論文の内容の要旨

論文題目　Global Metal Cycles in a Carbon-Constrained World
（炭素制約下における世界規模の金属資源循環）

氏名　　渡　卓磨

Climate change mitigation strategies could fundamentally alter future metal cycles through two drivers—implementation of decarbonization technologies and carbon constraints on production activities. The question thus arises as to how the global metal cycle will change in the future in a carbon-constrained world, and what interventions are needed to reconcile climate change mitigation with sustainable metal use. This thesis aims to provide scientific support for discussions in such areas through a series of analyses. After describing the research background in Chapter 1, Chapter 2 explores the state of research and research gaps by conducting a systematic review of more than 150 published studies. This review will serve to clarify the purpose and contribution of the thesis. The thesis is then divided into two main sections. The first (Chapters 3 and 4) examines the impact of deployed decarbonization technologies on the future global metal cycle, while the second (Chapters 5, 6, and 7) explores the impact of carbon constraints on the future global metal cycle. Together, these sections aim to model the *global metal cycles in a carbon-constrained world*.

Chapters 3 and 4 aim to identify the total extraction of materials, including mine waste, associated with the deployment of decarbonization technologies and the role of a circular economy in the energy transition. By linking global energy scenarios with material demand-supply models on a country-by-country basis, the analysis shows that the decarbonization of both the electricity and transport sectors will curtail fossil fuel production. However, paradoxically, this reduction in fossil fuel production is expected to increase material extraction associated with metal production by a factor of more than 7 by 2050 relative to 2015 levels. This substantial increase is primarily due to increases in the extraction of iron, copper, nickel, silver, tellurium, cobalt, and lithium used for the production of solar photovoltaics and electric vehicles (i.e., plug-in hybrid electric vehicles and battery electric vehicles). Specifically, around 70-95% of material extraction in 2050 is attributed to these metals and technologies. The analysis also shows that approximately 32–40% of the increase in material extraction is expected to occur in countries with weak, poor, and failing resource governance, implying that there is a high risk of improper management of the extracted materials. Countries with high levels of material extraction and insufficient governance include DR Congo, Guatemala, Iran, Venezuela, Cuba, Madagascar, and Zimbabwe. The analysis confirms the considerable potential of circular economy strategies regarding such issues. However, implementing a suite of circular economy strategies, including lifetime extension, servitization, and recycling, will not entirely offset the concomitant increase in material extraction. Responsible sourcing will be required in areas

where supply cannot be met by circular material flows. In the absence of such action from the consumption side, the decarbonization of the electricity and transport sectors may face an ethical conundrum in which global carbon emissions are reduced at the expense of an increase in socio-environmental risks at local mining sites. In this study, a series of analyses underscore the importance of proper management of extracted materials, which will increase rapidly along with the deployment of decarbonization technologies.

Chapters 5, 6, and 7 clarify the scale and timing of the impact of carbon constraints on production activities on future metal flows and stocks. Chapter 5 first explores the historical flows and stock dynamics of six major metals (iron, aluminum, copper, zinc, lead, and nickel) in 231 countries and regions over a 110-year period using a newly constructed dynamic metal cycle model. The analysis shows that substantial inequality exists in international metal stocks. Notably, in terms of per capita metal use, the top 20% of the population accounts for 60-75% of the world's total metal stock, while the bottom 20% accounts for only about 1%. International inequality in metal stocks has decreased over time due to the strong growth in developing countries, mainly those in Asia. However, the analysis shows that the continued reduction of metal stock inequality through this growth-led pathway will lead to an increase in global metal demand by a factor of 2 to 3 by the mid-21st century. Building upon these results, Chapters 6 and 7 explore the impacts of carbon constraints on global metal flows and stocks using an optimization routine coupled with a dynamic metal cycle model. The analysis shows that, under carbon constraints, primary production of all six metals will peak by 2030, and secondary production will surpass primary production by at least 2050. Consequently, cumulative ore requirements over the 21st century will remain below currently identified resources, implying that natural ore extraction will be limited by carbon constraints before existing resources can be depleted. In this case, the global in-use metal stocks will converge from the current level of about 4 t/capita to about 7 t/capita, on average, which is lower than the 12 t/capita that is currently used in high-income countries. This implies a need for increased material efficiency to meet the same demand for goods and services with less metal use. Importantly, realizing such system changes will require urgent and concerted international efforts involving all countries, but specific responsibilities will vary according to income level. Wealthy countries will need to use existing metal stocks more intensively and for longer periods to reduce stock replacement demand, while poor countries will need to develop long-lasting and material-efficient infrastructure to curtail stock expansion demand in the first half of the 21st century.

Finally, Chapter 8 summarizes the highlights of the preceding chapters and presents an outlook for future study. The thesis highlights the need for proper management of the extracted materials along with the deployment of decarbonization technologies, and the need to improve material efficiency to meet basic needs using metals that can be produced and used under the existing carbon constraints. The synthesis of the findings also suggests that these interventions are strongly interconnected and that both need to be addressed simultaneously. The approach presented in this thesis can be extended to a broad range of materials, including cement, biomass, and plastic, and can thus contribute to exploring future scenarios for a wide array of materials.