope), 8.6% of packages included more than one phone, including a few that put the treatment envelope into another box or bigger envelope, sending four or more phones. We received the first envelope with a phone back on 4 October 2019. On a single day, the most phones we received were 62 phones on both Friday 11 October and Monday 14 October (see Figure 7E.2 in Appendix 7.E).

[13]We did not specifically ask recipients to send only phones; 11% of the packages also contained non-phone items, such as phone covers and chargers included with the phones. Ongondo & Williams (2011) mention that it could be more likely to receive unwanted accessories with a pre-posted mail-back collection scheme. In our experiment, the percentage of envelopes with non-phone items was, however, the same across envelopes pre-posted and those hand-delivered (at the 5%-level).

[14]Developers have been able to ensure the thin smartphone by gluing many of the parts together, instead of using screws and other fixtures (Prakash et al., 2016). This has also complicated the ability to extract metals from smartphones during recycling.

thinner than a mobile phone, but also much heavier. With the total amount of 826 phones collected between 1 October 2019 and 28 February 2020 in official envelopes, we recovered 108.3 kg e-waste, which contains an estimated 54.71kg of metals worth USD 1,388, of which USD 1,213 was from the recovered gold (see Appendix 7.G for detailed calculations). If we include the 107 phones that we received in other envelopes and the 56 envelopes that we received from March 2020 to October 2020, we recovered 122kg of e-waste, with embedded metals worth USD 1,568.

As indicated above, the envelope return rate is 5.1% (745/14,625) if we only consider October to February in official envelopes, and 5.5% if we extend the time period to one year (October 2019 to October 2020), which increases the current official recycling rate in Switzerland by about 20% from a baseline of 25.3% (identified in the survey, Table 7.2). It is three to five times the return rate of previous mail-back campaigns in Australia, Europe, and the US that typically report an estimated 1-2% return rate of envelopes (Tanskanen & Butler, 2007; Litchfield et al., 2018). We suggest that the relatively high return rate can be attributed to the project being run by the employer of the target group, which might have fostered trust in the project – but we cannot test this hypothesis. While higher trust is likely to influence overall return rate levels, we do not believe that this fact will influence randomized treatment effects.

Some spill overs might have occurred after about a month, with the official deadline being 31 October 2019. On 30 October 2019, three official envelopes from treatments with postage (and no information about Campus Info) were deposited at Campus Info. We, therefore, show results both until 31 October 2019 (official deadline to submit the phones) and until 28 February 2020 when we received most phones. Afterwards only few phones were received and spill overs became more likely. Table 7.5 shows the return rate by envelope type and language and the total envelopes received by 31 October 2019 and the end of February 2020.

We find that none of the information treatments (envelopes three to eight) were statistically significantly different from the envelope with only postage (*env1_postage*) for the entire sample. However, the return rate of treatment two without any postage (*env2_nopostage*), i.e. with higher transaction costs, was not even half of the return rate of the treatment group with postage (significant at the 1%-level). Moreover, those who received a German envelope were three times as likely to return the envelope (see Table 7F.1 in Appendix 7.F for regression results). The reason for the high-levels of recycling in the German-speaking sample could come from the pre-existing recycling culture: Switzerland is often cited as one of the leading household waste recyclers in the world (Wong Sak Hoi, 2016). Switzerland was also the first country to implement a national e-waste collection and recycling system (Sinha-Khetriwal et al., 2005). In the survey, we also found that people who were born in Switzerland, were more likely to say that they recycle their previous phone (see

Envelope	**Until October 2019**			**Total until**
	English	**German**	**Total**	**Feb 2020**
No message, postage included (env1_postage)	1.3%	5.9%	4.6%	5.8%
No message, postage excluded (*env2_nopostage*)	0.6%	1.4%***	1.3%***	2.1%***
Swiss recycle more & postage incl. (*env3_social*)	3.3%*	5.9%	5.1%	6.3%
Recycle for nature & postage incl. (*env4_nature*)	2.1%	4.8%	4.1%	5.4%
Labour conditions & postage incl. (*env5_labour*)	0.4%*	5.8%	4.2%	5.3%
Data protection & postage incl. (*env6_data*)	2.4%	5.6%	4.7%	5.6%
Does your phone work & postage incl. (*env7_stillworks*)	1.8%	4.8%	4.0%	5.3%
Why keep your phone & postage incl. (*env8_whykeep*)	1.8%	4.6%*	3.8%	4.9%
TOTAL	1.8%	4.9%	4.0%	5.1%

Tab. 7.5: Return rates by envelope type. The stars indicate if the return rate is significantly different to the return rate of the first envelope (postage but no informational treatment) shown in the first row. For more detail on the regression analysis that compares various treatments, see Table 7F.1 in Appendix 7.F. *** $p<0.01$, ** $p<0.05$, *$p<0.1$

Table 7.3).

Last, in the English sample, receiving an *env3_social* envelope more than doubled the likelihood of returning the envelope before the project deadline (significant at the 10% level) compared to the group without any information (see Table 7F.1, Appendix 7.F). Given that the English sample is more likely to be foreigners, we believe that the social descriptive norm treatment – being told that the Swiss recycle ten times more than the rest of the world – became effective. Interestingly, in the English sample, the return rate of the *env5_labour* envelopes, reminding people of the bad labour conditions on mines, was significantly less than in the group without any information (*env1_postage*). If we consider the German-speaking sample only none of the information treatments increases return rates. In the German sample, treatment 8 (*env8_whykeep*) that asks why people still keep their phones even decreased return rates by 1.3 percentage points in comparison to no informational treatment (see Appendix 7.F).

7.4 Cost-benefit analysis of urban mining

7.4.1 Economic cost of urban mining

The cost of a mail-back urban mining project depends on various parameters. Total cost include the cost to make and distribute all envelopes to the public (or in our case all employees), and if postage is included, also the postage that was actually used for phones sent back. We did not have to pay postage cost for envelopes that were not returned, which is similar to many postal service around the world. To calculate the cost of one returned envelope $C_{returned\ env}$ we calculate:

$$C_{returned\ env} = \frac{C_{dist\ env} + C_{postage}(r_{return})}{r_{return}} \tag{7.1}$$

where $C_{dist\ env}$ is the cost to make and distribute one envelope, $C_{postage}$ is the postage cost for one returned envelope, which we only need to pay for all returned envelopes and dependent on the weight of a phone, and r_{return} is the return rate.

Table 7.6 shows various cost-scenarios of a mail-back envelope project considering the cost of the envelopes and the cost to initially distribute the envelopes to the public (columns 1 to 3) and the return postage (columns 4 and 5). The cost of one envelope in our project was USD 0.41, while the production cost of envelopes of another larger project in Australia was only USD 0.13 per envelope (Litchfield et al., 2018). All envelopes in our project were included with the ETH life magazine, and we did not have to incur any cost to distribute the 15,000 envelopes to the ETH community. However, other projects might have to carry this cost, which according to prices for bulk postage listed by the Swiss Post, is USD 0.15 per envelope initially distributed.

Lastly, we also consider the cost of postage per returned envelope with pre-paid postage; based on our postal costs, which was USD 1.27 per envelope returned with included postage. Although including postage adds to the cost of recovering an envelope, in our experiment, including postage more than doubled return rates: 2.1% of envelopes without postage were returned and 5.5% of envelopes including postage were returned. In contrast, additional information or priming did not change return rates significantly. In column 7 of Table 7.6, we show the cost per collected envelope. Note that this does not include the cost to extract the metals from the phone during the recycling process. In Switzerland this cost is, however, already covered by a prepaid recycling fee, which is included in the price of all phones sold in Switzerland (SENS, SWICO Recycling & SLRS, 2011).

We find that the including return postage, although an additional cost, actually reduces the cost to collect one old phone, due to the positive impact on return rates (see Eq. 7.1). Given the much higher return rate, we find that, keeping other cost parameters constant, the cost to collect one envelope is always less when return postage is included.

(1) Distribution cost	(2) Envelope costs	(3) Cost per envelope distributed (USD)	(4) Postage paid	(5) Postage per returned envelope (USD)	(6) Return rate	(7) Collection cost per envelope (USD)	(8) Loss per envelope collected (USD)
High	High	0.56	Yes	1.27	5.50	11.45	9.77
Free	High	0.41	Yes	1.27	5.50	8.72	7.04
High	Low	0.28	Yes	1.27	5.50	6.36	4.68
Free	Low	0.13	Yes	1.27	5.50	3.63	1.95
High	High	0.56	No	0	2.10	26.67	24.99
Free	High	0.41	No	0	2.10	19.52	17.84
High	Low	0.28	No	0	2.10	13.33	11.65
Free	Low	0.13	No	0	2.10	6.19	4.51

Tab. 7.6: Various cost scenarios to collect phones in an Urban Mining project. Considering initial distribution costs and high or low envelope cost and the impact of including postage. Distributing cost includes the cost to initially distribute all envelopes to the public, which was not included in our project. The envelope cost includes the design and production of all envelopes; the high envelope cost is USD 0.41 per envelope (similar to our project). Low envelope costs are USD 0.13 (similar to Lichtfield et al. 2018). Including postage influences both the total cost and the return rate (return rates based on our study). The financial loss to collect a phone is based on the market values of the metals embedded in a phone (USD 1.68, see Appendix A7).

7.4.2 Economic benefit of urban mining

If we consider the amount of metals per phone as identified by researchers at the University of Plymouth (Williams, 2019), then the average value of the metals in a phone is about USD 1.68 (see Appendix 7.G for the calculation). As shown in column 8 of Table 7.6, the cost of collecting the phones always exceeds the value of the metals in a phone, constituting a loss per phone collected between USD 1.95 and USD 24.99.

Although the metals' value in an average phone will be unlikely to offset the cost of recovering a phone, it could still be cost-effective to retrieve a phone if we internalize the cost of negative environmental externalities of sourcing these metals from primary resources, i.e. mines. The metals in a phone are mined all over the world and cause significant adverse environmental and health impacts, and by recycling phones the pressure on primary sources and their surroundings can be alleviated. We calculate the environmental costs related to the production of primary metals per phone to determine if including environmental benefits makes recovering phones through mail-back envelopes with postage a cost-effective policy.

Due to the different origins of metals embodied in the mobile phones of different brands, "a phone" in our calculations refers to the average phone used in Switzerland. Moreover, due to data constraints, we include only eleven of the metals found in a phone: gold, chromium, nickel, copper, tungsten, tin, silver, aluminium, tantalum, iron, and cobalt. However, these eleven metals constitute 97.5% of the market value of all metals embedded in a phone (USD 1.64 of USD 1.68; see Appendix 7.G). First, we use the life-cycle inventory database Ecoinvent (version 3.4 Wernet et al., 2016) to calculate the external impacts of primary metals in a phone. In a second step, we monetarize the environmental impact of these metals with factors identified by Galgani et al. (2020, Appendix A8). Third, we combine these results with the multi-regional input-output analysis database EXIOBASE3 (Stadler et al., 2018; Cabernard et al., 2019). This last step allows us to determine the world regions where the environmental costs related to metals' production embodied in an average Swiss phone occur (see Figure 7.1 and Table 7H.1 in Appendix 7.H). Meaning, the method allows to determine where metals in an average Swiss phone where mined, processed and therefore, where in the world the environmental costs of an average Swiss phone occur.

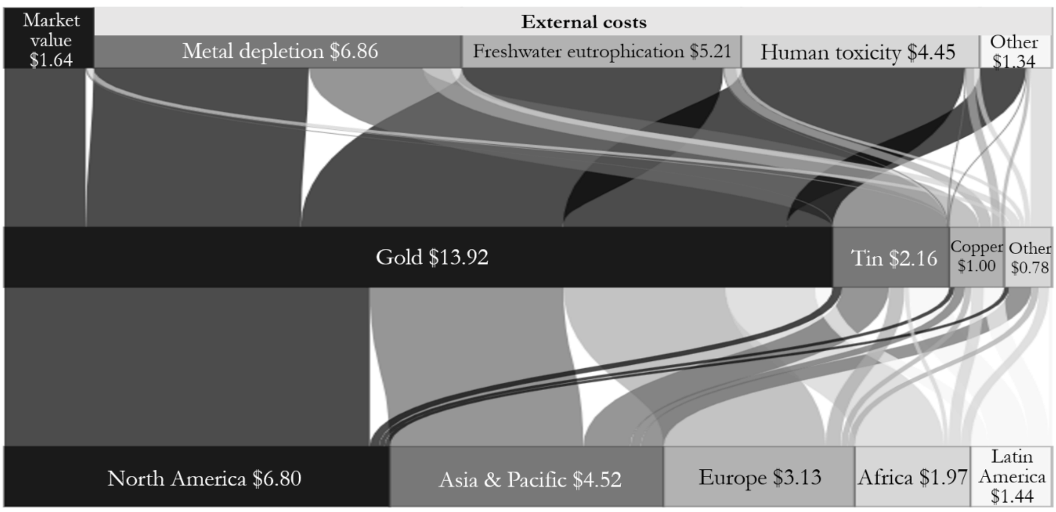


Fig. 7.1: Total costs of metals embodied in an average Swiss mobile phone. The total market value of the eleven metals in a phone for which we have is USD 1.64 and the total external cost is USD 17.86. The environmental costs per impact category, metal, and region are shown in detail in Appendix A8.

First, the monetisation of the environmental externalities reveals that the external costs of these eleven primary metals embodied in a phone are more than ten times higher than the current market price of these metals (USD 17.86 vs USD 1.64, see Figure 7.1). These external costs are about equally attributed to the impacts related to metal depletion (increased cost to society due to reduction of metal stocks), freshwater eutrophication, and human toxicity, while only a minor fraction is contributed to the other eleven impact categories we considered, such as for example freshwater ecotoxicity, ozone depletion, and water depletion (complete list of categories can be found in Appendix 7.H). Despite the low amount of gold embodied in a phone (0.036g, see Appendix 7.G), gold contributes to the largest share of both the market value of the metals in a phone (USD 1.47 or 87.4%) and the total environmental costs (USD 13.92 or 77.9%; Figure 7.1). In addition to gold, tin also contributes considerably to the environmental costs due to metal depletion.

Moreover, the supply chain analysis of metals embodied in Swiss phones reveals that about 60% of the environmental costs occur in North America, Asia and the Pacific, where most of gold and tin that enter Swiss consumed phones are mined (see Figure 7.1 and Table 7H.1 and 7H.2 in Appendix 7.H for detailed results). Since no metals are mined in Switzerland, no environmental costs occur in Switzerland.

Hence, if we take the total value of the metals in a phone into consideration, including environmental externalities, amounting to USD 19.54, collecting phones for recycling is cost-effective for all but one of the cost-scenarios considered in Table 7.6.

7.5 Discussion and conclusion

The demand for electronics, such as mobile phones and smartphones, adds to the global demand for metals. The increasing demand puts a lot of pressure on the environments where the metals are extracted. In Switzerland, many of the negative effects of consumption are far removed from the consumers' daily lives and surroundings. However, changing consumer behaviour — for example, by using a phone as long as possible, repairing broken devices, and recycling unused devices — could alleviate the negative impact in the area of extraction.

Old phones are a rich source of secondary metals and have large recycling potential. Even if only a small quantity of a particular metal is in an electronic item, it could mean very high concentrations compared to virgin ore. For example, although there is less than 0.04g of gold in an iPhone 4S with a weight of 140g, that is equivalent to the average amount of gold found in 5kg of gold ore (based on values from Berger et al. (2014) and Williams (2019)). Hence the concentration of gold in electronic waste is high. Moreover, despite the small amount of gold in a phone, gold accounts for 77.9% of the environmental impact and 87.4% of the market value of the metals in a phone. We estimate that there are 6.4 and 7.1 million unused phones dormant phones in Switzerland, containing an estimated 221t iron, 40t copper, 17t aluminium, and 242kg gold (using values from Williams, 2019), with an estimated true value (market price and environmental cost) of about USD 131 million lying around in Swiss drawers (USD 19.54 per phone). The market value of the metals only is about USD 11 million (USD 1.68 per phone).

Since the discovery of the mobile phone, there has also been an increasing amount of academic interest in phone waste generation. However, a meta-analysis of research on phone waste specifically (Sarath et al., 2015) find that most research in the field has been conducted on the material composition and technologies and techniques to extract metals from phones. Irresponsible e-waste recycling practices are also an increasingly prevalent research topic (Awasthi et al., 2019). Due to the high cost of extracting metals from obsolete electronic devices, e-waste is often exported to low-income countries for recycling, despite being prohibited under the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. Low-income countries do not have to technical capacity to safely recycle e-waste, and resort to burning and dissolution in acid (Robinson, 2009; Wang et al., 2016). These recycling methods result in extremely dangerous contaminants to local communities and environments (Yadav & Yadav, 2014; Kiddee et al., 2013; Nnorom & Osibanjo, 2009, for the toxicity of waste mobile phones). While responsible recycling practices are paramount to alleviating the negative externalities of the sector, it falls outside the scope of this paper.

In this study we focus on the recovery of obsolete devices, a topic that has been studied less and that could be considered a critical gap in the literature. Some of the lessons learned from phone recycling could also be extended to the recycling of other sources of electronic devices, such as insights regarding data protection issues. However, phones are in many aspects a unique case study and researchers need to be cautious when generalising lessons from phone recycling to other case studies. For example, phones are the most widely owned electronic item and typically has more hibernating stock and larger e-waste items that are difficult to store after use (Baxter & Gram-Hanssen, 2016).

Previous studies focused on existing collection campaigns: Ongondo & Williams (2011) list and describe all the UK's voluntary collection agencies and the methods they use to collect phones. Tanskanen & Butler (2007) describe collection campaigns in the USA and Finland. Litchfield et al. (2018) studies the response rates of various collection methods used by Victoria Zoos Australia, who collected more than 115,000 old mobile phones over six years by referring to gorilla conservation (mining for the metals in a phone threatens their habitat). However, since these studies considered existing recycling campaigns, they lack control groups or information on the number of people that were effectively treated.

In this study, we conducted a survey on a representative sample of 2,500 adults in German-speaking Switzerland to understand mobile phone usage and to design and implement a field experiment with 15,000 employees of one Swiss institution. We find that most people keep a phone only for about two years and most commonly replace it because it broke (40.4%), they wanted a better phone (20.8%) or they were unable to upload software (15.7%). This is slightly in contrast to Suter et al. (2017) who found that of 911 Swiss adolescents 58% replace their phone because they wanted a newer or better phone, 40% said they could get a new phone with a contract and 37% said their old phone was broken (however, multiple answers possible was possible).

We find the most common thing people do with their old device is to keep it at home. People had various reasons for keeping their old phone; about 70% of phones lying around in Swiss drawers are not in use anymore and could be recycled without significantly reducing the utility of their owners. In general, we believe that most people have not recycled their old devices because of the high transaction cost to get rid of a device. We test this hypothesis with an RCT by including postage to mail-back mobile phones for some participants but not for others and in addition randomize various messages to encourage recycling. The return rate in our field experiment was 5.1-5.5%, which increases the current recycling rate in Switzerland by about 20%. The total return rate in our project is also high compared to a study by Litchfield et al. (2018) with a return rate of 1.3% of mail-back envelopes. Since our project was conducted by the employer of the target group, it could have fostered trust and, therefore, increased the return rates. This preliminary finding could mean a large potential to run similar recycling campaigns within communities with high-levels of trust. However, since our research design does not allow to test this hypothesis directly, we recommend future research focus on testing the impact of trust on participation in urban mining.

We find that reducing transactional cost by including postage makes a significant difference to the return rate of obsolete devices. Despite previous research that suggests that mail-back envelopes are too costly (Litchfield et al., 2018; Tanskanen & Butler, 2007), we find that although including postage is an additional cost, it increases the return rate sufficiently to reduce the cost per phone collected. Informational treatments do not have a significant impact on return rates in general. However, for English speaking recipients, who we believe are more likely to be non-Swiss, a social descriptive message on Swiss recycling rates had a significant and positive impact on return rates. In general, German recipients were significantly more likely to return an envelope, possibly due to the pre-existing recycling norm; in the households' survey we also found that people born in Switzerland, are more likely to report recycling their previous phone. A disadvantage of this field experiment is that we do not have any other data on the participants, which means we cannot gain further insight into the participants who returned their phones. Moreover, the treatments only explain less than 1% of the spread in the data, indicated that characteristics and preferences of individuals' are highly relevant as drivers of return rates.

The return rate, even with lowered transactional cost, in our field experiment is insufficient to make the method cost-effective, when only considering the market value of the metals in a phone. However, the method is cost-effective when considering the total environmental savings from increasing the recycling rate. Using a life-cycle inventory database (Ecoinvent) and a multi-regional input-output database (EXIOBASE3), as well as estimates of full prices by Galgani et al. (2020), we estimate that mail-back envelopes with included postages collection method is cost-effective under most cost-scenarios. We therefore recommend that recycling needs to be as easy as possible, which could be done by lowering transactional cost of recycling. Increasing the return rate is the most important driver to make the method cost-effective.

Appendix

7.A Survey

Welcome!
This scientific study is conducted by the Swiss Federal Institute of Technology (ETH) Zurich in collaboration with LINK.
Data protection: All data we collect will be treated confidentially. We attach great importance to respecting private data protection. Your answers will not be linked to your name and/or email address. By participating in this study, you agree that the data collected may be analysed and published in aggregate form by ETH Zurich. Information that would allow you to be identified will not be published or used in any presentation under any circumstances.
Contact information: If you have any questions or comments about this study, please contact: panel@link.ch. If possible, please complete the questionnaire on a computer, as this ensures optimal presentation of the questions.

I have read the above information and would like to participate in this study.

Please indicate your gender.

- female
- male
- no information

In which year were you born?

- after 2000
- 2000
- ...
- 1929
- no information

Do you have children younger than 18 years old?

How many people live in your household, including you?

In which canton do you live?

Were you born in Switzerland?

Please state you marital status.

What was your total household income before taxes, including pension subsidies in

2017?[15]

- less than CHF 30,000
- 30,000 CHF to 49,999 CHF
- 50,000 CHF to 99,999 CHF
- CHF 100,000 to CHF 149,999
- 150,000 CHF to 199,999 CHF
- 200,000 CHF to 249,999 CHF
- CHF 250,000 to CHF 499,999
- more than CHF 500,000
- no information

What is your highest school-leaving qualification?

- compulsory school NOT completed
- Completed compulsory school
- Matura (grammar school)
- Vocational training
- University/ETH Bachelor
- University/ETH Master/Diploma
- University/ETH Doctorate
- University of Applied Sciences Bachelor
- University of Applied Sciences Master/Diploma
- University of Education Bachelor
- University of Education Master/Diploma
- Other
- no information

What is your current employment status?

- Full-time employee/employee
- Part-time employee/employee
- Independent
- Student/Pupil
- Apprentice
- Housewife/Househusband
- Unemployed and looking for work
- economically inactive
- no information

[15] All values in the article is given in USD, while all values in survey were asked in Swiss Francs (CHF). We converted to the survey values to USD with a 1:1 exchange rate. The average exchange rate for 2018 was CHF 1: USD 1.02; source: ofx.com.

Phone questions

Have you ever heard of FAIRPHONE?

- Yes
- No
- Not sure

Please note that in the next questions the term "mobile phone" always refers to all "mobile phones", "smartphones" and "natels".

Do you own a mobile phone?

Please estimate in which year you bought your current mobile phone.

- 2018
- ...
- 2009
- before 2009

Is this your first mobile phone?

Did you lose your last mobile phone or was it stolen?

- Yes, I have lost it.
- Yes, it was stolen.
- No, I have neither lost it nor has it been stolen.

Why did you replace your previous mobile phone with the current one? Please choose the statement that best applies.

- I wanted a better/newer mobile phone
- My previous mobile phone no longer supported software updates
- My previous mobile phone was too slow
- I have received a new mobile phone due to my mobile contract
- I have been given a new mobile phone
- My old one was broken and it could not be repaired
- My old one was broken and I didn't try to fix it

What did you do with your previous mobile phone? Please select the most applicable statement. I used it...

- still at home
- recycled
- sells
- given away or donated
- Returned to a mobile phone service provider
- disposed of in the normal rubbish
- I no longer know

If you still have your old mobile phone at home, why did you keep it? Please select the most applicable statement. I keep it...

- as a replacement or "emergency mobile phone"
- for a second SIM card
- for saving data, such as photos, etc.
- as a toy for children (not as a functioning mobile phone)
- for sentimental reasons or because I collect old mobile phones
- without SIM card (e.g. as an alarm clock, to listen to music, etc.)
- because I fear that otherwise my data will be misused by others
- I do not know

Does your old mobile phone still work?

- Yes
- No
- I am not sure

Would you be willing to sell your old mobile phone for CHF(*randomly generated prices between 2-100*)?

How many mobile phones not used for making calls do you and your family have at home?

- none
- 1
- ...
- 5
- more than 5

Exactly how many mobile phones not used for making calls do you and your family have at home?

Do you know where you could take an old mobile phone for recycling?

- Yes
- No, but I can easily find out
- No, I do not know

What do you think: What percentage of all Swiss recycle old mobile phones?

Gold questions

Have you bought gold jewellery in the last year?

How often have you bought gold bars or coins as an investment?

- Never before

- Once
- Twice
- Three times
- More than three times

How often have you bought gold bars or coins as a gift?

- Never before
- Once
- Twice
- Three times
- More than three times

Which of the following topics do you think best describe the problems in gold mining? Please select 3 topics.

- Financing of armed conflicts
- Land expropriations
- Child labour
- Conflicts between mining companies and the local population
- Low wages of workers
- Negative impact on workers' health
- Tax evasion
- Unsafe working conditions of the workers
- Water pollution
- Negative effects on the ecosystem
- Illegal mining
- Air pollution

How familiar are you with what this label represents? (Show FairTrade label)

- Not familiar at all
- Not very familiar
- Somewhat familiar
- Very familiar
- I am not sure

How often have you visited the FairTrade Max Havelaar website in the last two years?

- Never
- Once
- 2-5 times
- More than 5 times

7.B Stated supply curve for old phones

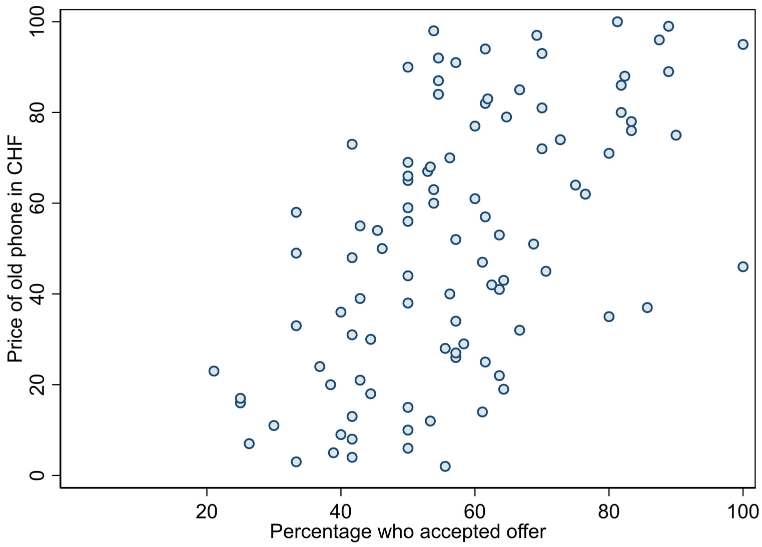


Fig. 7B.1: Stated supply curve for old phones. In our questionnaire we asked all participants (n=2,500) if they would be willing to sell their old mobile phone for a price randomly generated between CHF2-CHF100. The horizontal axis shows the percentage of people who accepted the price offered to sell their old phone for each price shown on the vertical axis. All values in the survey were asked in Swiss Francs (CHF). We converted to the survey values to USD with a 1:1 exchange rate. The average exchange rate for 2018 was CHF 1: USD 1.02 (source: ofx.com).

7.C Envelopes

env1_postage, English

env1_postage, German

env2_nopostage, English

env2_nopostage, German

env3_social, English

env3_social, German

env4_nature, English

env4_nature, German

env5_labour, English

env5_labour, German

env6_data, English

env6_data, German

env7_stillworks, English

env7_stillworks, German

env8_whykeep, English

env8_whykeep, German

Back of all envelopes with postage, English

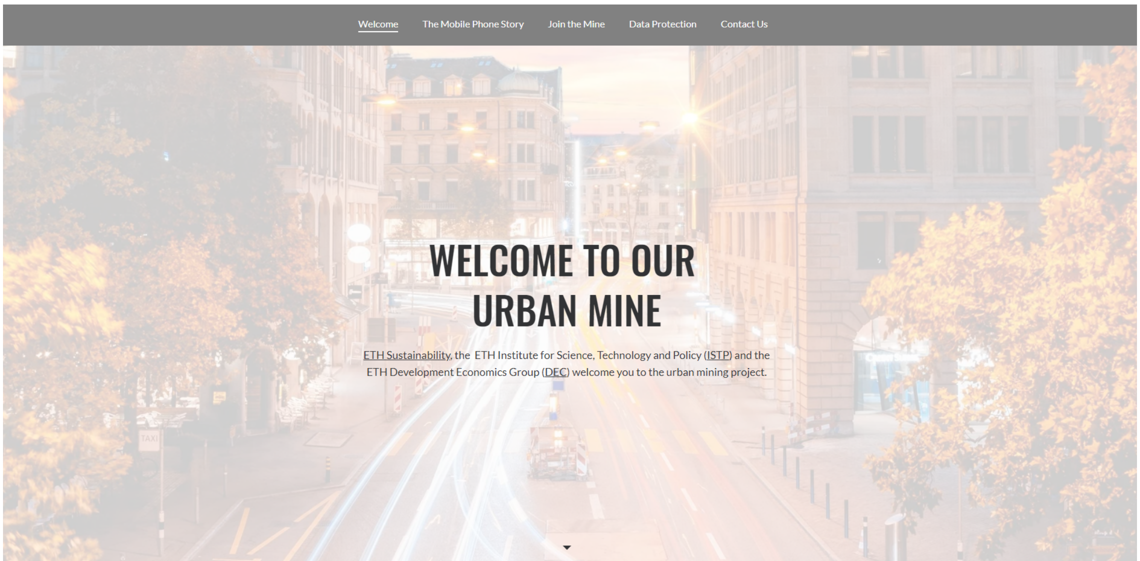
Back of all envelopes with postage, German

Back of envelope without postage, English

Back of envelope without postage, German

7.D Article and Website

Website
Address: www.urban-mining-project.ch



Article
Be an urban miner! There are over 40 materials in each mobile phone, including gold, silver and cobalt. These resources are mined all over the world. Although mining has many economic benefits, it also has negative impacts on the environment. Not to mention that working in a mine can be a tough job. You can alleviate the negative impact of your mobile phone by being an urban miner and recycling your old phone. If you still have an old mobile phone at home, isn't it time to recycle it? Join the ETH Urban Mining Project and recycle your old mobile phone to reduce its ecological footprint.

Damit wertvolle Rohstoffe nicht in der Schublade landen! In jedem Mobiltelefon befinden sich über 40 Materialen, darunter Gold, Silber und Kobalt. Diese Rohstoffe werden auf der ganzen Welt abgebaut. Der Bergbau hat auf der einen Seite zu Wirtschaftswachstum in vielen Ländern geführt, dort aber auch oft stark die Umwelt belastet. Ganz zu schweigen von den harten Arbeitsbedingungen in den Minen. Haben Sie noch ein altes Mobiltelefon zu Hause? Nehmen Sie am ETH Urban Mining Project teil und recyceln Sie Ihr altes Handy. So helfen Sie mit, den ökologischen Fussabdruck Ihres Mobiltelefons zu reduzieren.

7.E Number of envelopes received

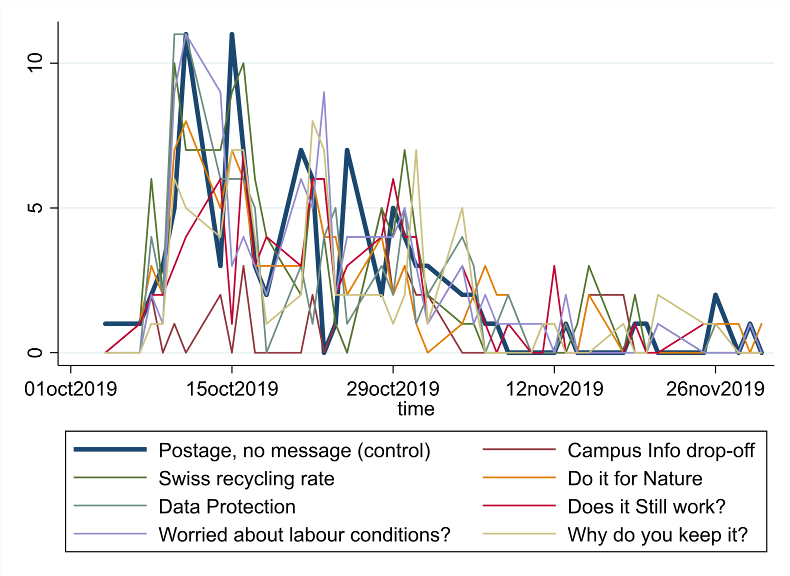


Fig. 7E.1: The daily number of envelopes of each type that we received. We could not see any clear pattern when we receive a certain envelope type back, which provides evidence that the envelopes were randomly distributed.

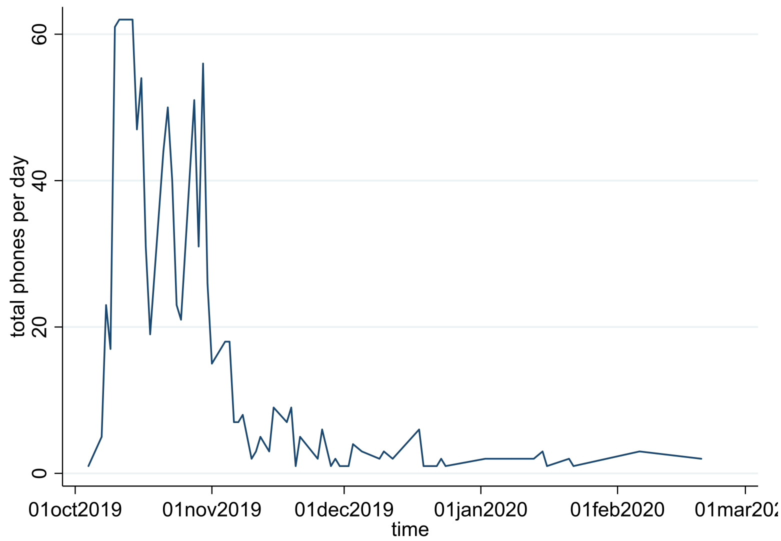


Fig. 7E.2: Number of envelopes received from October 2019 to end of February 2020. Spikes were recorded on Mondays followed by a slight decrease during the rest of the week. No phones were received on weekends.

7.F Regression results for return rates

Dep var: envelope returned	**(1)**	**(2)**	**(3)**	**(4)**
Sample (language)	**Both**	**Both**	**German**	**English**
Reference group: no message & postage included (*env1_postage*)				
No message & postage excluded (*env2_nopostage*)	-0.033***	-0.033***	-0.043***	-0.007
	(0.005)	(0.005)	(0.007)	(0.006)
Message: Swiss recycle more & postage incl. (*env3_social*)	0.005	0.005	0.000	0.016*
	(0.007)	(0.007)	(0.009)	(0.009)
Message: Recycle for nature & postage incl. (*env4_nature*)	-0.004	-0.005	-0.009	0.006
	(0.007)	(0.007)	(0.009)	(0.008)
Message: Labour conditions & postage incl. (*env5_labour*)	-0.003	-0.003	-0.000	-0.009*
	(0.007)	(0.007)	(0.009)	(0.006)
Message: Data protection & postage incl. (*env6_data*)	-0.007	-0.007	-0.011	0.003
	(0.007)	(0.007)	(0.009)	(0.007)
Message: Does your phone still work & postage incl. (*env7_stillwork*)	0.001	0.000	-0.002	0.009
	(0.007)	(0.007)	(0.009)	(0.008)
Message: Why keep your phone & postage incl. (*env8_whykeep*)	-0.010	-0.0102	-0.015*	0.002
	(0.006)	(0.006)	(0.009)	(0.007)
German		0.031***		
		(0.003)		
Constant	0.044***	0.022***	0.057***	0.013***
	(0.005)	(0.005)	(0.006)	(0.005)
Observations	14,625	14,625	10,380	4,245
R-squared	0.003	0.009	0.004	0.004

Tab. 7F.1: Regression results of the return rate of envelopes. Only the period to project deadline (31 October 2019) is considered. Robust standard errors in parentheses. Significance on the 10% level (*), 5% level (**), or 1% level (***).

7.G Metals (quantity and value) in phones

Metal	Amount in phone	% of weight	Price /gram (USD)	Total value in phone (USD)	% of value	Total weight of collected phones	Total value of collected phones (USD)
Gold	36mg	0.05	40.78	1.468	87.35%	0.03	1’212.72
Chromium	7.0g	10.57	0.01	0.050	3.00%	5.78	41.63
Silicon	13g	19.63	0.00	0.032	1.88%	10.74	26.04
Nickel	2.7g	4.08	0.01	0.031	1.83%	2.23	25.35
Copper	6.0g	9.06	0.00	0.029	1.73%	4.96	24.06
Tungsten	900mg	1.36	0.03	0.027	1.62%	0.74	22.53
Tin	0.7g	1.06	0.01	0.010	0.60%	0.58	8.37
Silver	20mg	0.03	0.40	0.008	0.48%	0.02	6.69
Praseodymium	30mg	0.05	0.25	0.007	0.45%	0.02	6.19
Aluminum	2.5g	3.77	0.00	0.004	0.24%	2.07	3.26
Tantalum	20mg	0.03	0.16	0.003	0.19%	0.02	2.68
Iron	33.0g	49.82	0.00	0.003	0.17%	27.26	2.39
Germanium	2mg	0.00	1.24	0.002	0.15%	0.00	2.05
Cobalt	70mg	0.11	0.03	0.002	0.12%	0.06	1.65
Molybdenum	70mg	0.11	0.03	0.002	0.11%	0.06	1.49
Dysprosium	2mg	0.00	0.28	0.001	0.03%	0.00	0.47
Indium	2mg	0.00	0.21	0.000	0.02%	0.00	0.35
Niobium	10mg	0.02	0.04	0.000	0.02%	0.01	0.32
Gadolinium	5mg	0.01	0.02	0.000	0.01%	0.00	0.08
Antimony	7mg	0.01	0.01	0.000	0.00%	0.01	0.05
Neodymium	160mg	0.24	0.00	0.000	0.00%	0.13	0.01
TOTAL	**66.23g**	**100**	**N/A**	**1.68**	**100%**	**54.71kg**	**1’388.37**

Tab. 7G.1: Amount and values of metals embedded in a phone. Prices were taken from World Gold Council (gold), Metal Bulletin (chromium, indium and antimony), LME (nickel, copper, tin, aluminium, cobalt), Metalary (tungsten), silverprice.com (silver), Institut fur Selten Erden (praseodymium), Statista (silicon, tantalum, germanium, gadolinium, neodymium), Index Mundi, tradingeconomics (molybdenum), Kitco (dysprosium), Nobiumprice.com (niobium), March 2020 and converted from USD to CHF with exchange rate 1USD:0.91CHF. The amount of metals in a phone is based on values by Williams (2019)

7.H External costs (in USD) of metals embodied in an average phone in Switzerland

	North America	Asia & Pacific	Europe	Africa	Latin America	Total per metal
Gold	6.46	3.07	2.64	1.49	0.26	13.92
Tin	0.17	0.87	0.28	0.08	0.75	2.16
Copper	0.10	0.19	0.12	0.22	0.38	1.00
Chromium	0.02	0.10	0.02	0.08	0.00	0.23
Iron	0.01	0.13	0.03	0.01	0.02	0.19
Tungsten	0.01	0.07	0.01	0.05	0.00	0.15
Aluminium	0.00	0.03	0.00	0.01	0.02	0.07
Silver	0.03	0.01	0.01	0.01	0.00	0.06
Nickel	0.00	0.04	0.00	0.00	0.00	0.05
Cobalt	0.00	0.01	0.00	0.01	0.00	0.02
Tantalum	0.00	0.00	0.00	0.00	0.00	0.01
Total per region	**6.80**	**4.52**	**3.13**	**1.97**	**1.44**	**17.86**

Tab. 7H.1: Regions of the impact of external costs due to mining and processing of specific metals. We link the external cost to various regions by using the multi-regional input-output database EXIOBASE3 (Stadler et al. 2018). All external cost are shown in USD the average phone in Switzerland.

	Metal depletion	Freshwater eutrophication	Human toxicity	Climate change	Particulate matter formation	Freshwater ecotoxicity	Fossil depletion	Marine eutrophication	Terrestrial acidification	Marine ecotoxicity	Photochemical oxidant formation	Water depletion	Terrestrial toxicity	Ozone depletion
Gold	4.01	4.88	4.17	0.33	0.14	0.16	0.08	0.06	0.03	0.03	0.02	0	0.01	0
Tin	2.13	0.01	0.01	0	0.01	0	0	0	0	0	0	0	0	0
Copper	0.53	0.23	0.17	0.02	0.01	0.01	0	0	0	0	0	0	0	0
Chromium	0.01	0.02	0.01	0.13	0.03	0	0.03	0	0	0	0	0	0	0
Steel	0.1	0.01	0.01	0.05	0.01	0	0.01	0	0	0	0	0	0	0
Tungsten	0.01	0.03	0.06	0.02	0.01	0	0	0.01	0	0	0	0	0	0
Aluminium	0.01	0.01	0.01	0.03	0.01	0	0.01	0	0	0	0	0	0	0
Silver	0.02	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0	0
Nickel	0.02	0	0	0.01	0	0	0	0	0	0	0	0	0	0
Cobalt	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0
Tantalum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total per impact category	**6.86**	**5.21**	**4.45**	**0.61**	**0.22**	**0.18**	**0.14**	**0.08**	**0.04**	**0.03**	**0.03**	**0.01**	**0.01**	**0**

Tab. 7H.2: External cost of the embodied metals in a phone by impact category. Results were calculated with the life-cycle inventory database Ecoinvent and by applying the monetisation factors from True Price (Galgani et al. 2020). For a detailed description of the various impact categories see Galgani 2020:17-20. All external cost are shown in USD for an average phone used in Switzerland

Chapter 8

Conclusion

8.1 Revisiting main findings and contribution to literature

We study various aspects of the gold supply chain's upstream and downstream parts. We focus specifically on artisanal gold miners in the upstream part of the gold supply chain. Artisanal gold miners are usually informal labourers, who use basic tools with limited capital investment to mine gold (Jønsson & Bryceson, 2009). Given the sector's informality, very little data is available, making it extremely difficult to understand the sector's size, scope, and impact (Lahiri-Dutt et al., 2019). In addition, due to the sector's informality, it operates with little to no regulatory oversight, resulting in inefficient operation, hazardous working conditions, and human rights abuses. For example, the sector is collectively the largest anthropogenic emitter of mercury, a toxic, non-biodegradable metal that can cause severe health implications for local communities and beyond.

The second part of the dissertation focuses on various behavioural and technical changes in the downstream part of the supply chain that could alleviate problems in the upstream part of the supply chain. Including the potential of using blockchain to increase traceability and transparency from mine to market, understanding the demand for responsibly-sourced gold, specifically certified gold, and lastly, ways to increase sourcing gold from e-waste in the country of consumption, which would alleviate pressure from primary resources.

8.1.1 Upstream part of gold supply chain

Due to the lack of data, changes in the world gold price are often assumed to be the primary motivation for people to take up artisanal mining (Grynberg et al., 2021; Seccatore et al., 2014; Hruschka & Echavarria, 2011; Seccatore et al., 2014). However, using world gold prices as an indication of the size of local activities is problematic since the market structure and competitiveness of local gold markets, specifically the relationship between the world gold price and local gold price, has been overlooked in the literature.

In Chapter 2, we collected primary data on the market structures of local gold markets on four artisanal mines in Burkina Faso. We asked miners who sold gold in the last month various questions about the price they received, the number of buyers available to them, and their knowledge of world gold prices. We find that the pandemic worsened many pre-existing market imperfections of local gold markets, specifically reducing the number of traders that can purchase gold from miners. On the other hand, the world gold market is highly competitive with many buyers and sellers and widely available price information. Despite the availability of price information, we find that local miners have limited knowledge of world prices. However, even if they knew global gold prices, due to lack of credit and inability to store gold safely, miners are pressed to sell gold immediately, even at very low prices. Therefore, the worsening of local market imperfections during the pandemic led to a substantial decrease in local gold prices and local gold miners' income, despite world gold prices reaching a record high.

In addition, the lack of data on artisanal mining activities and lifecycles, such as when the operations of a specific artisanal mine started, expanded, and ended, makes it difficult to determine the sector's impact. Again, researchers have relied on fluctuations in the world gold price to estimate the impact of artisanal mining activities on local communities (Bazillier & Girard, 2020). However, in Chapter 2 we find that local gold prices do not necessarily follow global gold prices. Therefore we argue that a more refined analysis that does not rely on changes in the world gold price to determine the impact of artisanal mining on local communities is necessary.

In Chapter 3, we use high-resolution satellite images to supplement data on artisanal mines with starting dates, which allows us a more refined temporal analysis of the impact of an artisanal mine. Although previous studies have used satellite images to find artisanal mines (see Saavedra & Romero, 2021; Guenther, 2018; Gallwey et al., 2020), as far as we know, we are the first to use high-resolution satellite images to supplement existing data with temporal information.

We measure the impact of artisanal mines on neighouring households' expenditure, wealth, children's health, and education. Opening an artisanal mine positively affects expenditure and wealth – expenditure and wealth of households neighbouring an artisanal mine increase by 6%. Artisanal gold mining also positively impacts education; children are about 2% more likely to be enrolled in school, also when controlling for wealth. However, we do not find that artisanal mining has any significant impact on reducing infant mortality. In addition, we find that expenditure on alcohol and tobacco is about four times more around artisanal mines than the increases in general household expenditure.

Many stakeholders, including multilateral organisations, academics and NGOs, have recommended that host governments formalise artisanal mining sectors to increase monitoring and allow miners to invest in more efficient mining operations (Hinton, 2005; Vogel et al., 2018; Siegel & Veiga, 2010). We also differentiate between mines that are formal and informal. However, we do not find that a lenient definition of formalisation – merely registering artisanal mines – significantly impacts the well-being of neighbouring households.

Lastly, in the upstream section of the dissertation, we also considered other possible interventions that could improve the health and safety of artisanal miners. In Chapter 4, we examined potential interventions to mitigate some of the health risks associated with artisanal mining, specifically increasing miners' protection behaviour when handling mercury. Despite the potential severe health implications of mercury contamination, we, similar to many other studies, find very little use of personal protective equipment by artisanal miners (Sana et al., 2017; Tomicic et al., 2011; Fadlallah et al., 2020; Long et al., 2015). In this study, we evaluate the impact of knowledge of mercury, perception of danger, and access to personal protective equipment to hinder miners from adopting protective behaviour. Although many studies have worked on mercury use in artisanal gold mining (Cossa et al., 2021), we are not aware of any studies that evaluate the impact of these determinants on actual protective behaviour.

We collected primary data on four artisanal gold mines in Burkina Faso. We used surveys to determine knowledge and risk perception of mercury, a field experiment to determine the impact of free access to personal protective equipment on usage, and hair samples to identify groups more at risk of mercury exposure. We found that thinking mercury is dangerous does not necessarily lead to higher use of personal protective equipment, specifically masks, and gloves. While higher knowledge is correlated slightly to higher reported usage of PPE, we find that increased access to PPE has the most significant increase in reported usage, especially for gloves. Although, this was only true if miners received the PPE for free and not if it was merely available for sale in their area. Our results from the hair samples also suggest that mercury and gold traders and miners who use mercury often are most at risk of high exposure and should be targeted in interventions.

8.1.2 Downstream part of gold supply chain

In the downstream part of the supply chain, I first assess the possibility of using blockchain to reduce the cost of due diligence when sourcing from artisanal miners. Various governments and organisations, such as the OECD, have specific guidelines for responsible gold sourcing. Since refiners are a bottleneck in the gold supply chain, adhering to these guidelines has increased the due diligence cost for refiners. Refineries reduce the sourcing cost by buying most of their gold from a few industrial mines, building personal relationships with them, and being present at the mine site. Given the small quantity of gold a group of artisanal miners produces, it is too expensive for refiners to build the same relationships with artisanal miners. Therefore, due to the high due diligence costs, many artisanal miners are excluded from formal supply chains.

In Chapter 5, I evaluate the potential of using a blockchain system to reduce the due diligence cost when sourcing from artisanal miners. A blockchain can reduce cost by eliminating the need for central authority and personal trust relationships and by decentralising trust into the blockchain system. I conducted various interviews with experts throughout the supply chain and found that the problem with using blockchain is linking the physical world (gold) and the digital world (the blockchain). Linking these two systems cannot be done automatically, for example differentiating between the inherent qualities of different pieces of gold, such as geochemical fingerprinting. However, it would need to be done manually by adding a tag, which requires the intervention of an authorised body and weakens the trust on the blockchain (Brugger, 2019).

An alternative and increasingly popular way to verify that gold was sourced responsibly are through certification schemes (Mori Junior et al., 2015). Certification schemes set standards and guidelines and then verify that standards are met by auditing, testing, or other means. Gold is sourced under compliant companies that are then certified. The result is a highly fragmented certification landscape, making it difficult for the average consumer to understand and navigate. I identified 15 different schemes that certify gold, each with its own guidelines, verification method, where in the world they operate, and on which type of mining they focus (Fisher & Childs, 2013; Kickler & Franken, 2017; Mori Junior et al., 2015).

In addition, since certified gold is a type of credence good (Darby & Karni, 1973), meaning the good has certain qualities that can not be judged by consumption, consumers cannot learn from past purchases to understand their preferences for certified gold. Therefore, retailers and banks are still driving the demand for certified gold.

However, jewellers and banks face different concerns when sourcing certified gold. The additional certification cost is a more significant issue for investors than for jewellers. Since gold is only a small part of the total cost of a piece of jewellery, the certification mark-up for jewellery is small. Banks, however, buy 99.999% pure gold directly from the refiner, and the certification mark-up is larger for them. The size of the jeweller also determines the demand for certified gold. While smaller goldsmiths are involved in the production and feel connected to the gold and final product, large international companies could ensure responsible sourcing to avoid reputation damage. However, the total demand for certified gold remains low since small goldsmiths, who have the highest demand for certified gold, account for a very small percentage of the aggregate demand for gold in jewellery.

In Chapter 7, we study the possibilities of increasing sourcing metals, including gold, from secondary sources such as industrial waste. Old electronic equipment such as mobile phones contains a wide range of metals, which could be reintroduced back into the supply chain after the device has been discarded. However, many people keep their phones at home after they replaced it (Baxter & Gram-Hanssen, 2016; Speake & Yangke, 2015; Ongondo & Williams, 2011; Thiébaud et al., 2018), withholding these metals from re-entering the supply chain and constituting a significant lost resource (Scharnhorst et al., 2005; Hira et al., 2018). We surveyed a large and representative sample in German-speaking Switzerland and found that most people have at least one phone at home. Most hibernating phones could be recycled without significantly diminishing the owner's utility.

Since we believe that most phones have not been recycled due to the high effort, or high transaction cost, to get rid of old devices, we conducted a randomised control trial to evaluate the impact of various informational treatments and reduce the transaction cost of recycling. We randomly distributed mail-back envelopes to 15,000 employees at the ETH Zürich. Envelopes had different messages on it, including information about data protection and protecting nature.

We varied the transactional cost of returning an envelope by not including return postage on some of the envelopes. This meant recipients needed to either buy the correct postage or drop the envelope at the ETH Zürich Campus Info service desks. We found that while reducing transaction costs for participants by including return postage, and more than doubling the return rate of phones, no informational treatment had a significant impact.

While the market value of the metals in a phone is than the average marginal collection cost (using values from Williams, 2019). However, if we consider the full environmental cost of the metals in a phone, which we calculated conducting a multi-regional input and output analysis and monetising the environmental saving (Wernet et al., 2016; Galgani et al., 2020). A mail-back envelope method is cost-effective, especially when reducing transactional cost for consumers. While reducing transactional cost by including return postage on envelopes increases the marginal cost of collecting a phone, it reduces average marginal cost by significantly increasing the collection rate of phones.

8.2 Limitations and pathways for future research

8.2.1 The role of domestic purchasing programs in local gold markets

During the COVID-19 pandemic, local gold prices decreased significantly in most countries. However, some reports mentioned that local gold prices in Ecuador and the Philippines, where central banks act as domestic gold buyers, were less affected by the pandemic (World Gold Council, 2021b). The governmental body responsible for artisanal mining in Burkina Faso, ANEEMAS, is currently acting as a domestic buyer in a very small number of mining areas, which were unfortunately not covered during our study. Since we did not survey any mines in the area where ANEEMAS acts as a central purchaser, a limitation of our study in Chapter 2 is that we are unable to assess the efficiency and viability of the ANEEMAS central buying program during the pandemic. However, this is an essential topic for future research.

Acting as a central buyer does have significant potential for two reasons. First, if central buyers have cash liquidity, they could make local markets more competitive, potentially reducing external shocks. Second, central buying could increase the government's control over the artisanal mining sector, which often operates in a policy vacuum and is said to be "out of control" (Ralph et al., 2018; Mawowa, 2013). To extend their control over the largely informal artisanal mining sectors, other governments, including those of Peru and Colombia, are also considering acting as central gold purchasers in their countries (Vargas, 2021).

However, governments should take care when designing domestic purchase programmes. During a previous regime, from 1986-1996, the Burkinabè government, through the *Comptoir Burkinabe des Métaux Précieux* (Burkinabe Precious Metal Counter, CBMP), bought gold from licensed traders at prices that were determined by the world gold price. Despite efforts to control the gold trade, an estimated 40-60% of gold was still illegally traded, also by the CBMP agents themselves (Werthmann, 2017; Côte & Korf, 2018; Grätz, 2013). Central buying programs had similar problems with illicit trading and rent-seeking in Ghana in the 1990s (Hilson & Pardie, 2006) and present-day Zimbabwe (Spiegel, 2009). An important topic for future research would therefore be to assess under which conditions a domestic purchasing program would effectively increase the competitiveness of local markets and decrease illicit trade.

8.2.2 Improving data on artisanal mining

In Chapter 3, we estimated the impact of artisanal mines on neighbouring households in Burkina Faso. A limitation of the study is that we treated artisanal mines as homogeneous, except for differentiating between formal and informal mines. In reality, however, artisanal mining is an umbrella term that includes various mining operations with different levels of mechanisation, declining or booming production, and ranging from a few to tens of thousands of miners. Brugger & Zanetti (2020) found that the type of artisanal mine greatly impacts how people allocate their labour and capital. Smaller sites in Burkina Faso, which often have declining production, are more likely to attract local workers who complement their agriculture income with mining and do not want to go far from their homes. Larger and more productive sites are more likely to attract miners from all over the country and neighbouring countries, who fully substituted mining for agriculture. Brugger &

Zanetti (2020) also found that three out of four miners send remittances back to their families, and those moving far away from home are even more likely to send remittances. Therefore, the type of artisanal mine would have a large impact on cash flows. In the case of smaller mines, miners are more likely to spend their income locally or send remittances to family in the vicinity of the mine, which would have a large influence on the impact of the mine on local households.

We explored the possibility of differentiating between large and small artisanal mines by using the size of the area of the mine as seen on satellite images. However, due to a lack of data on known large and small mines, we could not verify the accuracy of this method. In addition, artisanal mines could experience various gold rushes. For example, Brugger & Zanetti (2020) described how the large artisanal mine Alga grew in eight segments, or gold rushes, from 1998 to 2017. Therefore, the temporal aspect of the artisanal mines needs to be refined. However, publicly available high-resolution images provide insufficient coverage to allow such an analysis. An important topic for future research would be differentiating between large and small mines. Given these data deficiencies, alternative data sources could be explored, such as using lower resolution satellite images that measure surface roughness in combination with data from fieldwork or secondary data.

8.2.3 Measurement of PPE usage and willingness to pay

In Chapter 4, we determine miners' preferred protection strategies against mercury exposure by relying on miners' reported usage of PPE and other protective strategies. However, this could be subject to social desirability bias if miners incorrectly report using PPE because they think that is the sought-after answer. Reported usage could also be subject to recall bias by overestimating the number of times that PPE was used. A limitation of the study is that we rely solely on the reported usage of PPE.

We only consider a binary outcome of PPE usage, not allowing for more detailed analysis, including the frequency of use or the correct use of PPE. A more refined analysis could, for example, use detailed record-keeping from the miners, such as diaries recording information about the frequency and context of each interaction with mercury. Detailed information captured in diaries could also be used to measure the adoption of various cost-free best practices, such as burning gold amalgams in a dedicated location outside, away from other people and structures. Evaluating the effectiveness of adopting a broader range of cost-free best practices would ensure more cost-effective interventions.

However, detailed record-keeping is complicated by the low literacy of artisanal gold miners. Objective measurements could also be considered for future research, such as sensors that measure mercury exposure or reusable masks with changeable activated carbon filters, which could be removed to analyse the amount of mercury captured in the filter.

Lastly, a more refined analysis that could reveal the willingness to pay for PPE, possibly by selling PPE at different subsidised prices, could inform a broader range of policy options, including the efficacy of subsidies versus free distribution. It is possible that asking for a small subsidised price for PPE could result in a selection effect in only people who want PPE purchasing it, which could result in higher usage. However, previous studies on bed nets (Cohen & Dupas, 2010) and solar lamps (Rom & Günther, 2019) did not find a significant difference between usage when receiving items for free or at subsidised prices. A possible topic for future research would be to test the impact of such cost-sharing initiatives on PPE usage in an artisanal mining context.

8.2.4 Consumers' role in the demand for certified gold

During interviews with experts, I found that the demand for certified gold is not driven by consumers but by retailers. The average consumer does not buy gold often and does not clearly understand their demand for gold, the complexities of the gold industry, or the value of certified gold. In addition, certified gold is a type of credence good, making it more difficult for consumers to understand their preferences through consumption, even for consumers with high-frequency consumption (Darby & Karni, 1973).

While retailers still drive the demand for certified gold, they are influenced by consumers' perceptions. Although the current demand for responsibly-sourced gold jewellery or investments is low, many believe that the industry is likely to follow the same path as the garment industry, which saw a significant increase in responsible consumption driven by activists, NGOs, and consumers (Gomelsky, 2020; Grünenfelder et al., 2018). In Chapter 6, I aimed to understand retailers' demand for certified gold and, to a lesser degree, how retailers' demand is shaped by consumers. Since the role of retailers, especially the flow of information between retailer and consumer, has been largely overlooked in the literature, this is an important avenue for future research.

8.2.5 Better understanding the drivers of participation in urban mining

Using a mail-back envelope to assess the feasibility of urban mining has many benefits. A mail-back envelope allows us to randomise on an individual level, limit spillovers, have a defined control group, include informational treatments, and vary the transactional costs of recycling. A disadvantage of this field experiment is that we do not have any other data on the participants, which means we cannot gain further insight into the participants who returned their phones. Moreover, the lack of data on other characteristics of participants contributes to low Pseudo R-square values; the treatments explain less than 1% of the spread in the data. The only personal characteristic we could derive from the envelopes is whether people prefer to receive communication in English or German, which already explained a larger share of the recycling behaviour compared to the treatments. This could be driven by an existing recycling culture (Wong Sak Hoi, 2016; Sinha-Khetriwal et al., 2005) and that we believe that Swiss recipients were more likely to opt for communication in German.

Previous studies have mentioned that mail-back envelopes are expensive to collect phones from recycling (Tanskanen & Butler, 2007; Litchfield et al., 2018). However, since we were able to compare the effectiveness of mail-back envelopes by having a control group, we found that mail-back envelopes increase collections of phones by more than the increase in prices. High return rates result in a decrease in the marginal cost of collecting an envelope and making it a cost-effective strategy.

Return rates in our study were three to five times that of previous mail-back campaigns in Australia, Europe, and the US that typically reports a 1-2% return rate of envelopes (Tanskanen & Butler, 2007; Litchfield et al., 2018). We suggest that this relatively high return rate could be due to the project being conducted by participants' employer (ETH Zürich), which fostered trust in the project. However, since we did not have a group outside of the ETH Zürich, we are not able to evaluate this, and we recommend this as an interesting future research opportunity. If return rates within trust communities were significantly higher, then there would be a high potential to conduct recycling campaigns within businesses or communities with high-levels of trust.

8.3 Policy recommendations throughout the supply chain

8.3.1 Artisanal mining

We find artisanal mining has considerable potential to alleviate poverty. However, due to little oversight, other indicators of well-being, such as children's health, do not necessarily improve in the vicinity of an artisanal mine. To fully harness the sector's potential, increased oversight beyond a narrow definition of formalisation, such as "paper formalisation" or merely registering mines, would be necessary. In addition, we recommend interventions that focus on increasing the competitiveness of local markets have a large potential to alleviate poverty and make markets more resilient to external shocks. Making local markets more competitive includes correcting power symmetries by increasing the number of gold collectors available to miners and increasing miners' knowledge of world gold prices, possibly by broadcasting world gold prices on local radio.

We also recommend increased access to proper PPE for artisanal miners. Giving miners access to free personal protective equipment could have significant health benefits for individual miners. We found a significant increase in miners' reported usage when they received PPE for free. Given the very low levels of knowledge of cost-free practices to avoid mercury exposure, the large benefits of following best practice guidelines, and that reported usage of PPE is weakly correlated to higher knowledge of mercury, we recommend that information and awareness campaigns should be done in combination to distributing gear for free.

8.3.2 Refineries

Once artisanal gold is exported, it is difficult to confirm provenance. Gold sourced by artisanal miners accumulates from miners to trading house (point before export) through a myriad of local gold buyers and collectors (Grätz, 2004; Guéniat & White, 2015; Telmer, 2020). The collectors mix gold from different sources, which is cast into semi-refined doré bars by the gold trading houses. Doré bars still contain some secondary and trace metals that could be used to determine the provenance of gold. However, once the doré bars are exported to specialist refineries, they remove all the secondary and trace metals to create 99.999% pure gold. Any company that would like to include information on the provenance of the gold they sourced using geochemical analysis is dependent on refiners disclosing this information. In addition, making this information public could also contribute to developing a reference database of the composition of gold ore across the world.

8.3.3 Disposal of e-waste

To further increase responsible gold sourcing practices, extracting gold and other metals from secondary sources, such as e-waste, is vital (Vidal et al., 2013). Comprehensive retailer responsibility policies — making companies throughout the supply chain responsible for the waste generated by their products — are crucial but only a first step towards a more circular economy. Making recycling easy for consumers is more effective than any informational treatment. Getting hibernating mobile phones back from consumers is more expensive than the value of the metals in a phone, except when we consider all the environmental costs of mining and the advantage of not generating more e-waste. Prepaid recycling fees, such as the advance recycling fee included in new devices sold in Switzerland, should cover the cost of recycling devices and the cost of collecting devices for recycling. Any method that reduces the transactional cost for consumers to return phones for recycling, such as the mail-back envelope, is essential to improve the cost-effectiveness of collection. Even though reducing transaction cost increases the total cost of collection campaigns, it decreases the marginal cost of collecting items due to increased return rates.

8.4 Conclusion

The gold supply chain is highly complex. Gold mines include a range of actors from large multi-national mining companies to millions of informal artisanal miners, including women and children, who mine gold with elementary methods and limited capital investment. Gold is traded through various traders, from a few highly secured operations to thousands of illicit and informal traders. Gold is then transformed, shaped, and refined into different forms, and purities and for an assortment of uses, from jewellery, investment to smartphones.

Gold means something different to people worldwide, from a potential income to alleviate poverty, a keepsake symbolising personal milestones, or a source of investment. While gold mining could secure additional incomes for many miners in resource-rich countries such as Burkina Faso, an expanding informal mining sector also has significant negative impacts on local communities, such as environmental degradation, severe public health concerns, and various human rights abuses. In Switzerland, gold is a commodity that provides job opportunities in trading and refinement and the potential for secure investments and supply of luxury consumer goods.

Given the complex and far-reaching nature of the gold supply chain, no single solution would address the inequalities and negative externalities in the gold sector. Instead, all actors involved would need to continuously search for policies that could improve the sector. Such policies include supporting and formalising local gold markets, giving technical support to miners, increasing transparency from mine to market, stimulating the demand for responsible sourcing, and expanding urban mines in high-income countries. We could move to more responsible and fair gold supply chains through incremental changes.

Bibliography

Abad, S. Q., Rodríguez-González, P. & Alonso, J. I. G. (2016). Evidence of the direct adsorption of mercury in human hair during occupational exposure to mercury vapour. *Journal of Trace Elements in Medicine and Biology*, *36*, 16–21.

Achabou, M. A. & Dekhili, S. (2013). Luxury and sustainable development: Is there a match? *Journal of business research*, *66*(10), 1896–1903.

Afrifa, J., Essien-Baidoo, S., Ephraim, R. K., Nkrumah, D. & Dankyira, D. O. (2017). Reduced egfr, elevated urine protein and low level of personal protective equipment compliance among artisanal small scale gold miners at bibiani-ghana: a cross-sectional study. *BMC public health*, *17*(1), 1–9.

Ali, S. H. (2006). Gold mining and the golden rule: a challenge for producers and consumers in developing countries. *Journal of Cleaner Production*, *14*(3-4), 455–462.

Ali, S. H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., ... Yakovleva, N. (2017). Mineral supply for sustainable development requires resource governance. *Nature*, *543*(7645), 367–372.

Allcott, H. (2011). Social norms and energy conservation. *Journal of Public Economics*, *95*(9-10), 1082–1095.

Andorfer, V. A. & Liebe, U. (2015). Do information, price, or morals influence ethical consumption? A natural field experiment and customer survey on the purchase of Fair Trade coffee. *Social science research*, *52*, 330–350.

ANEEMAS & Effigis Geo-Solutions Inc. (2018, May). *Report : Projet D'Appui Au Dévelopment du Secteur Minier du Burkina Faso.*

Aram, S. A., Lartey, P. O., Amoah, S. K. & Appiah, A. (2021). Gold eco-toxicology: Assessment of the knowledge gap on the environmental and health effects of mercury between artisanal small scale and medium scale gold miners in Ghana. *Resources Policy*, *72*, 102108.

Arthur, C. & Domiter, A. (2017). *UNIDO to help Burkina Faso work towards elimination of mercury use in the artisanal and small-scale gold mining sector.* Retrieved 22 September 2021, from `https://www.unido.org/news/`

unido-help-burkina-faso-work-towards-elimination-mercury-use-artisanal-and-small-scale-gold-mining-sector

Artisanal Gold Council. (2021). *Gold prices data.* Retrieved 22 September 2021, from https://www.artisanalgold.org/gold-prices-data/

Athey, S. & Imbens, G. W. (2022). Design-based analysis in difference-in-differences settings with staggered adoption. *Journal of Econometrics*, *226*(1), 62–79.

Aubynn, A. (2009). Sustainable solution or a marriage of inconvenience? The coexistence of large-scale mining and artisanal and small-scale mining on the Abosso Goldfields concession in Western Ghana. *Resources Policy*, *34*(1-2), 64–70.

Awasthi, A. K., Li, J., Koh, L. & Ogunseitan, O. A. (2019). Circular economy and electronic waste. *Nature Electronics*, *2*(3), 86–89.

Bafilemba, F. & Lezhnev, S. (2015). *Congo's conflict gold rush* (Tech. Rep.). Enough Project. Retrieved 21 October 2021, from https://limacharlienews.com/wp-content/uploads/2019/03/April-29-2015-Congo-Conflict-Gold-Rush-reduced.pdf

Balineau, G. & Dufeu, I. (2010). Are Fair Trade goods credence goods? A new proposal, with French illustrations. *Journal of business ethics*, *92*(2), 331–345.

Banchirigah, S. M. (2006). How have reforms fuelled the expansion of artisanal mining? evidence from sub-saharan africa. *Resources Policy*, *31*(3), 165–171.

Barrett, C. B. & Carter, M. R. (2010). The power and pitfalls of experiments in development economics: some non-random reflections. *Applied Economic Perspectives and Policy*, *32*(4), 515–548.

Bashwira, M.-R., Cuvelier, J., Hilhorst, D. & Van der Haar, G. (2014). Not only a man's world: women's involvement in artisanal mining in eastern DRC. *Resources Policy*, *40*, 109–116.

Baxter, J. & Gram-Hanssen, I. (2016). Environmental message framing: enhancing consumer recycling of mobile phones. *Resources, Conservation and Recycling*, *109*, 96–101.

Bazillier, R. & Girard, V. (2020). The gold digger and the machine. Evidence on the distributive effect of the artisanal and industrial gold rushes in Burkina Faso. *Journal of Development Economics*, *143*, 102411.

Beckmann, J. & Czudaj, R. (2013). Gold as an inflation hedge in a time-varying coefficient framework. *The North American Journal of Economics and Finance*, *24*, 208–222.

Bell, F. G. & Donnelly, L. J. (2006). *Mining and its Impact on the Environment.* CRC press.

Bento, A. L. (2017). All That is Gold Does Not Glitter: Mercury Exposure to Children in Artisanal and Small Scale Gold Mines and the Inadequacy of the Minamata Convention. *Journal of International Business and Law*, *16*(2), 10.

Berger, V., Mosier, D., Bliss, J. & Moring, B. (2014). Sediment-Hosted Gold Deposits of the World-Database and Grade and Tonnage Models. Open-File Report 2014-1074, June 2014, Virginia, Reston. *US Geological Survey*.

Berglund, C. (2006). The assessment of households' recycling costs: The role of personal motives. *Ecological Economics*, *56*(4), 560–569.

Bertran Alvarez, Y., Coué, B. & Schein, P. (2016). *Supply chains of artisanal gold in West Africa. A study of the supply chain in two gold-producing regions of Burkina Faso and Senega.* Retrieved 22 September 2021, from https://www.responsiblemines.org/wp-content/uploads/2018/04/Publication-supply-chains-artisanal-gold-west-africa_-ENGL_-baja.pdf

Black, P., Richard, M., Rossin, R. & Telmer, K. (2017). Assessing occupational mercury exposures and behaviours of artisanal and small-scale gold miners in Burkina Faso using passive mercury vapour badges. *Environmental research*, *152*, 462–469.

Blore, S. (2013). *Responsible Sourcing of Artisanal Gold in Eastern DRC: Pilot Status and Planning* (Tech. Rep.). Partnership Africa Canada.

Boadi-Kusi, S. B., Hansraj, R., Mashige, K. P. & Ilechie, A. A. (2016). Factors associated with protective eyewear use among cocoa farmers in Ghana. *Injury prevention*, *22*(5), 365–369.

Boese-O´Reilly, S., Dahlmann, F., Lettmeier, B. & Gustav, D. (2004). *Removal of barriers to the introduction of cleaner artisanal gold mining and extraction technologie in Kadoma, Zimbabwe.* Retrieved 09 October 2021, from https://iwlearn.net/resolveuid/886be3abb7f723d8653bf38e9e678e7b

Bordo, M. D. (1981). The classical gold standard: Some lessons for today. *Review*.

Borusyak, K. & Jaravel, X. (2017). Revisiting event study designs. *Available at SSRN 2826228*.

Bose-O'Reilly, S., McCarty, K. M., Steckling, N. & Lettmeier, B. (2010). Mercury exposure and children's health. *Current problems in pediatric and adolescent health care*, *40*(8), 186–215.

Bose-O´Reilly, S., Dahlmann, F., Lettmeier, B. & Drasch, G. (2004). *Reference and HBM Values.* Retrieved 05 October 2021, from https://iwlearn.net/resolveuid/886be3abb7f723d8653bf38e9e678e7b

Bose-O'Reilly, S., Lettmeier, B., Gothe, R. M., Beinhoff, C., Siebert, U. & Drasch, G. (2008). Mercury as a serious health hazard for children in gold mining areas. *Environmental research*, *107*(1), 89–97.

Bose-O'Reilly, S., Lettmeier, B., Shoko, D., Roider, G., Drasch, G. & Siebert, U. (2020). Infants and mothers levels of mercury in breast milk, urine and hair, data from an artisanal and small-scale gold mining area in Kadoma/Zimbabwe. *Environmental research*, *184*, 109266.

Bovea, M. D., Ibáñez-Forés, V., Pérez-Belis, V. & Juan, P. (2018). A survey on consumers' attitude towards storing and end of life strategies of small information and communication technology devices in Spain. *Waste Management*, *71*, 589–602.

Bray, N. (2012). Minerals not to die for. *Organisation for Economic Cooperation and Development. The OECD Observer*(292), 16.

Brottem, L. V. & Ba, L. (2019). Gendered livelihoods and land tenure: The case of artisanal gold miners in Mali, West Africa. *Geoforum*, *105*, 54–62.

Bruederle, A. & Hodler, R. (2019). Effect of oil spills on infant mortality in nigeria. *Proceedings of the National Academy of Sciences*, *116*(12), 5467–5471.

Brugger, F. (2019). *Blockchain won't help with conflict minerals.* Retrieved 22 May 2019, from https://ethz.ch/en/news-and-events/eth-news/news/2019/04/blog-brugger-blockchain-conflict-minerals.html

Brugger, F. & Zanetti, J. (2020). "In my village, everyone uses the tractor": Gold mining, agriculture and social transformation in rural Burkina Faso. *The Extractive Industries and Society*, *7*(3), 940–953.

Brune, L., Kerwin, J. T. & Li, Q. (2021). How important is temptation spending? maybe less than we thought. *World Bank Economic Review*.

Bugmann, A., Brugger, F., Zongo, T. & van der Merwe, A. (2022). "doing asgm without mercury is like trying to make omelets without eggs". understanding the persistence of mercury use among artisanal gold miners in burkina faso. *Environmental Science & Policy*, *133*, 87–97.

Bugmann, A. A. (2020). *Power Dynamics in Gold Supply Chains: A political ecology perspective on the access to the gold and mercury market in the artisanal and small-scale gold mining sector in Burkina Faso* (Unpublished master's thesis). ETH Zurich.

Cabernard, L., Pfister, S. & Hellweg, S. (2019). A new method for analyzing sustainability performance of global supply chains and its application to material resources. *Science of the Total Environment*, *684*, 164–177.

Caravati, E. M., Erdman, A. R., Christianson, G., Nelson, L. S., Woolf, A. D., Booze, L. L., ... others (2008). Elemental mercury exposure: an evidence-based consensus guideline for out-of-hospital management. *Clinical Toxicology*, *46*(1), 1–21.

Chan, L. & Bishop, B. (2013). A moral basis for recycling: Extending the theory of planned behaviour. *Journal of Environmental Psychology*, *36*, 96–102.

Charles, E., Thomas, D. S., Dewey, D., Davey, M., Ngallaba, S. E. & Konje, E. (2013). A cross-sectional survey on knowledge and perceptions of health risks associated with arsenic and mercury contamination from artisanal gold mining in Tanzania. *BMC public health*, *13*(1), 1–8.

Childs, J. (2008). Reforming small-scale mining in sub-Saharan Africa: Political and ideological challenges to a Fair Trade gold initiative. *Resources Policy*, *33*(4), 203–209.

Childs, J. (2010). 'Fair trade'gold: A key to alleviating mercury pollution in sub-Saharan Africa? *International Journal of Environment and Pollution*, *41*(3-4), 259–271.

Christensen, D. (2019). Concession stands: How mining investments incite protest in Africa. *International organization*, *73*(1), 65–101.

Cohen, J. & Dupas, P. (2010). Free distribution or cost-sharing? Evidence from a randomized malaria prevention experiment. *The Quarterly Journal of Economics*, 1–45.

Compaore, W. F., Dumoulin, A. & Rousseau, D. P. (2020). Metals and metalloid in gold mine pit lakes and fish intake risk assessment, Burkina Faso. *Environmental geochemistry and health*, *42*(2), 563–577.

CONTAM. (2012). Scientific opinion on the risk for public health related to the presence of mercury and methylmercury in food. *Efsa Journal*, *10*(12), 2985.

Cossa, H., Scheidegger, R., Leuenberger, A., Ammann, P., Munguambe, K., Utzinger, J., ... Winkler, M. S. (2021). Health Studies in the Context of Artisanal and Small-Scale Mining: A Scoping Review. *International Journal of Environmental Research and Public Health*, *18*(4), 1555.

Côte, M. & Korf, B. (2018). Making concessions: Extractive enclaves, entangled capitalism and regulative pluralism at the gold mining frontier in Burkina Faso. *World Development*, *101*, 466–476.

Czajkowski, M., Hanley, N. & Nyborg, K. (2017). Social norms, morals and self-interest as determinants of pro-environment behaviours: the case of household recycling. *Environmental and Resource Economics*, *66*(4), 647–670.

Damalas, C. A. & Abdollahzadeh, G. (2016). Farmers' use of personal protective equipment during handling of plant protection products: determinants of implementation. *Science of the Total Environment*, *571*, 730–736.

Darby, M. R. & Karni, E. (1973). Free competition and the optimal amount of fraud. *The Journal of law and economics*, *16*(1), 67–88.

De Barros Santos, E., Moher, P., Ferlin, S., Fostier, A. H., Mazali, I. O., Telmer, K. & Brolo, A. G. (2017). Proof of concept for a passive sampler for monitoring of gaseous elemental mercury in artisanal gold mining. *Scientific reports*, *7*(1), 1–11.

DeJong, T. (2019, June). *Desk Review of Artisanal and Small-Scale Gold Mining (ASGM) in Burkina Faso* (Tech. Rep.). USAID Artisanal Mining and Property Rights Task Order under the Strengthening Tenure and Resource Rights II (STARR II) IDIQ. Retrieved 22 September 2021, from `https://www.land-links.org/wp-content/uploads/2019/10/USAID-AMPR-Burkina-Faso-ASGM-Desk-Review_FINAL.pdf`

Dillon, B. (2012). Using mobile phones to collect panel data in developing countries. *Journal of international development*, *24*(4), 518–527.

Dooyema, C. A., Neri, A., Lo, Y.-C., Durant, J., Dargan, P. I., Swarthout, T., ... others (2012). Outbreak of fatal childhood lead poisoning related to artisanal gold mining in northwestern nigeria, 2010. *Environmental health perspectives*, *120*(4), 601–607.

Down, C. G., Stocks, J. et al. (1977). Environmental Impact of Mining. *Environmental impact of mining.*.

Drasch, G., Böse-O'Reilly, S., Beinhoff, C., Roider, G. & Maydl, S. (2001). The Mt. Diwata study on the Philippines 1999—assessing mercury intoxication of the population by small scale gold mining. *Science of the Total Environment*, *267*(1-3), 151–168.

Drasch, G., Wanghofer, E. & Roider, G. (1997). Are blood, urine, hair, and muscle valid biomonitors for the internal burden of men with the heavy metals mercury, lead and cadmium?

Drechsel, F., Engels, B. & Schäfer, M. (2019). *"The mines make us poor": Large-scale mining in Burkina Faso* (Tech. Rep.). GLOCON Country Report.

Durizzo, K., Asiedu, E., van der Merwe, A. & Günther, I. (2022). Economic recovery but stagnating mental health during a global pandemic? evidence from ghana and south africa. *Review of Income and Wealth*.

Durizzo, K., Asiedu, E., Van der Merwe, A., Van Niekerk, A. & Günther, I. (2021). Managing the COVID-19 pandemic in poor urban neighborhoods: The case of Accra and Johannesburg. *World Development*, *137*, 105175.

Echavarria, C. (2014). 'what is legal?'formalising artisanal and small-scale mining in colombia. *IIED, London and ARM, Colombia*, *79*.

Eichengreen, B. J., Eichengreen, B. & Flandreau, M. (1997). *The gold standard in theory and history.* Psychology press.

El Azhari, A., Rhoujjati, A., El Hachimi, M. L. & Ambrosi, J.-p. (2017). Pollution and ecological risk assessment of heavy metals in the soil-plant system and the sediment-water column around a former Pb/Zn-mining area in NE Morocco. *Ecotoxicology and environmental safety*, *144*, 464–474.

Engels, B. (2017). Not all glitter is gold: Mining conflicts in Burkina Faso. In *Contested extractivism, society and the state* (pp. 149–169). Springer.

Epstein, M. J. & Yuthas, K. (2011). Conflict minerals: Managing an emerging supply-chain problem. *Environmental Quality Management*, *21*(2), 13–25.

Esteban, M. & Castaño, A. (2009). Non-invasive matrices in human biomonitoring: a review. *Environment international*, *35*(2), 438–449.

Evans, D. (2016). Why Don't Economists Do Cost Analysis in Their Impact Evaluations? *Development Impact*. Retrieved 20 August 2021, from https://blogs.worldbank.org/impactevaluations/why-don-t-economists-do-cost-analysis-their-impact-evaluations

Evans-Pughe, C. (2010). Blood and treasure. *Engineering & Technology*, *5*(15), 60–63.

Fadlallah, M. A., Pal, I. & Hoe, V. C. (2020). Determinants of perceived risk among artisanal gold miners: A case study of Berber locality, Sudan. *The Extractive Industries and Society*, *7*(2), 748–757.

Fairtrade. (2018). *Fairtrade-bananen,so funktioniert der faire handel.* Retrieved 30 November 2018, from https://www.maxhavelaar.ch/produkte/produktkategorien/bananen.html

Farrell, L. A., Hamann, R. & Mackres, E. (2012). A clash of cultures (and lawyers): Anglo Platinum and mine-affected communities in Limpopo Province, South Africa. *Resources Policy*, *37*(2), 194–204.

Federal Office for the Environment. (2017). *Mercury: first Minamata Convention conference in Geneva.* Retrieved 19 April 2018, from https://www.bafu.admin.ch/bafu/en/home/documentation/news-releases/anzeige-nsb-unter-medienmitteilungen.msg-id-67994.html

Federal Statistical Office of Switzerland. (2019). *Language – facts and figures.* Retrieved 17 February 2021, from https://www.eda.admin.ch/aboutswitzerland/en/home/gesellschaft/sprachen/die-sprachen---fakten-und-zahlen.html

Federal Statistical Office of Switzerland. (2021). *Population.* https://www.bfs.admin.ch/bfs/en/home/statistics/population.html.

Feichtner, I., Krajewski, M. & Roesch, R. (2019). *Human rights in the extractive industries.* Springer.

Fischhoff, B., Slovic, P., Lichtenstein, S., Read, S. & Combs, B. (1978). How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits. *Policy sciences*, *9*(2), 127–152.

Fisher, E. & Childs, J. (2013). An ethical turn in African mining: Voluntary regulation through Fair Trade. In *Mining and Social Transformation in Africa* (pp. 144–161). Routledge.

Fisher, E., Mwaipopo, R., Mutagwaba, W., Nyange, D. & Yaron, G. (2009). "The ladder that sends us to wealth": Artisanal mining and poverty reduction in Tanzania. *Resources Policy*, *34*(1-2), 32–38.

Frey, B. S. & Meier, S. (2004). Social comparisons and pro-social behavior: Testing "conditional cooperation" in a field experiment. *American Economic Review*, *94*(5), 1717–1722.

Fritz, M. M., McQuilken, J., Collins, N. & Weldegiorgis, F. (2018). Global Trends in Artisanal and Small-Scale Mining (ASM): A review of key numbers and issues. *HAL Working Papers*(hal-02547257).

Galgani, P., De Adelhart Toorop, R. & De Groot Ruiz, A. (2020). *Monetisation factors for true pricing.* True Price Foundation. Retrieved 20 August 2021, from https://trueprice.org/wp-content/uploads/2020/03/Monetisation-Factors-for-True-Pricing.pdf

Gallwey, J., Robiati, C., Coggan, J., Vogt, D. & Eyre, M. (2020). A Sentinel-2 based multispectral convolutional neural network for detecting artisanal small-scale mining in Ghana: Applying deep learning to shallow mining. *Remote Sensing of Environment*, *248*, 111970.

Gamu, J., Le Billon, P. & Spiegel, S. (2015). Extractive industries and poverty: A review of recent findings and linkage mechanisms. *The Extractive Industries and Society*, *2*(1), 162–176.

Garda World. (2021). *Burkina Faso: COVID-19 restrictions remain in place nationwide as of 14 January/update 10.* Retrieved 22 September 2021, from https://www.garda.com/crisis24/news-alerts/429346/burkina-faso-covid-19-restrictions-remain-in-place-nationwide-as-of-jan-14-update-10

Geenen, S. (2013). 'Who seeks, finds': How artisanal miners and traders benefit from gold in the eastern Democratic Republic of Congo. *The European Journal of Development Research*, *25*(2), 197–212.

Gegenbauer, S. & Huang, E. M. (2012). iPods, Ataris, and Polaroids: A personal inventories study of out-of-use electronics in Swiss households. In *Proceedings of the 2012 acm conference on ubiquitous computing* (pp. 531–535).

Geiger, J. (2020). Context matters: Three ways of how the context influences recycling behaviour.

Gerritsen, L. (2013). *Tin and Tantalum Road Trip.* Retrieved 9 August 2018, from https://www.fairphone.com/en/2013/11/08/tin-and-tantalum-road-trip/

Gibson, D. G., Pereira, A., Farrenkopf, B. A., Labrique, A. B., Pariyo, G. W. & Hyder, A. A. (2017). Mobile phone surveys for collecting population-level estimates in low- and middle-income countries: a literature review. *Journal of medical Internet research*, *19*(5), e139.

Glahder, C. M., Appel, P. W. & Asmund, G. (1999). Mercury in soap in Tanzania.

Global Footprint Network. (2020). *Case Studies: Switzerland.* Retrieved 23 September 2021, from https://www.footprintnetwork.org/2017/01/10/switzerland/?_ga=2.39536995.1743245909.1632380401-394334728.1632380401

Goldstein, N. J., Cialdini, R. B. & Griskevicius, V. (2008). A room with a viewpoint: Using social norms to motivate environmental conservation in hotels. *Journal of Consumer Research*, *35*(3), 472–482.

Gomelsky, V. (2020). *'Do You Know Where Your Watch's Gold Came From?'.* Retrieved 19 February 2021, from https://www.nytimes.com/2020/11/19/fashion/watches-supply-chain-transparency-chopard.html

Goodman-Bacon, A. (2021). Difference-in-differences with variation in treatment timing. *Journal of Econometrics*.

Gottesfeld, P., Tirima, S., Anka, S. M., Fotso, A. & Nota, M. M. (2019). Reducing lead and silica dust exposures in small-scale mining in northern Nigeria. *Annals of work exposures and health*, *63*(1), 1–8.

Grätz, T. (2004). Gold trading networks and the creation of trust: A case study from northern Benin. *Africa*, *74*(2), 146–172.

Grätz, T. (2013). The" frontier" revisited: gold mining camps and mining communities in West Africa. *ZMO Working Papers*.

Grynberg, R., Kandaswamy, V. & Singogo, F. (2021). The ASGM sector in Africa–A child of misery and desperation? *Development Southern Africa*, 1–14.

Grünenfelder, D., Starmanns, M. & Manríquez Roa, T. (2018). *A Precious Transition, Demanding more transparency and responsibility in the watch and jewellery sector* [type]. Retrieved 4 October 2021, from https://www.wwf.ch/sites/default/files/doc-2018-12/2018_12_07_WWF%20Watch%20and%20Jewellery%20Report%202018_final_e_0.pdf

Gu, F., Summers, P. A. & Hall, P. (2019). Recovering materials from waste mobile phones: Recent technological developments. *Journal of Cleaner Production*, *237*, 117657.

Guéniat, M. & White, N. (2015). A golden racket: The true source of Switzerland's "Togolese" gold. *Public Eye Report*.

Guenther, M. (2018). Local effects of artisanal mining: Emppirical evidence from Ghana. In *Presentation at the international conference'environmental economics: a focus on natural ressources', orléans.*

Gurita, N., Fröhling, M. & Bongaerts, J. (2018). Assessing potentials for mobile/smartphone reuse/remanufacture and recycling in Germany for a closed loop of secondary precious and critical metals. *Journal of Remanufacturing*, *8*(1), 1–22.

Hainmueller, J. & Hiscox, M. J. (2015). Buying green? Field experimental tests of consumer support for environmentalism. *Field Experimental Tests of Consumer Support for Environmentalism*.

Hale, T., Webster, S., Petherick, A., Phillips, T. & Kira, B. (2020). *Oxford COVID-19 Government Response Tracker.* Retrieved 12 January 2021, from `https://www.bsg.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker`

Hall, G. E. & Pelchat, P. (1997). Evaluation of a direct solid sampling atomic absorption spectrometer for the trace determination of mercury in geological samples. *Analyst*, *122*(9), 921–924.

Hertwich, E. G. & Peters, G. P. (2009). Carbon footprint of nations: a global, trade-linked analysis. *Environmental science & technology*, *43*(16), 6414–6420.

Herzog, S., Nellen, A., Ryser, S., Tran, V. & Ruysschaert, D. (2015). *Gold in Switzerland: Certification Schemes as the New Gold Rush* (Tech. Rep.). The Graduate Institute Geneva.

Hewitt, A. (2015). *The Ups and Downs of Gold Recycling.*

Hilson, G. (2010). Child labour in African artisanal mining communities: Experiences from Northern Ghana. *Development and Change*, *41*(3), 445–473.

Hilson, G., Gillani, A. & Kutaula, S. (2018). Towards sustainable pro-poor development? a critical assessment of fair trade gold. *Journal of Cleaner Production*, *186*, 894–904.

Hilson, G. & Maconachie, R. (2017). Formalising artisanal and small-scale mining: insights, contestations and clarifications. *Area*, *49*(4), 443–451.

Hilson, G. & McQuilken, J. (2014). Four decades of support for artisanal and small-scale mining in sub-Saharan Africa: a critical review. *The Extractive Industries and Society*, *1*(1), 104–118.

Hilson, G. & Pardie, S. (2006). Mercury: an agent of poverty in Ghana's small-scale gold-mining sector? *Resources Policy*, *31*(2), 106–116.

Hilson, G. & Potter, C. (2005). Structural adjustment and subsistence industry: artisanal gold mining in Ghana. *Development and change*, *36*(1), 103–131.

Hilson, G., Van Bockstael, S., Sauerwein, T., Hilson, A. & McQuilken, J. (2021). Artisanal and small-scale mining, and COVID-19 in sub-Saharan Africa: A preliminary analysis. *World Development*, *139*, 105315.

Hilson, G., Zolnikov, T. R., Ortiz, D. R. & Kumah, C. (2018). Formalizing artisanal gold mining under the Minamata convention: Previewing the challenge in Sub-Saharan Africa. *Environmental Science & Policy*, *85*, 123–131.

Himelein, K. & Kastelic, J. G. (2021). The Socio-Economic Impacts of Ebola in Liberia: Results from a High Frequency Cell Phone Survey, Round 5.

Hinton, J. (2005). Communities and small scale mining: An integrated review for development planning. *Washington, DC: World Bank*.

Hinton, J., Veiga, M. & Beinhoff, C. (2003). Women, mercury and artisanal gold mining: risk communication and mitigation. In *Journal de physique iv (proceedings)* (Vol. 107, pp. 617–620).

Hira, M., Yadav, S., Morthekai, P., Linda, A., Kumar, S. & Sharma, A. (2018). Mobile Phones—An asset or a liability: A study based on characterization and assessment of metals in waste mobile phone components using leaching tests. *Journal of hazardous materials*, *342*, 29–40.

Hruschka, F. & Echavarria, C. (2011). Rock-solid chances for responsible mining. In *Arm series on responsible asm no. 3. medellín.*

Hruschka, F., Melcher, F. & Kain-Bückner, B. (2016). *Analytical Tools to Constrain the Origin of Gold from Conflict-affected and High-Risk Areas. Scoping Study based on the DR Congo.*

Hunter, M., Sibanda, M., Opala, K. & Modi, L. P. (2021, May). *Illicit gold markets in East and Southern Africa* (Tech. Rep.). Global Initiative.

IMF. (2014). *Burkina faso. imf country report no. 14/230.* Retrieved https://www.imf.org/external/pubs/ft/scr/2014/cr14230.pdf, from `02June2021`

INSD and ICF International. (2012a). *Enquête démographique et de santé et à indicateurs multiples.* Retrieved 22 September 2021, from `http://www.burkinadoc.milecole.org/Pieces_Jointes/PDFs/Conna%C3%AEtre_le_Burkina/Rep%C3%A8res_Statistiques/Stat_burkinabf_eds_2010.pdf`

INSD and ICF International. (2012b). *Enquête Démographique et de Santé et à Indicateurs Multiples du Burkina Faso 2010.* Retrieved 05 October 2021, from https://dhsprogram.com/pubs/pdf/FR256/FR256.pdf

International Labour Office. (1999). *Small-scale mining on the increase in developing countries.* Retrieved 05 May 2021, from https://www.ilo.org/global/about-the-ilo/newsroom/news/WCMS_007929/lang--en/index.htm

International Labour Office. (2005). *Eliminating child labour in mining and quarrying* (Tech. Rep.). Retrieved 21 October 2021, from https://asmhub.mn/uploads/files/eliminating-child-labour-in-mining-and-quarrying-ilo.pdf

Islam, M. T., Dias, P. & Huda, N. (2020). Waste mobile phones: A survey and analysis of the awareness, consumption and disposal behavior of consumers in Australia. *Journal of Environmental Management*, *275*.

Ito, K., Ida, T. & Tanaka, M. (2015). *The persistence of moral suasion and economic incentives: Field experimental evidence from energy demand* (Tech. Rep.). National Bureau of Economic Research.

Jaques, E., Zida, B., Billa, M., Greffié, C. & Thomassin, J.-F. (2006). Artisanal and small-scale gold mines in burkina faso: today and tomorrow. *Small-scale mining, rural subsistence and poverty in West Africa*, 115–134.

Jønsson, J. B. & Bryceson, D. F. (2009). Rushing for gold: mobility and small-scale mining in East Africa. *Development and Change*, *40*(2), 249–279.

Jønsson, J. B., Charles, E. & Kalvig, P. (2013). Toxic mercury versus appropriate technology: Artisanal gold miners' retort aversion. *Resources Policy*, *38*(1), 60–67.

Kaminski, J. (2011). Cotton dependence in burkina faso: Constraints and opportunities for balanced growth. *Yes Africa can: Success stories from a dynamic continent*, 107–124.

Kamlongera, P. J. & Hilson, G. (2011). Poverty alleviation in rural Malawi: is there a role for artisanal mining? *Journal of Eastern African Studies*, *5*(1), 42–69.

Kang, H.-Y. & Schoenung, J. M. (2005). Electronic waste recycling: A review of US infrastructure and technology options. *Resources, Conservation and Recycling*, *45*(4), 368–400.

Kickler, K. & Franken, G. (2017). *Sustainability schemes for mineral resources: a comparative overview.* Bundesanstalt für Geowissenschaften und Rohstoffe.

Kiddee, P., Naidu, R. & Wong, M. H. (2013). Electronic waste management approaches: An overview. *Waste Management*, *33*(5), 1237–1250.

Knoblauch, A. M., Farnham, A., Ouoba, J., Zanetti, J., Müller, S., Jean-Richard, V., ... others (2020). Potential health effects of cyanide use in artisanal and small-scale gold mining in Burkina Faso. *Journal of Cleaner Production*, *252*, 119689.

Laffont, L., Sonke, J. E., Maurice, L., Monrroy, S. L., Chincheros, J., Amouroux, D. & Behra, P. (2011). Hg speciation and stable isotope signatures in human hair as a tracer for dietary and occupational exposure to mercury. *Environmental science & technology*, *45*(23), 9910–9916.

Lahiri-Dutt, K., McQuilken, J. et al. (2019). DELVE state of the artisanal and small-scale mining sector-India. In *State of the artisanal and small-scale mining sector.* World Bank Group.

Lanzano, C., Luning, S. & Ouédraogo, A. (2021). *Insecurity in Burkina Faso–beyond conflict minerals: the complex links between artisanal gold mining and violence.* Nordiska Afrikainstitutet.

Lassen, C., Maag, J., Jonsson, J. B. & Sarunday, C. (2016). *Country Reports on Mercury Trade and Use for Artisanal and Small-Scale* (Tech. Rep.). World Bank.

LBMA. (2018). *LBMA 2018 annual review.* Retrieved 28 July 2021, from https://www.lbma.org.uk/articles/lbma-2018-annual-review

Levesque, D. L., Arif, A. A. & Shen, J. (2012a). Association between workplace and housing conditions and use of pesticide safety practices and personal protective equipment among North Carolina farmworkers in 2010. *Int J Occup Environ Med (The IJOEM)*, *3*(2 April).

Levesque, D. L., Arif, A. A. & Shen, J. (2012b). Effectiveness of pesticide safety training and knowledge about pesticide exposure among Hispanic farmworkers. *Journal of occupational and environmental medicine*, *54*(12), 1550–1556.

Li, Y.-F., Chen, C., Li, B., Wang, J., Gao, Y., Zhao, Y. & Chai, Z. (2008). Scalp hair as a biomarker in environmental and occupational mercury exposed populations: Suitable or not? *Environmental research*, *107*(1), 39–44.

Litchfield, C. A., Lowry, R. & Dorrian, J. (2018). Recycling 115,369 mobile phones for gorilla conservation over a six-year period (2009-2014) at Zoos Victoria: A case study of 'points of influence'and mobile phone donations. *PloS one*, *13*(12), e0206890.

Liu, J. (2016). Covered in Gold: Examining gold consumption by middle class consumers in emerging markets. *International Business Review*, *25*(3), 739–747.

Long, R. N., Sun, K. & Neitzel, R. L. (2015). Injury risk factors in a small-scale gold mining community in Ghana's Upper East Region. *International journal of environmental research and public health*, *12*(8), 8744–8761.

Martin, A. (2019, April). The dark world of the zama zamas. Retrieved 21 October 2021, from https://globalinitiative.net/wp-content/uploads/2019/04/ENACT-Policy-Brief-008-Zama-Zama-24Apr1115-WEB.pdf

Mawowa, S. (2013). The political economy of artisanal and small-scale gold mining in central Zimbabwe. *Journal of Southern African Studies*, *39*(4), 921–936.

Max Havelaar Foundation. (2020). *Annual report 2020.*

Melcher, F., Sitnikova, M. A., Graupner, T., Martin, N., Oberthür, T., Henjes-Kunst, F., ... Dawaele, S. (2008). Fingerprinting of conflict minerals: columbite-tantalite ("coltan") ores. *Sga News*, *23*(1), 7–14.

Memon, Q. U. A., Wagan, S. A., Chunyu, D., Shuangxi, X., Jingdong, L. & Damalas, C. A. (2019). Health problems from pesticide exposure and personal protective measures among women cotton workers in southern Pakistan. *Science of the Total Environment*, *685*, 659–666.

Metcalf, S. M. & Veiga, M. M. (2012). Using street theatre to increase awareness of and reduce mercury pollution in the artisanal gold mining sector: a case from Zimbabwe. *Journal of Cleaner Production*, *37*, 179–184.

Mondlane, S. (2017). *Report on Artisanal and Small-Scale Mining in Africa: Selected Countries Policy Profile Review on ASM* (Tech. Rep.). https://delvedatabase.org/uploads/resources/ASMStudyReport2017.pdf.

Morewedge, C. K., Shu, L. L., Gilbert, D. T. & Wilson, T. D. (2009). Bad riddance or good rubbish? Ownership and not loss aversion causes the endowment effect. *Journal of Experimental Social Psychology*, *45*(4), 947–951.

Mori Junior, R., Franks, D. & Ali, S. (2015). Designing Sustainability Certification for Impact: Analysis of the design characteristics of 15 sustainability standards in the mining industry. *University of Queensland (Ed.). Brisbane*.

Morton, J., Carolan, V. A. & Gardiner, P. H. (2002). Removal of exogenously bound elements from human hair by various washing procedures and determination by inductively coupled plasma mass spectrometry. *Analytica Chimica Acta*, *455*(1), 23–34.

Mwaanga, P., Silondwa, M., Kasali, G. & Banda, P. M. (2019). Preliminary review of mine air pollution in Zambia. *Heliyon*, *5*(9), e02485.

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. *Decentralized Business Review*, 21260.

Neumann, M., Barume, B., Ducellier, B., Ombeni, A., Näher, U., Schutte, P., ... Weyns, Y. (2019). *Traceability in Artisanal Gold Supply Chains in the Democratic Republic of the Congo Lessons Learned from the Kampene Gold Pilot Project* (Tech. Rep.). Bundesanstalt fur Geowissenschaften und Rohstoffen.

Nnorom, I. C. & Osibanjo, O. (2009). Toxicity characterization of waste mobile phone plastics. *Journal of Hazardous Materials*, *161*(1), 183–188.

Norton, T., Beier, J., Shields, L., Househam, A., Bombis, E. & Liew, D. (2014). A guide to traceability: A practical approach to advance sustainability in global supply chains. *United Nations Global Compact Office: New York, NY, USA.*

Nuttall, K. L. (2006). Interpreting hair mercury levels in individual patients. *Annals of Clinical & Laboratory Science*, *36*(3), 248–261.

Ofosu-Mensah, E. A. et al. (2011). Historical overview of traditional and modern gold mining in ghana. *International Research Journal of Library, Information and Archival Studies*, *1*(1), 006–022.

Okoffo, E. D., Mensah, M. & Fosu-Mensah, B. Y. (2016). Pesticides exposure and the use of personal protective equipment by cocoa farmers in Ghana. *Environmental Systems Research*, *5*(1), 1–15.

O'Neill, J. D. & Telmer, K. (2017). *Estimating Mercury Use and Documenting Practices in Artisanal and Small-scale Gold Mining (ASGM).*

Ongondo, F. & Williams, I. (2011). Mobile phone collection, reuse and recycling in the UK. *Waste Management*, *31*(6), 1307–1315.

Ottenbros, I., Boerleider, R., Jubitana, B., Roeleveld, N. & Scheepers, P. (2019). Knowledge and awareness of health effects related to the use of mercury in artisanal and small-scale gold mining in Suriname. *Environment international*, *122*, 142–150.

Ouédraogo, O. & Amyot, M. (2013). Mercury, arsenic and selenium concentrations in water and fish from sub-Saharan semi-arid freshwater reservoirs (Burkina Faso). *Science of the total environment*, *444*, 243–254.

Oyekale, A. S. (2018). Cocoa farmers' compliance with safety precautions in spraying agrochemicals and use of personal protective equipment (PPE) in Cameroon. *International Journal of Environmental Research and Public Health*, *15*(2), 327.

Pavilonis, B., Grassman, J., Johnson, G., Diaz, Y. & Caravanos, J. (2017). Characterization and risk of exposure to elements from artisanal gold mining operations in the bolivian andes. *Environmental research*, *154*, 1–9.

Perks, R. & Schneck, N. (2021). COVID-19 in artisanal and small-scale mining communities: Preliminary results from a global rapid data collection exercise. *Environmental Science & Policy*, *121*, 37–41.

Phelps, R. W., Clarkson, T. W., Kershaw, T. G. & Wheatley, B. (1980). Interrelationships of blood and hair mercury concentrations in a North American population exposed to methylmercury. *Archives of Environmental Health: An International Journal*, *35*(3), 161–168.

Picard, R. (2015). Geoinpoly: Stata module to match geographic locations to shapefile polygons.

Picard, R. (2019). Geonear: Stata module to find nearest neighbors using geodetic distances.

Pijpers, R. J. & Luning, S. (2021). 'We have so many challenges': Small-scale mining, Covid-19 and constant interruptions in West Africa. *Anthropology Today*, *37*(2), 10–14.

Pokorny, B., von Lübke, C., Dayamba, S. D. & Dickow, H. (2019). All the gold for nothing? impacts of mining on rural livelihoods in northern burkina faso. *World Development*, *119*, 23–39.

Prakash, S., Dehoust, G., Gsell, M., Schleicher, T. & Stamminger, R. (2016). Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz". *Dessau-Roßlau: UBA Texte*, *11*, 2016.

Ralph, O., Gilles, N., Fon, N., Luma, H. & Greg, N. (2018). Impact of artisanal gold mining on human health and the environment in the Batouri Gold District, East Cameroon. *Academic Journal of Interdisciplinary Studies*, *7*(1), 25.

Rasmi, A. (2019). *Scientists put an iPhone in a blender to find out what mobile phones are really made of.* Retrieved 20 March 2020, from `https://qz.com/1576186/scientists-shredded-an-iphone-to-find-out-what-its-really-made-of/`

Razo, I., Carrizales, L., Castro, J., Díaz-Barriga, F. & Monroy, M. (2004). Arsenic and heavy metal pollution of soil, water and sediments in a semi-arid climate mining area in Mexico. *Water, Air, and Soil Pollution*, *152*(1), 129–152.

Reuben, A., Frischtak, H., Berky, A., Ortiz, E. J., Morales, A. M., Hsu-Kim, H., ... Pan, W. K. (2020). Elevated hair mercury levels are associated with neurodevelopmental deficits in children living near artisanal and small-scale gold mining in Peru. *GeoHealth*, *4*(5), e2019GH000222.

Reuters. (2018). *Burkina Faso declares state of emergency in north following attacks.* Retrieved 22 September 2021, from `https://www.reuters.com/article/us-burkina-security/burkina-faso-declares-state-of-emergency-in-north-following-attacks-idUSKCN1OU0OV`

Rezaei, R., Seidi, M. & Karbasioun, M. (2019). Pesticide exposure reduction: extending the theory of planned behavior to understand iranian farmers' intention to apply personal protective equipment. *Safety Science*, *120*, 527–537.

Rheault, M. (2018). *Cartographie des principaux sites miniers artisanaux aneemas, dgmgc, dgpe, burkina faso.*

Risher, J. (1999). Toxicological profile for mercury.

Ritchie, H. & Roser, M. (2019). *Age structure.* Retrieved 05 October 2021, from `https://ourworldindata.org/age-structure`

Roberts, R. J., Dixon, R. D. & Merkle, R. K. (2016). Distinguishing between legally and illegally produced gold in South Africa. *Journal of Forensic Sciences*, *61*, S230–S236.

Robinson, B. H. (2009). E-waste: an assessment of global production and environmental impacts. *Science of the Total Environment*, *408*(2), 183–191.

Rom, A. & Günther, I. (2019). *Decreasing Emissions by Increasing Energy Access? Evidence from a Randomized Field Experiment on Off-Grid Solar* (Tech. Rep.). ETH Working Paper.[Online] Available at: https://ethz. ch/content/dam/ethz ....

Roser, M. & Ortiz-Ospina, E. (2013). Global extreme poverty. *Our World in Data*. Retrieved 21 October 2021, from `https://ourworldindata.org/extreme-poverty`

Ross, M. L. (2004). How do natural resources influence civil war? Evidence from thirteen cases. *International organization*, *58*(1), 35–67.

Rötzer, N. & Schmidt, M. (2018). Decreasing metal ore grades—is the fear of resource depletion justified? *Resources*, *7*(4), 88.

Saavedra, S. & Romero, M. (2021). Local incentives and national tax evasion: The response of illegal mining to a tax reform in Colombia. *European Economic Review*, *138*, 103843.

Salvato, N. & Pirola, C. (1996). Analysis of mercury traces by means of solid sample atomic absorption spectrometry. *Microchimica Acta*, *123*(1-4), 63–71.

Sana, A., De Brouwer, C. & Hien, H. (2017). Knowledge and perceptions of health and environmental risks related to artisanal gold mining by the artisanal miners in Burkina Faso: a cross-sectional survey. *The Pan African Medical Journal*, *27*.

Sarath, P., Bonda, S., Mohanty, S. & Nayak, S. K. (2015). Mobile phone waste management and recycling: Views and trends. *Waste Management*, *46*, 536–545.

Scharnhorst, W., Althaus, H.-J., Classen, M., Jolliet, O. & Hilty, L. M. (2005). The end of life treatment of second generation mobile phone networks: Strategies to reduce the environmental impact. *Environmental Impact Assessment Review*, *25*(5), 540–566.

Seccatore, J., Veiga, M., Origliasso, C., Marin, T. & De Tomi, G. (2014). An estimation of the artisanal small-scale production of gold in the world. *Science of the Total Environment*, *496*, 662–667.

SECO. (2021). *Better Gold Initiative for Artisanal and Small-Scale Mining.* Retrieved 23 September 2021, from https://www.seco-cooperation.admin.ch/dam/secocoop/de/dokumente/themen/handel/factsheet-bgi-for-asm.pdf.download.pdf/Factsheet%20Swiss%20Better%20Gold%20Initiative.pdf

SENS, SWICO Recycling & SLRS. (2011). *Report of the Technical Inspectorate SENS, SWICO Recycling, SLRS* (Tech. Rep.).

Shandro, J. A., Veiga, M. M. & Chouinard, R. (2009). Reducing mercury pollution from artisanal gold mining in Munhena, Mozambique. *Journal of Cleaner Production*, *17*(5), 525–532.

Siegel, S. & Veiga, M. M. (2009). Artisanal and small-scale mining as an extralegal economy: De soto and the redefinition of "formalization". *Resources policy*, *34*(1-2), 51–56.

Siegel, S. & Veiga, M. M. (2010). The myth of alternative livelihoods: artisanal mining, gold and poverty. *International Journal of Environment and Pollution*, *41*(3-4), 272–288.

Silveira, G. T. & Chang, S.-Y. (2010). Cell phone recycling experiences in the United States and potential recycling options in Brazil. *Waste Management*, *30*(11), 2278–2291.

Sinha-Khetriwal, D., Kraeuchi, P. & Schwaninger, M. (2005). A comparison of electronic waste recycling in Switzerland and in India. *Environmental Impact Assessment Review*, *25*(5), 492–504.

Sjöberg, L. (2003). The different dynamics of personal and general risk. *Risk Management*, *5*(3), 19–34.

Slovic, P. (1988). Risk perception. In *Carcinogen risk assessment* (pp. 171–181). Springer.

SNL Metals and Mining. (2020). *Snl metals and mining dataset.*

Sollazo, R. (2018). *L'or à la croisée des chemins : Étude d'évaluation des chaînes d'approvisionnement en or produit au Burkina Faso, au Mali et au Niger.* Retrieved 22 September 2021, from https://mneguidelines.oecd.org/Evaluation-des-chaines-approvisionnement-en-or-produit-au-Burkina-Faso-Mali-Niger.pdf

Speake, J. & Yangke, L. N. (2015). What do I do with my old mobile phones? I just put them in a drawer": Attitudes and perspectives towards the disposal of mobile phones in Liverpool, UK. *Human Geographies*, *9*(2), 241.

Spiegel, S. J. (2009). Resource policies and small-scale gold mining in Zimbabwe. *Resources Policy*, *34*(1-2), 39–44.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., ... Tukker, A. (2018). EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables. *Journal of Industrial Ecology*, *22*(3), 502–515.

STATISTA. (2015). *Gold mining industry direct and indirect employment by world region 2013.* Retrieved 4 September 2021, from `https://www.statista.com/statistics/524325/gold-mining-industry-employment-worldwide-by-region/`

Steckling, N., Bose-O'Reilly, S., Pinheiro, P., Plass, D., Shoko, D., Drasch, G., ... Hornberg, C. (2014). The burden of chronic mercury intoxication in artisanal small-scale gold mining in Zimbabwe: data availability and preliminary estimates. *Environmental Health*, *13*(1), 1–20.

Steckling, N., Tobollik, M., Plass, D., Hornberg, C., Ericson, B., Fuller, R. & Bose-O'Reilly, S. (2017). Global burden of disease of mercury used in artisanal small-scale gold mining. *Annals of global health*, *83*(2), 234–247.

Stiglitz, J. E. (2005). Making Natural Resources into a Blessing rather than a Curse. *Covering Oil: A Reporter's Guide to Energy and Development*, 13–19.

Strong, L. L., Thompson, B., Koepsell, T. D. & Meischke, H. (2008). Factors associated with pesticide safety practices in farmworkers. *American journal of industrial medicine*, *51*(1), 69–81.

Sun, D. T., Gasilova, N., Yang, S., Oveisi, E. & Queen, W. L. (2018). Rapid, selective extraction of trace amounts of gold from complex water mixtures with a metal–organic framework (MOF)/polymer composite. *Journal of the American Chemical Society*, *140*(48), 16697–16703.

Sunrise. (2021). *Your old mobile phone is worth something.* Retrieved 11 November 2020, from `https://www.sunrise.ch/en/residential/sunrise-produkte/buyback.html`

Suter, L., Waller, G., Willemse, I., Genner, S. & Süss, D. (2017). Handyverhalten und Nachhaltigkeit.

Swenson, J. J., Carter, C. E., Domec, J.-C. & Delgado, C. I. (2011). Gold mining in the Peruvian Amazon: global prices, deforestation, and mercury imports. *PloS one*, *6*(4), e18875.

Tanskanen, P. & Butler, E. (2007). Mobile phone take back learning's from various initiatives. In *Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment* (pp. 206–209).

Telmer, K. (2020). *Fifty thousand gold shops in the world's artisanal gold supply chain.* Retrieved 28 July 2021, from `https://www.artisanalgold.org/publications/`

articles/fifty-thousand-gold-shops-in-the-world-s-artisanal-gold-supply-chain/

Telmer, K. & Veiga, M. (2009). World emissions of mercury from artisanal and small scale gold mining. In *Mercury fate and transport in the global atmosphere* (pp. 131–172). Springer.

Thaler, R. H. & Sunstein, C. R. (2017). *Nudge: Improving decisions about health, wealth, and happiness.* HeinOnline.

Thiébaud, E., Hilty, L. M., Schluep, M., Widmer, R. & Faulstich, M. (2018). Service lifetime, storage time, and disposal pathways of electronic equipment: a Swiss case study. *Journal of Industrial Ecology*, *22*(1), 196–208.

Thorsen, D. (2012). Children working in mines and quarries. *Evidence from West and Central Africa. Briefing Paper*(4).

Tomicic, C., Vernez, D., Belem, T. & Berode, M. (2011). Human mercury exposure associated with small-scale gold mining in Burkina Faso. *International archives of occupational and environmental health*, *84*(5), 539–546.

Tratschin, R., VonFelten, N., Zulauf, C., Kaufmann, C., Ghielmini, S., Nothiger, M., ... Anuradha, V., R (2017, December). *Expert Study on the Swiss Gold Sector and related Risks of Human Rights Abuses* (Tech. Rep.). EBP Schweiz AG.

Travnikov, O., Dastoor, A., Friedman, C., Ryzhkov, A., Selin, N. & Song, S. (2015). *Global Mercury Modelling: Update of Modelling Results in the Global Mercury Assessment 2013.*

Tukker, A., Bulavskaya, T., Giljum, S., De Koning, A., Lutter, S., Simas, M., ... Wood, R. (2014). The global resource footprint of nations. *Carbon, water, land and materials embodied in trade and final consumption calculated with EXIOBASE*, *2*(8).

UNCTAD. (2020). *Digital Economy Growth and Mineral Resources: Implications for Developing Countries.* Retrieved 4 September 2021, from https://unctad.org/system/files/official-document/tn_unctad_ict4d16_en.pdf

UNDP, P. (2020). The next frontier-human development and the anthropocene. *Human Development Report 2020*.

UNECA. (2011). *Minerals and Africa's Development. The International Study Group Report on Africa's Mineral Regimes* (Tech. Rep.). United Nations Economic Commission for Africa. Retrieved 22 September 2021, from https://archive.uneca.org/sites/default/files/PublicationFiles/mineral_africa_development_report_eng.pdf

UNODC. (2018). *Alluvial gold exploitation: Evidence from remote sensing 2016* (Tech. Rep.). Retrieved 05 May 2021, from https://www.unodc.org/documents/publications/Evoa_2016_in_1.pdf

US Department of Labour. (2019). *Findings on the worst forms of child labour: Burkina faso.* Retrieved 5 May 2021, from https://www.dol.gov/sites/dolgov/files/ILAB/child_labor_reports/tda2019/Burkina-Faso.pdf

US Embassy in Burkina Faso. (2021). *Covid-19 information.* Retrieved 22 September 2021, from https://bf.usembassy.gov/u-s-citizen-services/covid-19-information/

USGS. (2021). *National Minerals Information Center: Gold Statistics and Information.* Retrieved 4 September 2021, from https://www.usgs.gov/centers/nmic/gold-statistics-and-information

Valente, T. M. & Gomes, C. L. (2009). Occurrence, properties and pollution potential of environmental minerals in acid mine drainage. *Science of the Total Environment*, *407*(3), 1135–1152.

Van der Merwe, A. & Brugger, F. (2021). *"case study: The digital device life cycle: From mining to e-waste".*

Van der Merwe, A. & Günther, I. (2020). Old mobile phones: A potential gold mine. *Policy Paper*.

Van der Merwe, A., G"unther, I. & Brugger, F. (2022). *Rising gold prices but lower incomes for gold miners: evidence on market imperfections from burkina faso during covid-19.*

Vargas, C. (2021). *Colombia, Peru may centralize purchase of gold to combat crime, environmental destruction.* Retrieved 05 October 2021, from https://cn.reuters.com/article/us-latam-mining-idUSKCN2AU2DM

Veiga, M. M. & Marshall, B. G. (2017). Teaching artisanal miners about mercury pollution using songs. *The Extractive Industries and Society*, *4*(4), 842–845.

Verbrugge, B. & Geenen, S. (2019). The gold commodity frontier: A fresh perspective on change and diversity in the global gold mining economy. *The Extractive Industries and Society*, *6*(2), 413–423.

Vidal, O., Goffé, B. & Arndt, N. (2013). Metals for a low-carbon society. *Nature Geoscience*, *6*(11), 894–896.

Vogel, C., Musamba, J. & Radley, B. (2018). A miner's canary in Eastern Congo: Formalisation of artisanal 3T mining and precarious livelihoods in South Kivu. *The Extractive Industries and Society*, *5*(1), 73–80.

Wang, Z., Zhang, B. & Guan, D. (2016). Take responsibility for electronic-waste disposal. *Nature News*, *536*(7614), 23.

Wendling, Z., Emerson, J., Esty, D., Levy, M., de Sherbinin, A. et al. (2018). Environmental Performance Index New Haven. *CT: Yale Center for Environmental Law & Policy*.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230.

Werthmann, K. (2009). Working in a boom-town: Female perspectives on gold-mining in Burkina Faso. *Resources policy*, *34*(1-2), 18-23.

Werthmann, K. (2017). The drawbacks of privatization: Artisanal gold mining in burkina faso 1986–2016. *Resources Policy*, *52*, 418–426.

WHO. (2000). *Chapter 6.9 mercury.*

WHO. (2020). *Coronavirus.* Retrieved 19 January 2021, from `https://www.who.int/health-topics/coronavirus#tab=tab_3`

WHO and UNEP. (2008). *Guidance for indentifying populations at risk from mercury exposure.*

Williams, A. (2019). *Scientists use a blender to reveal what's in our smartphones.* Retrieved 20 March 2020, from `https://www.plymouth.ac.uk/news/scientists-use-a-blender-to-reveal-whats-in-our-smartphones`

WITS. (2021). *Burkina Faso Trade.* Retrieved 02 June 2021, from `https://wits.worldbank.org/countrysnapshot/en/BFA`

Wong Sak Hoi, G. (2016). *Is Switzerland the world champion of recycling?* Retrieved 24 March 2021, from `https://www.swissinfo.ch/eng/fact-check_is-switzerland-the-world-champion-of-recycling/42382610`

World Bank. (2015). *International Development Association Project Paper on a Proposed Additional Credit in the Amount of Sdr 32.7 Million (USD45 Million Equivalent) to the United Republic Of Tanzania for the Sustainable Management of Mineral Resources Project.*

World Bank. (2021). *Databank: World Development Indicators.* Retrieved 19 January 2021, from `https://databank.worldbank.org/source/world-development-indicators`

World Gold Council. (2020). *Goldhub; Gold prices.* Retrieved 19 January 2021, from `https://www.gold.org/goldhub/data/price-and-performance`

World Gold Council. (2021a). *Above-ground stocks.* Retrieved 4 September 2021, from `https://www.gold.org/goldhub/data/above-ground-stocks`

World Gold Council. (2021b). *Central bank domestic ASGM purchase programmes.* Retrieved 2 July 2021, from gold.org/goldhub/research/central-bank-asgm

World Gold Council. (2021c). *Demand and supply.* Retrieved 4 September 2021, from https://www.gold.org/goldhub/data/demand-and-supply

World Health Organisation. (2017). *Mercury and health.* Retrieved 19 October 2020, from https://www.who.int/news-room/fact-sheets/detail/mercury-and-health

World Health Organization. (2016). Artisanal and small-scale gold mining and health. *Technical paper*, *1*.

Worthington, A. C. & Pahlavani, M. (2007). Gold investment as an inflationary hedge: Cointegration evidence with allowance for endogenous structural breaks. *Applied Financial Economics Letters*, *3*(4), 259–262.

Yadav, S. & Yadav, S. (2014). Investigations of metal leaching from mobile phone parts using TCLP and WET methods. *Journal of Environmental Management*, *144*, 101–107.

Ye, B.-J., Kim, B.-G., Jeon, M.-J., Kim, S.-Y., Kim, H.-C., Jang, T.-W., … Hong, Y.-S. (2016). Evaluation of mercury exposure level, clinical diagnosis and treatment for mercury intoxication. *Annals of Occupational and Environmental Medicine*, *28*(1), 1–8.

Younger, P. L., Banwart, S. A. & Hedin, R. S. (2002). *Mine water: hydrology, pollution, remediation* (Vol. 5). Springer Science & Business Media.

Zapata Diomedi, B. & Nauges, C. (2016). Pesticide-handling practices: the case of coffee growers in Papua New Guinea. *Australian Journal of Agricultural and Resource Economics*, *60*(1), 112–129.

Zeng, X., Mathews, J. A. & Li, J. (2018). Urban mining of e-waste is becoming more cost-effective than virgin mining. *Environmental Science & Technology*, *52*(8), 4835–4841.

Curriculum Vitae

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