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# Technology, resources and geography in a paradigm shift: the case of critical and conflict materials in ICTs

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# Technology, resources and geography in a paradigm shift: the case of critical and conflict materials in ICTs

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**ABSTRACT**
Critical and conflict materials (CCMs) are providing an important material infrastructure for recent technological shifts. Relying on text analysis of US Patent and Trademark Office (USPTO) data, this exploratory study examines the technological and geographical linkages between technological paradigms and selected CCMs. Our descriptive analysis finds evidence of a clear association between information and communication technologies (ICTs) and CCM intensity over time, and of a striking resource–technology divide between value-creating and -extracting activities across the Global North and the Global South and their regions. The paper emphasizes the need for a more critical, spatially sensitive approach to studying resource-based technological change to expose its uneven development consequences.

**KEYWORDS**
critical and conflict materials; paradigm shift; technological demand; geography of technology; geography of resource supply

**JEL** O30, Q34, Q55, R11
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## 1. INTRODUCTION

In the current world economic scene, two major developments appear to be strengthening the strategic interdependence between advanced manufacturing and mining industries. The first is an evolving global division of labour and capital involving the geographical expansion and 'unbundling' of global production networks and global value chains (GPNs/GVCs) across space (Baldwin, 2011). The second is an ongoing paradigm shift centred on the transition from analogue to digital, and innovations in information and communication technologies (ICTs), to an emerging, albeit uncertain, technological paradigm predicated on, amongst others, artificial intelligence (AI), automation, big data, cloud computing and electric vehicles (Brixner et al., 2020; Sukhodolov, 2019). The mining of several critical raw materials, including so-called 'conflict minerals' – that is, those specifically associated with armed conflict, human rights abuses and corruption – and their combination, refining and ultimate use in many new advanced electronic and electrical products, are providing a critical material infrastructure for these shifts. This has far-reaching implications for regions, countries, governments, firms and resource-dependent value chains.

Existing research into critical and conflict materials (CCMs) has largely focused on the (negative) impacts of mineral extraction in source countries, the functional and geographical relationship between minerals production and consumption, and security of supply. Yet missing is work that takes a more dynamic perspective by examining how technological innovation is shaping the demand for these important inputs, and how the spatial dimensions of this relationship have evolved in terms of the specific geography of technological innovation and sourcing of CCMs. This is an important gap, and starting to address it would shed light on the wider impact of technological progress on economic, social and political developments across space.

This paper is exploratory in nature and aims to open up a promising research agenda. It focuses on the relationship between technological change and selected CCMs used, for example, in the production of lithium-ion batteries, crucial for manufacturing of smart phones, computers, electric cars, etc. We explore this relationship through two main perspectives: innovation and its geographies. On the one hand, we are interested in studying whether and to what extent the ICT-based paradigm has driven technological demand for CCMs in new inventions; if ICTs have relied on other technological fields that use CCMs intensely; and how these relationships have changed over time. Adopting then a geographical lens, we consider the ownership of innovations, mostly by firms,

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proxying the geography of CCM technological demand, and comparing it with that of CCM supply sources. The rationale behind exploring spatially the link between innovation and resource demand is to stimulate further research on several emerging debates, such as the potential for resource-based GVCs to foster domestic technological upgrading; the spatiality of negative externalities associated with technology generation; and the socio-economic responsibilities of innovators.

Our analysis uses a novel method to trace the CCM content of technological innovations, relying on textual data of patent filings. The descriptive analysis points to a striking resource–technology divide in ICT value chains between value-creating and -extracting activities across the Global North and Global South and their regions. The paper thus suggests the need for a more critical, spatially sensitive approach to studying resource-based technological change, one that exposes the geographically uneven development consequences created, sustained or mitigated by technological progress (Coenen & Morgan, 2020; Phelps et al., 2018).

The remainder of the paper is structured as follows. The next section provides the background literature, and the relevance of an economic geography of innovation perspective. The third section describes the data and the general empirical strategy, and defines the selected CCMs. The fourth section presents the analysis from the technological innovation side, whilst the fifth section considers the main features of CCM-related technological demand at national and subnational levels, comparing it with CCM supply. The sixth section concludes and highlights directions for future research.

## 2. LITERATURE BACKGROUND

Our starting point is the claim that recent trajectories of technological change are giving rise to increased demand for critical raw materials. Several different terms have been used to capture these dynamics. For example, Ali et al. (2019) invoke the idea of 'technology minerals', while Linton (2017) introduces the concept of 'emerging technology supply chains' (ETSCs). Within this broad frame, the existing literature addresses several themes. One is the link between the extraction, control and export of a subset of critical resources – 'conflict minerals' in particular – and instability, conflict and violation of human rights (e.g., Berman et al., 2017; Church & Crawford, 2018). Relatedly, the literature explores public and private regulatory initiatives aimed at managing or regulating conflict minerals in supply chains (e.g., Kim & Davis, 2016; Young et al., 2019). Another prominent theme is security of supply (e.g., Stoop et al., 2019; Ziemann et al., 2012). A feature of many (but not all) technology minerals/materials is that geological deposits, production and refining capacity are concentrated in a relatively small number of countries and subnational regions. Many are also commercially non-substitutable in the short term. These observations have led to growing interest in 'material criticality' (Roelich et al., 2014), concerned with the strategic importance of certain raw elements in the production of modern technologies (Kiggins, 2015). A further focus is material flow analysis that seeks to map out the stocks and flows of critical raw materials across time and space throughout their life-cycle (Hao et al., 2017; Sun et al., 2019).

Our exploratory study departs significantly from the above work. Most fundamentally, rather than production or consumption, it is centrally concerned with the dynamics of innovation in technological paradigms implicated in CCMs and the associated geographies. Existing studies on resource-based technology have not ignored invention outright. However, the focus has tended to be on innovation within specific technological areas, for example, batteries (Feng & Magee, 2020). Moreover, with few exceptions, the relationship with CCMs has largely been neglected.

Recent work in the technological change literature has called scholarly attention to the 'dark side of innovation' and its harmful consequences, unevenly distributed through the networks and value chains in the global division of labour (e.g., Biggi & Giuliani, 2021; Phelps et al., 2018). Such inequality has spatial footprints at various geographical scales. It is therefore crucial to advance research at the intersection of technological change and regional studies to better understand the role of innovation in the production of unfolding patterns of inequality (Coenen & Morgan, 2020; Giuliani, 2018). This imperative is especially prescient within the context of CCMs given their association with negative social, environmental and economic impacts in subnational regions and countries where they are extracted.

Against this backdrop, our approach seeks to place CCM-based innovation in the ICT paradigm centre stage and provide a preliminary geographical view on the resource–technology relationship. By using patents, a widely accepted measure of the level of inventive activity (Jaffe & Rassenfosse, 2017), we explore the relationship between technological paradigm shifts, innovative activity and changing patterns of resource demand. The concept of technological paradigms directs attention to how historically dominant technological domains are underpinned by shared understandings of technological problems, search heuristics and bodies of knowledge (Dosi, 1988; Mun et al., 2019). Technological paradigms are characteristically associated with clusters of pervasive and interrelated innovations. To the extent that the production of these constituent technologies may depend on selected material inputs, technological paradigms might have distinctive resource signatures. This suggests a linkage between innovation and raw materials/minerals, with the invention of new resource-dependent technologies (directly and indirectly) giving rise to resource demand. Indeed, technological paradigms may be associated with a degree of technological-cum-resource 'lock-in' (Unruh, 2000), in that innovative efforts may build on past technological knowledge which itself is predicated on certain resource inputs. It is possible that this relationship in technological trajectories may weaken over time as, for example, firms and inventors seek to reduce their dependence on certain inputs through materials substitution. Patents allow us to systematically investigate these dynamics: first, by examining whether innovative activity in broad technological domains (here ICTs) is associated with specific materials/minerals (notably CCMs); and second, by exploring the cumulative nature of resource-dependent technological trajectories.

Another strength of our approach is that it can provide geographically informed insights into debates about value capture in natural resources (Atienza et al., 2020; Bridge, 2008). Moving beyond a focus on production and consumption, we can examine the spatial and organizational value added of resource-dependent technological innovation within the context of CCMs. Theoretical inspiration comes from debates about the geography of value creation in resource-dependent GVCs (Breul et al., 2019; Lebdioui et al., 2020; Murphy & Schindler, 2011). A central idea of the GVC concept is that the production of a final product is the result of multiple, spatially dispersed activities coordinated by lead (often multinational) firms. Activities associated with the invention and control of new technological knowledge are widely seen as offering greater opportunities for value creation.

A recurrent theme in economic geography is that these high value-added activities are spatially concentrated. New technologies, especially more complex ones, are developed and owned by actors in a relatively small number of territories and subnational regions (Iammarino & McCann, 2013). Such locales, characterized by clusters of interrelated firms, high-skilled workers and system resources, occupy an important position within GVCs. Applied to CCM-related technologies, these insights suggest that patenting is likely to be concentrated in locations with institutional and technological capabilities in related domains (e.g., chemicals, electronics and information technology), and the ability to cash in on the presence of global 'gatekeepers' (Feldman et al., 2021; Lema et al., 2021; Martin & Trippl, 2017). Organizationally, we might expect the ownership of patents to be dominated by multinational enterprises (MNEs), especially larger ones with well-established pipelines for global knowledge sourcing (Berman et al., 2020). Such firms, mostly headquartered in power- and knowledge-intensive urban centres and regional clusters, are those governing their global-scale supplier networks.

The above calls into question whether many countries and regions where CCMs are extracted are well placed to capture greater economic value through the production and control of new technologies. Reinforcing these doubts is a body of earlier work on the hypothesized 'resource curse' identifying several factors – boom-and-bust commodity prices, appreciating real exchange rates and over-specialization – which may impede technological upgrading in resource-rich economies (Hayter & Patchell, 2017; Sachs & Warner, 2001). Other studies have emphasized how MNE-controlled GVCs in the extractive sector may develop only weak backward and forward linkages with local economies (Bridge, 2008; Emel et al., 2011; Scholvin, 2020). In doing so, they limit the opportunities for technological learning and the localized ownership of new technologies, such that extractive regions may remain little more than 'places of extraction' (Atienza et al., 2020). More positively, recent contributions have highlighted the possibilities for domestic firms to engage in innovative activities in areas such as extractive and processing equipment (Figueiredo & Piana, 2016; Pietrobelli et al., 2018). Yet, against a backdrop where control in knowledge-intensive domains is spatially and organizationally concentrated, the prospects for the spaces of extraction to become dominant in the generation of CCM-based complex technologies seem distant.

Shifts in the geography of CCM-related innovation may nevertheless take place over time. The rise of East Asia, and China in particular, has been a major development in an evolving international division of labour. An important feature of this dynamic has been growing involvement in technologies known to be associated with CCMs, such as semi-conductors and batteries. Moreover, economies such as China, South Korea and Taiwan have not only developed manufacturing capabilities, but also accumulated significant innovative capabilities, allowing domestic firms to capture greater economic rents in GVCs (Lee & Gereffi, 2021). What this suggests is that, over recent decades, technology-related demand for CCMs may increasingly be traced to geographies and firms in East Asian countries and regions.

We intervene in these debates by providing preliminary, exploratory insights into two sets of questions:

- Innovation, and the demand for CCMs: To what extent is the ICT paradigm CCM intensive? Does it rely on other technologies that use CCM intensively? Has this reliance changed over time?
- The geography of CCM demand and supply: What is the organizational, national and subnational geography of CCM-related technologies? How does it compare with CCM supply?

## 3. DATA, TEXT ANALYSIS AND DEFINITION OF CCM

### 3.1. Measuring CCM–technology links

We rely on text analysis to construct the main measures of interest. The data source is PatentsView, a platform providing structured information about the universe of all patents granted by the US Patents and Trademark Office (USPTO) between 1976 and 2017. The descriptive texts of all patents issued over this period are examined to see if they contain keywords that comprise selected CCMs (as defined below). The absolute and relative frequencies of keyword appearance for each International Patent Classification (IPC) technology classes are obtained. For each class, these measures consider whether patent texts mention each of the CCM keywords at least once. More formally, we define the following general measure of relative frequency for keyword $k$ and technology $i$:

$$f_i^k = \frac{\sum_{p \in i} 1_p(k \in T_p)}{\sum_p 1_p(p \in i)}$$

where the numerator is the count of patents $p$ belonging to technology $i$ that mention keyword $k$ at least once in their associated text corpus $T_p$ (i.e., the absolute frequency), and the denominator is the total number of patents issued in technology $i$. We never count multiple appearances of the same keyword in the same patent, only considering whether a keyword appears *at least once*.[1] We also use patent data to acquire three further sources of information: (1) the timing of technological developments; (2) the identity of the assignees (i.e., the entity owning the patent); and (3) their geographical location.

Our method relies on the definition of keywords that accurately capture CCMs as described in the relevant literature. We examine six key CCMs, thus defining the keyword list as the set:

$$K = \{\text{tin, tungsten, tantalum, gold, cobalt, lithium}\}$$

The first four, also known as the '3TG', are increasingly used in electronic components such as semiconductors and electrical energy capacitors, and widely defined as conflict minerals, that is, minerals that 'in politically unstable areas can be used to finance armed groups, fuel forced labour and other human rights abuses, and support corruption and money laundering' (European Commission, 2020). Cobalt and lithium are also featured because they are critical materials with wide process and/or product applications (including batteries) whose demand is expected to increase significantly (e.g., to meet the needs of electric vehicles). Although not officially designated a conflict mineral, more than half the world's cobalt supply is extracted from the Democratic Republic of Congo (DRC), a country with a recent history of instability and conflict (e.g., Frankel, 2016). Lithium is mostly sourced from Australia, China and the so-called Lithium Triangle of South America (Chile, Argentina and Bolivia).

The substantive significance of our six CCMs is therefore twofold: (1) they are identified as important material inputs to technologies which are part of ongoing technological paradigm shifts; and (2) their extraction, refining and processing have been associated with negative social, economic and environmental externalities in various supplying regions.

### 3.2. Validation of the proposed method

Recent years have witnessed the growing application of text analysis and mining to patents (Petralia et al., 2016). Such analysis is not without shortcomings. Our keyword search is potentially susceptible to 'false-positives'. These might arise if CCMs are mentioned in conjunction with negations (e.g., if the keyword denotes something being replaced as an input). Our method also relies on the assumption that keyword mentions and intensity of CCM use are positively correlated.

To validate our approach, we investigate the degree to which global trends in keyword appearance predict global production of each CCM from 1976 to 2017, using data from the British Geological Survey.[2] We estimate the elasticity of mineral production to keyword occurrence by regressing the natural log of new production onto the natural log of relative frequency of keyword occurrence in the patents' text in that same year for each element (Figure 1). The histogram denotes the magnitude of these elasticities, along with 90% confidence intervals (CIs); the scatterplots below visualize this relationship. Our measure appears to fit the production data quite well, with the exception of tungsten. While aggregated, we believe that these findings offer encouraging, albeit qualified, validation of our keyword-based approach.[3] Figure A1 in the Appendix in the supplemental data online superimposes the relative frequency of at least one keyword mention onto commodity production, showing that the two measures closely track each other.

## 4. EXPLORATORY ANALYSIS: TECHNOLOGY

### 4.1. CCM keyword contribution

Our main interest in this section is to explore whether and to what extent the ICT paradigm has driven the technological demand for CCMs over recent decades. Considering the relative frequency of CCMs keyword appearance over time by IPC section and subclass for all patents,[4] by far the highest is found in chemistry and metallurgy: this is unsurprising, given the direct relationship between this set of technologies and the chosen keywords.[5] Electricity also displays high relative frequencies: indeed, much of the patent growth in recent years, and especially since 1997, is driven by ICTs and electronics, mostly included in this section. For instance, the top 10 subclasses (four-digit, IPC4) in 2017 included battery technologies, capacitors and semiconductor technologies. In general, cobalt, gold, lithium, tantalum, tin and tungsten are all relevant, albeit differently across technological groups. Lithium and gold, in particular, represent a large share for many technologies.[6]

We are interested in how relative frequencies of keyword-use differ depending on whether patents belong to ICTs and related AI applications,[7] or other technological sectors. We test for statistically significant differences between ICTs and other types of technologies in terms of how intensely the selected keywords are mentioned in the patent text at least once. Figure 2 shows conditional means of relative frequency of keywords by three broad technology groups: ICTs excluding AI ('ICT'), AI technologies within the ICTs list ('AI'), and all other technologies. Conditional means are broken down by intervals of five years, to track how this relationship changed over time. Ninety per cent CIs are also constructed around each mean to allow a comparison across groups and within each group over time.

On average, technologies related to ICTs use keywords relatively more intensely: within any period, relative

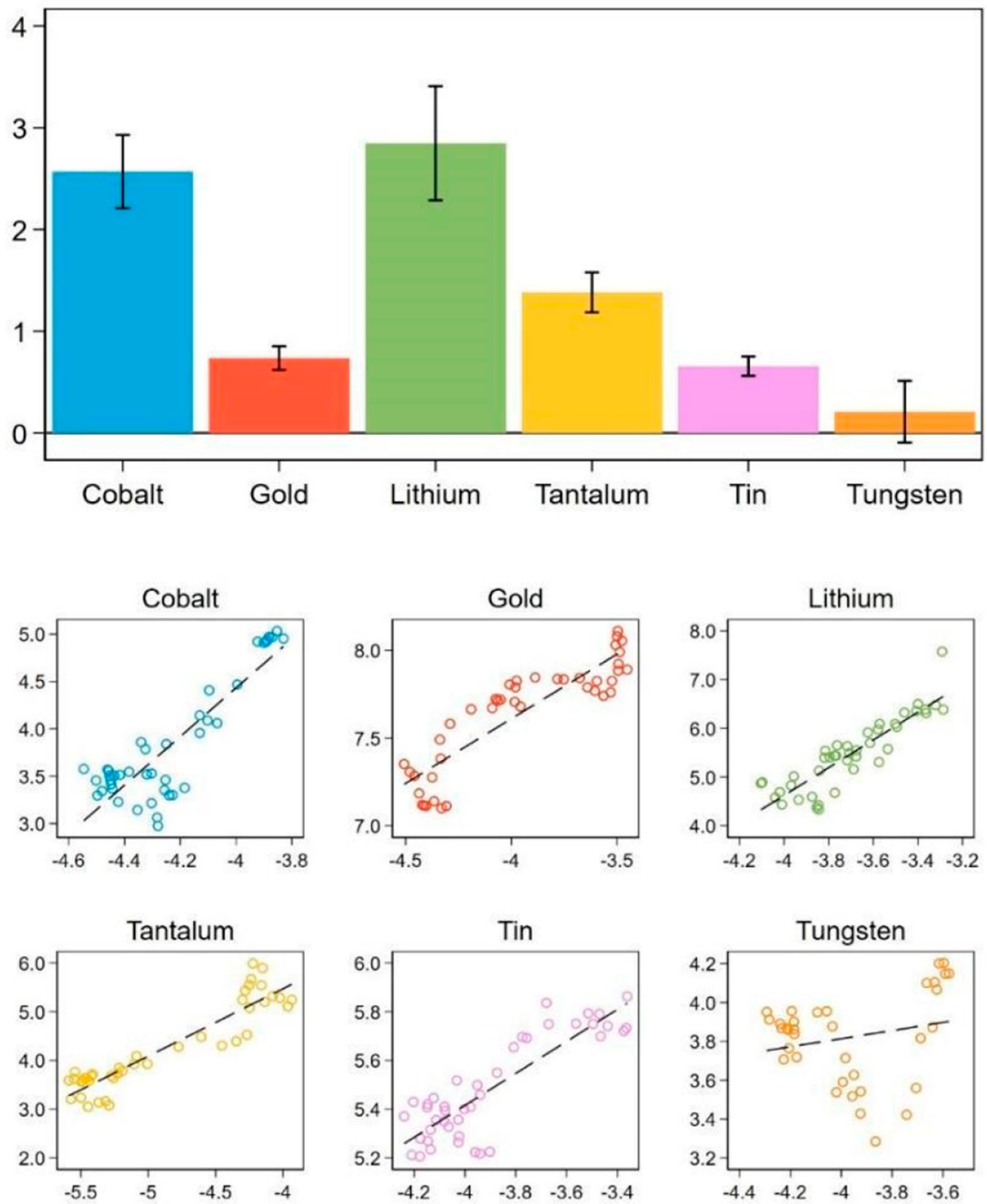


**Figure 1.** Elasticity of mineral production to keyword occurrence.
Note: Elasticities were obtained by regressing the natural log of new production in each year onto the natural log of relative frequency of keyword occurrence in the patents' text that same year.

frequencies are at least twice as high in ICTs than other technologies. Yet, AI patents within ICTs show even lower frequencies than all other technologies. Also noteworthy is that, over time, all technology groups display growing intensities of keyword appearance. This is especially true for ICTs: since 1975, the relative frequency for the use of at least one of the selected keywords grew by nearly 50%, settling at significantly higher levels at the end of the observed period.

We interpret these results as suggesting an association between changing technological paradigms and CCM-related innovation. This interpretation is further supported by the analysis revealing that ICTs are statistically significantly different from other technologies in the extent to which constituent patents reference CCMs. Yet our findings for ICTs do not appear to be driven by AI technologies within the aggregate, which show only a weak relationship with CCMs.

## 4.2. Citation analysis for ICTs

Beyond looking at the text of patents themselves, backward citations in ICTs/AI can be used to get a sense of how, over time, these technologies have relied on others that previously tended to use CCM keywords intensely. We produce a dataset of all citations between IPC subclasses based on the universe of citations made by all patents ever issued by the USPTO since 1976. We collapse citation counts by subclass pairs in each year, weighting citations by patents assigned to multiple subclasses equally. Larger subclasses (those with more patents) will

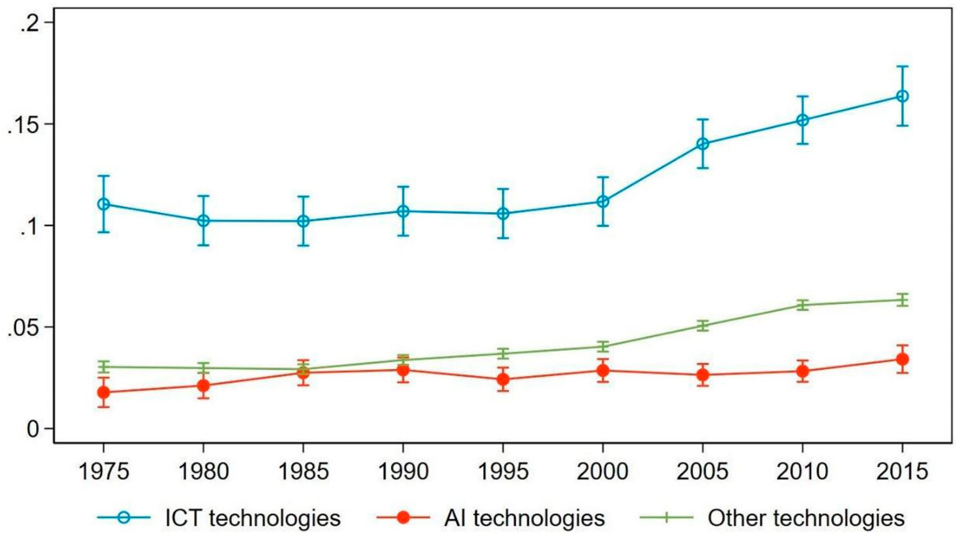


**Figure 2.** Relative frequency of at least one keyword by IPC4 class type.
Note: Calculations exclude International Patent Classification (IPC) subclasses with fewer than 10 patents and, for 'other tech.', belonging to chemistry and metallurgy. Vertical bars give 90% confidence intervals (CIs). All artificial intelligence (AI) technologies are a subset of ICT ones.

tend to send more citations. We thus divide the number of citations made by each subclass by the total number of patents in that group (expressing the result in thousands). We refer to this as the (backward) citation rate $c_{ij}$ for each citing IPC4 technology class $i$ and cited class $j$. Since patent citations have increased over time, we demean each technology's citation rate by the average number of citations made across all classes in that same year (Hall et al., 2001). Next, we regress this demeaned citation rate onto the relative frequency of CCM keyword appearance in the cited class, interacted with a citing-technology period dummy capturing five-year interval groups from 1980 to 2015 (using a sample that runs until 2017). We additionally control for period trends and citing technology fixed effects to address systematic differences between IPC subclasses. More formally, we estimate the following empirical model:

$$\tilde{c}_{ij,t} = f^{k}_{j,t} \times \lambda_t + \lambda_t + \phi_i + \upsilon_{ij,t}$$

where $\tilde{c}_{ij,t}$ is the demeaned citation rate; $f^{k}_{j,t}$ is the relative frequency of keyword $k$ in cited technology $j$; $\lambda_t$ is a citing technology period trend; and $\phi_i$ is a citing technology fixed effect. The term $\upsilon_{ij,t}$ is a residual error.[8] We can thus track these effects over time by looking at how they change across interacted coefficients. Figure 3 summarizes the results with respect to the relative frequency of at least one keyword using a coefficient plot; the lines track the marginal effect for IPC subclasses falling within ICT/AI and other technologies, respectively.[9]

Throughout the period, the higher the relative frequency of CCM keyword appearance in a technology, the more likely this technology was to be cited by ICT/AI patents. Consistent with Dosi's (1988) conception of technological paradigms, these findings are indicative of a path- and CCM-dependent technological trajectory within the domain of ICT/AI. This backward citation relationship weakened until the 1990s, strengthened until 2005, when it appeared to weaken again although remaining positive. In recent years, even though patents in ICT/AI have tended to name keywords more frequently in their own descriptive text (as in the previous section), they also have relied relatively less than other technological fields on technologies naming the CCM keywords intensely in the past. Future research should monitor these dynamics in the light of regulatory frameworks adopted by governments and international organizations since the early 2010s (e.g., US Dodd–Frank Act, 2010; Organisation for Economic Co-operation and Development's (OECD) Due Diligence Guidance, 2011; Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains, 2015; European Union's Conflict Minerals Regulation, 2017), and examine their role in encouraging companies to substitute away from technologies that use CCMs.

## 5. EXPLORATORY ANALYSIS: GEOGRAPHY

### 5.1. Firms, world regions and countries

This section provides a preliminary answer to our second research question: What are the organizational, national and subnational geographies of CCM-related ICT/AI technologies? And have they changed over time? We are not interested in studying where the innovative activity takes place, but rather mapping the geography of ownership of economic rights associated to patents and new technologies, which are more accurately captured through the assignee.[10]

Similar to section 4.1, we start by looking at which assignees own the patents that use the chosen keywords most intensely. Because our focus is on individual actors,

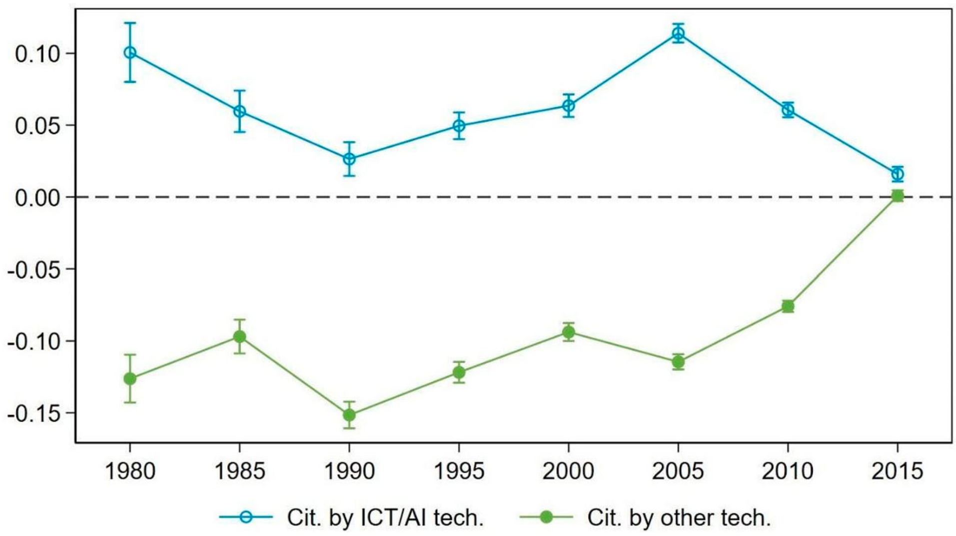


**Figure 3.** Marginal effects of at least one keyword frequency on citation rate, 1980–2015.
Note: Citation rates are de-meaned by year. Calculations exclude citing and cited International Patent Classification (IPC) sub-classes with fewer than 10 patents. Vertical bars give 90% confidence intervals (CIs). All regressions control for period trends and citing IPC dummies.

counts of patents with at least one of the keywords of interest are used, rather than shares. This is for two reasons. First, we are interested in the actors most active in patenting CCM-related inventions. Second, looking at shares on all patents would potentially bring a small assignee with very few patents that happen to mention one of the keywords on top of the list.

Among the top 50 assignees in ICT/AI we find many familiar electronics MNEs – primary located in Japan, closely followed by the United States, and then South Korea, for example, Samsung, IBM, Canon, Micron Technology, Sony, Intel, AMD and Apple, together with a few chemical–pharmaceutical giants, for example, Du Pont, Bristol-Myers Squibb, Pfizer, known historically for their wide technological diversification (Cantwell, 1995). Their dominance is consistent with theory and evidence framing large MNEs in a handful of advanced economies as major drivers of leading technology paradigms.

To quantitatively investigate differences in the relative frequency measure across country groups, Figure 4 provides conditional means of relative frequency of keyword use by three macro-regions of origin of patent assignees: the Americas, Asia and Europe. We adopt the official definition provided by the United Nations, excluding Africa and Oceania from the analysis due to insufficient observations. Additionally, we break down conditional means by intervals of five years to track how this relationship changed over time. Similar to Figure 2, we also construct 90% CIs around each mean, allowing a comparison across and within each group over time.

Starting from comparable levels of keyword-use intensity around the mid-1970s, ICT/AI patents across the three regions started to diverge. By the 1990s, our measure suggests that technologies produced in the Americas tended to rely more intensely on CCMs than those in Asia or Europe. However, while average relative frequency tended to drop in Europe over subsequent periods, it increased in Asia. In the 2010–15 period, the reliance on CCMs of Asia's newly developed ICT/AI technologies was well above Europe, and just above the Americas (although the two averages cannot be distinguished at conventional levels of statistical significance). In 2015, the average relative frequency for Asian patents was higher than it had ever been since 1985, with point estimates even reaching an all-time high for our sample period. This indicates that CCM demand associated with the ICT/AI paradigm has increasingly been driven by technological innovation controlled by MNEs and local actors in emerging Asian countries and regions. This finding is consistent with a prolific literature on fast followers, catch-up and innovation in the ICT paradigm within industrializing Asia.[11] Amongst others, linkages between local firms and foreign MNEs and technology-oriented institutions have been particularly important in ensuring the transition from technology-diffusion to technology-creation stages of industrial development (e.g., Ernst, 2005).

Given the 'conflict-related' nature of our selected materials, we undertake a very preliminary geographical analysis of the empirical relationship between demand for CCMs and conflict/violence. We use yearly data on state and non-state armed conflicts, our relative frequency of keyword appearance measures, and global mineral production data. While largely exploratory,[12] the analysis confirms a correlation between global technological demand for CCMs and armed conflict in the Middle East, Africa and the Americas (notably Central and South America). By contrast, this statistical association is entirely absent in Europe and Asia (or North America). These very preliminary findings warrant further empirical investigation, including at a more granular spatial level.

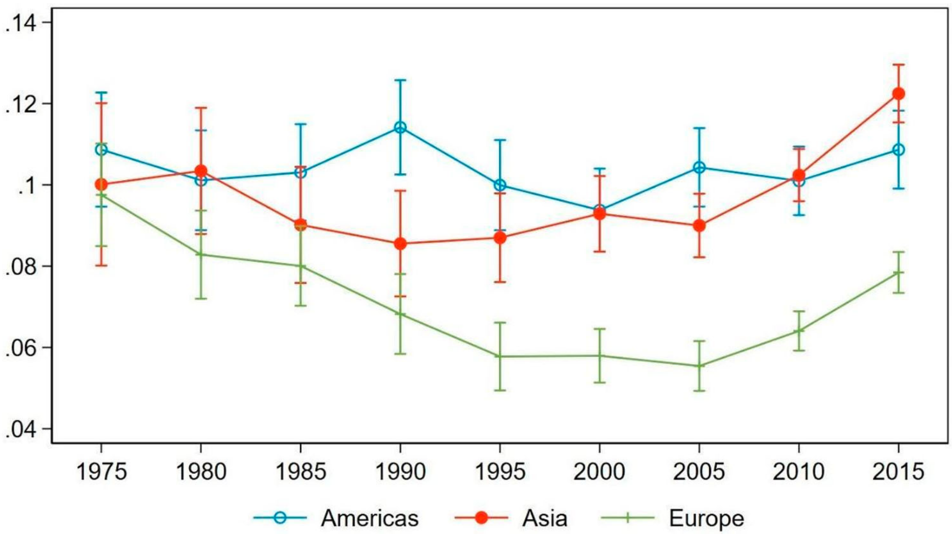


**Figure 4.** Relative frequency of at least one keyword in information and communication technology (ICT)/artificial intelligence (AI) by selected United Nations regions.
Note: Calculations exclude International Patent Classification (IPC) subclasses with fewer than 10 patents. Vertical bars give 90% confidence intervals (CIs). All AI technologies are a subset of ICT ones.

## 5.2. Subnational locations

Figure 5 focuses on the subnational location of assignees.[13] We retain only assignees that developed at least one patent in ICT/AI that mentioned at least one keyword of interest over the 2000–17 period. These are mapped onto their reported location, dropping assignees with fewer than 10 patents. The size of point markers is proportional to the number of the assignees' patents with at least one keyword.

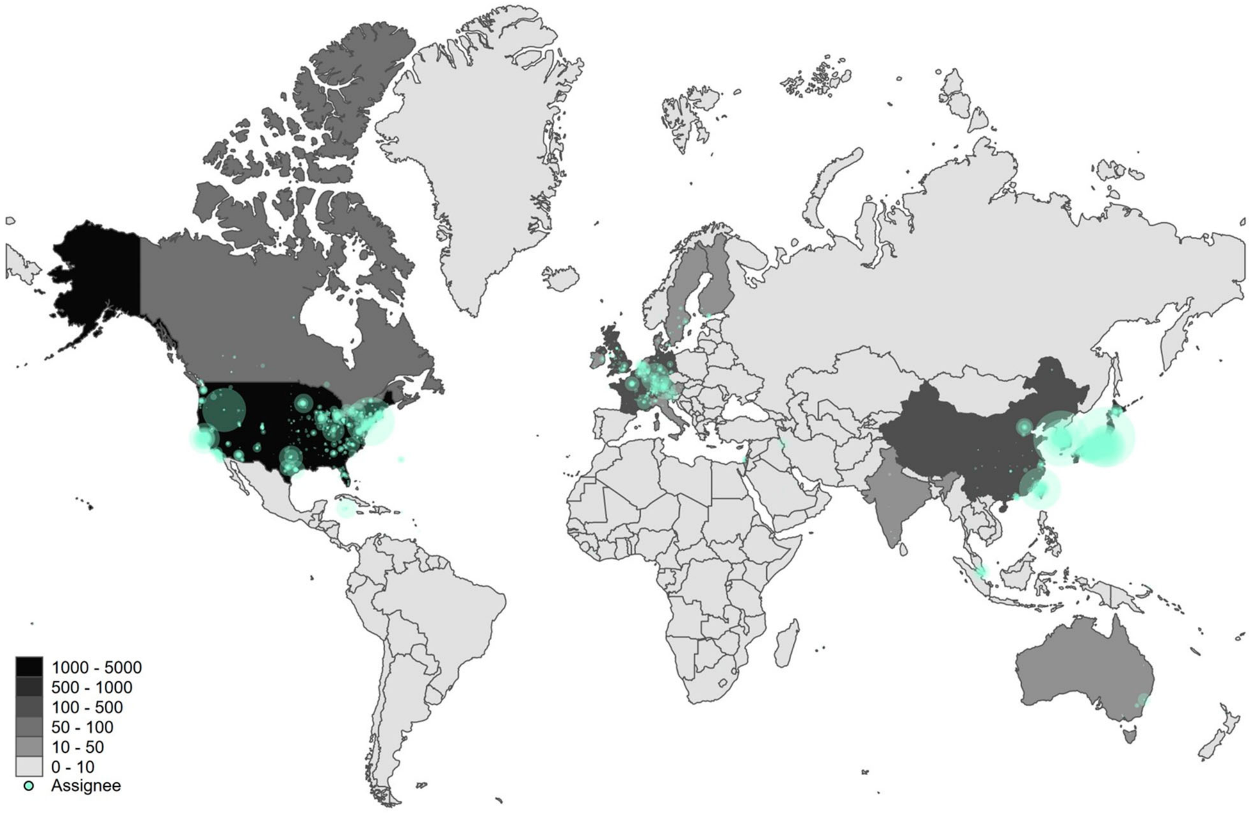


**Figure 5.** Counts of assignees in information and communication technology (ICT)/artificial intelligence (AI) with patents mentioning at least one keyword, 2000–17.
Note: The marker size of assignees is proportional to the number of assignees' patents mentioning at least one keyword. Readers of the print issue can view the figure in colour online at https://doi.org/10.1080/00343404.2022.2077326.

Country polygons are coloured in varying shades of blue depending on the counts of all assignees represented on the map, divided into six size categories ranging from fewer than 10 to more than 1000. Despite the abundance of mines for these raw materials in Africa and South America, no locations in these continents innovate in the ICT/AI area that rely on them – highlighting a geographical disconnect between resource supply and the control of technological innovation. This provides evidence that the presence of critical raw materials has, by itself, not created a context for source countries to expand value capture in GVCs.

Using ArcMap 10.3 software, the maps shown in Figure 6 display the specific geography of the world's most productive assignees, that is, those with more than 100 CCM-related ICT/AI patents in the case of the United States and Europe, and 500 in the case of Asia. The top assignees in the United States number 116 (out of a total of 2559), and are mostly concentrated in Silicon Valley, for example, Intel in Santa Clara, Apple in Cupertino and the only non-business owner in the top 50: the Board of University of California; New York State, for example, IBM in Armonk, General Electric in Schenectady, Xerox and Eastman Kodak in Rochester, Bristol-Myers Squibb and Pfizer in New York; and Texas, for example, Hewlett Packard and Texas Instruments in Dallas.

There are 27 top assignees in Europe (out of 804 in total), located in Germany, France, the Netherlands, Austria and the UK. Prime locations are the renowned and most innovative manufacturing regions in south and south-west Germany, for example, Munich, which hosts the only German company in the top 50, Infineon Technologies, located in Stuttgart, Baden-Württemberg, and the area south of Frankfurt, in Hesse; and Berlin. In France, assignees with the highest patent intensity are mostly concentrated in Paris; in Figure 6b the pointer in Crolles (Grenoble) in the region of Rhône-Alpes flags the presence of ST Microelectronics France, the largest plant in the country. Very few other locations appear, showing the strong spatial agglomeration of top assignees of CCM-related ICT patents: Eindhoven, Philips' headquarters, and Amsterdam in the Netherlands; the region of Carinthia (Villach), a semiconductors hub in Austria; and the UK cluster of Cambridge.

The top assignees in Asia total 51 (out of 1588): in this case the threshold was 500, confirming the large and rising Asian prominence in ICT/AI inventions relying on CCMs. Relevant MNEs are located mostly in Japan, in the Tokyo metropolitan region (e.g., SEL, Canon, Toshiba, Sony), followed by the large electronic clusters around Osaka (e.g., Sharp, Panasonic, Nitto Denko, Sanyo) and in the Nagano prefecture (e.g., Seiko). Top assignees in South Korea are strongly agglomerated in the metropolitan region of Seoul; other notable urban agglomerations are Taipei, Singapore and Beijing.

Several observations follow from the above. One is that the production and control of new technological knowledge related to CCMs in the ICT paradigm is highly spatially concentrated in major urban areas and regional

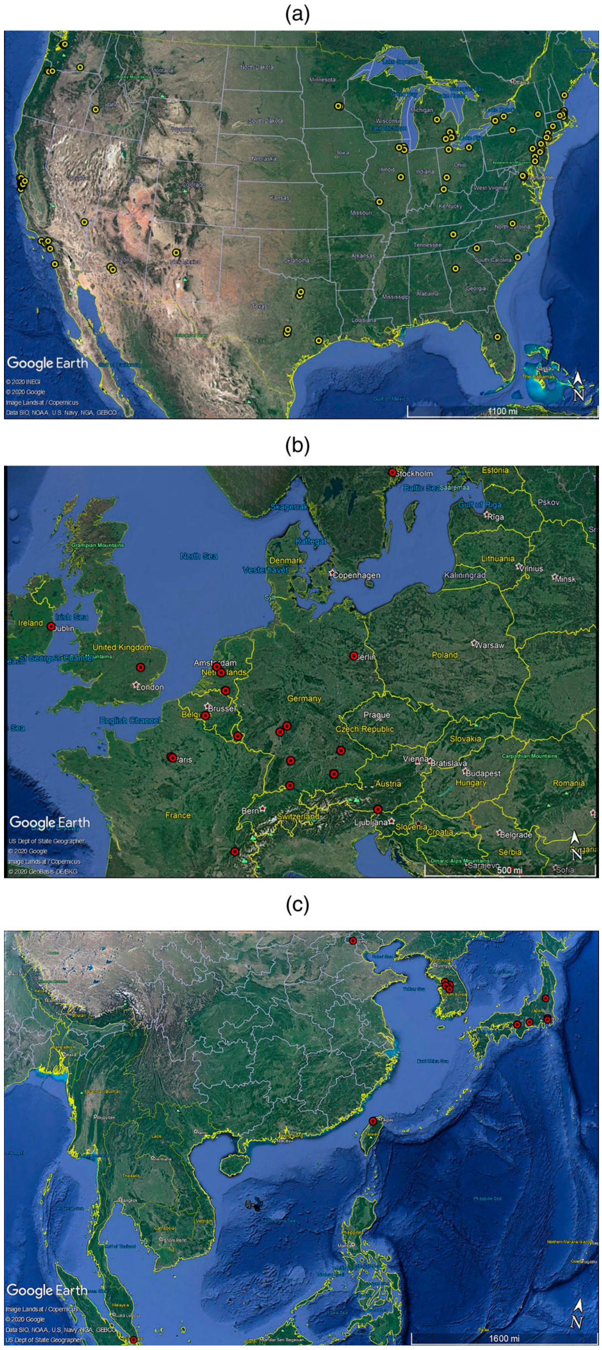


**Figure 6.** Location of top assignees in terms of number of critical and conflict materials (CCM)-related patents in information and communication technology (ICT)/artificial intelligence (AI): (a) United States (threshold more than 100 patents); (b) Europe (threshold more than 100 patents); and (c) Asia (threshold more than 500 patents).

clusters within a relatively small number of countries in the Global North. Another is the dominant role of large MNEs – including many high-profile technology 'giants'. Such insights suggest that worldwide CCM-related demand is, directly or indirectly, related to the innovative activities of a small number of leading corporates located in few subnational locations with favourable urban and regional assets. This is highly consistent with growing evidence on the regional inequality implications of

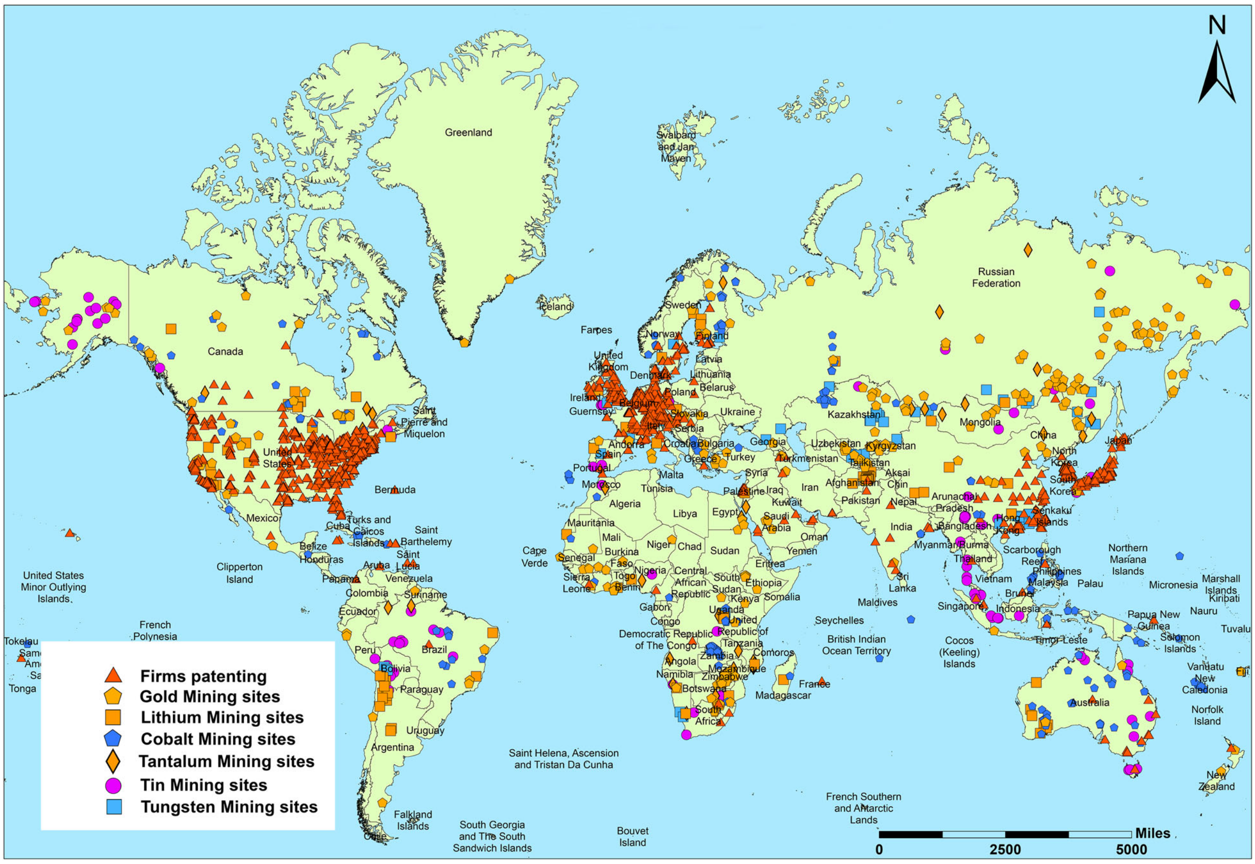


**Figure 7.** Geography of critical and conflict materials (CCM)-based information and communication technology (ICT)/artificial intelligence (AI) patent assignees and CCM mining sites.

globalization in the Global North (e.g., Crescenzi & Iammarino, 2017; Feldman et al., 2021).

We then broadly compare the geography of CCM-related technology ownership with that of mining sites for our six selected CCMs: data come from the Mineral Resources Data System (MRDS) and refer to the US Geological Survey 2017. Figure 7 (and Figure A4 in the Appendix in the supplemental data online) shows the striking resource–technology divide: the concentration of mining sites is mainly found in specific regions of the Global South in Sub-Saharan Africa and South America, and in some developing countries in Central Asia; by contrast assignees are almost exclusively located in the Global North, highly concentrated in a few hotspots.[14]

## 6. CONCLUSIONS AND THE NEXT STEPS

The relationship between technological innovation and natural resources has been a longstanding concern for scholars, though the predominant focus has been on the impact of technological advances on resource scarcity, efficiency and price (e.g., Marañon & Kumral, 2019). The present paper moves the focus of the debate to CCMs, a set of resources where there has been very limited work from an economic geography perspective.

Our exploratory analysis makes several important contributions. First, we find evidence of a significant increase in overall innovative activity related to CCMs over our sample period. This rise tallies with data from other sources which documents rising production and consumption of CCMs over a similar time frame. Our goal in the present paper was not to establish a causal linkage between these concurrent trends. Yet it is plausible to suggest that innovation and increased demand for key CCMs are related. Second, we find that technological applications associated with the ICT paradigm have a particularly strong association with CCMs. Although only indicative, our descriptive exercise lends weight to the claim that specific technological paradigms have distinctive resource signatures, with potentially important implications for resource demand and associated geographies. Third, whilst past work within the frame of material flow analysis has usefully mapped out the sources, production and consumption of a number of CCMs (Sun et al., 2019; Ziemann et al., 2012), our analysis goes one step further by exposing a significant spatial disparity between the locations where large amounts of CCMs are extracted and those where most of CCM-based technological returns are appropriated. Some of the former are high-income (e.g., Australia) and middle-income (e.g., China) economies, but many are low-income ones (e.g., DRC). On the other hand, a relatively small number of metropolitan regions and clusters in the Global North – hosting the largest MNEs who also act as main nodes and flagships in the relevant GPNs and GVCs – appear to be dominating the high value-added parts of CCM-dependent value chains. These combined findings further lay challenge to optimistic accounts about both the potential for places of the Global South to couple resource-based with knowledge-based development, and for peripheral regions of the Global North to reap the benefits of globalization through cutting-edge investments in innovation.

It is important to caveat our findings. The fact that a patent contains a relevant keyword does not mean that the respective technology impacts physical demand for CCMs. Moreover, patent counts are only a rough approximation of the technology's actual CCM-intensity, or whether it increases or reduces resource inputs (e.g., though efficiency or substitution). Furthermore, USPTO data may provide a somewhat geographically biased picture of the true level of inventive activity across space, in that inventors from certain countries (e.g., United States and Canada) are more likely to file for patents in the United States than other countries (de Rassenfosse et al., 2013). That said, while some geographical bias is possible, it is unlikely that any other source of patent data would offer a more comprehensive picture, particularly one that focuses on ICTs and stretches back to the 1970s. Finally, our aggregated approach – wherein we group different CCMs together – may also conceal important differences across individual materials, e.g., in the geographies of both technology demand and CCM extraction. We nevertheless believe that our novel patent-based approach usefully complements past work relying on trade statistics, input–output tables, and physical estimates of material inputs in production and consumption.

Future research lines are multiple, not least because ours is one of the first studies of its kind, investigating a topic with a wide range of academic and applied implications. One direction is to develop and refine the methods used in the present study; for example, deploying more advanced text mining and machine learning techniques to identify and discriminate innovations which are resource demand-creating or -reducing. Undertaking more detailed work, which seeks to capture input–output relationships linking the supply and demand of specific CCMs along the entire GVC, would also be highly valuable in understanding uneven regional development. Taking account of both technology, product and organizational aspects, such studies would help to shed light on both value capture *and* value extraction within the context of CCMs, and the extent to which this is organizationally mapped onto the control of technological innovation. Another critically important issue is investigating the causal connections between technological change, technological demand and negative territorial outcomes such as conflict and violence related to CCM extraction – with a particular need for work at subnational scales. Research should also be undertaken into policy and other factors influencing CCM-related technological change. One line of enquiry would be to examine whether government-mandated supply chain due diligence/reporting requirements – at various scales of governance, for example, local, national and macro-regional – are effective in stimulating technological innovation and diffusion aimed at reducing dependence on regulated CCMs. Such studies could additionally seek to investigate the extent to which regulation (at the national or subnational scale) only stimulates innovation locally, or whether innovators elsewhere are responsive to policy signals in other jurisdictions.

More generally, further exploration of the nexus between technological paradigms and their critical resource intensity through the lens of economic geography would substantially improve the current policy response. In particular, it could help inform and support a move from exclusively top-down internationally fragmented regulatory frameworks to globally coordinated, multi-governance and place-sensitive ones (Coenen & Morgan, 2020; Giuliani, 2018; Phelps et al., 2018). Being able to disentangle the specific geography of resource–technology linkages and their consequences can uncover policy and other opportunities for those places – in both the Global North and Global South – currently struggling to reap the returns to technological progress within an evolving global division of labour.

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No potential conflict of interest was reported by the authors.

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## NOTES

1. We also construct a similarly defined variable considering for each patent whether *any* of the keywords appears at least once. This differs from the sum of all relative frequencies for each keyword in a given technology because the same patent might be mentioning multiple keywords. In these instances, again, we only count that patent once.
2. See https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS/.
3. In an unreported analysis, we also considered a three-year lag between patenting and resource extraction, confirming this result.
4. Relevant graphs at IPC class/subclass levels are available from the authors upon request.
5. Thus, Section C (Chemistry and metallurgy) is later excluded due to the tendency of these technologies to prevail in terms of keywords for reasons unlikely related to the applications of interest here.
6. For further details, see Figure A2 in the Appendix in the supplemental data online.
7. For operational definitions of ICT and AI technologies, see the Appendix in the supplemental data online.
8. Interacting the relative frequency coefficient with period dummies allows us to 'break down' the effect of relative frequency of keyword use in the cited technology by each period.
9. Analogous results for each CCM keyword are available from the authors upon request.
10. We additionally checked the location of all inventors associated with patents in our sample, and assigned located patents on this basis by retaining the mode of all the locations of the patents' listed inventors. We then compared matching rates for country location based on assignees with that based on inventors. For over 90% of all patents in our sample, these locations coincided (the results are available from the authors upon request).
11. See, for example, https://www.theguardian.com/global-development/2021/nov/25/battery-arms-race-how-china-has-monopolised-the-electric-vehicle-industry/.
12. See 'Technological demand for CCMs and conflict/violence: preliminary evidence' and Table A3 in the Appendix in the supplemental data online.
13. Cf. also Figure A3 in the Appendix in the supplemental data online.
14. Our analysis restricts the sample to assignees with at least one ICT patent mentioning one of the relevant keywords. As such, there may well be some firms patenting in regions in Africa or South America, just not within the scope of our analysis.

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