Dynamic Isotopic and Probabilistic Modelling of Global Metal Flows: Integrating Isotope Geochemistry, Bayesian Inference, and System Dynamics to Advance Industrial Ecology

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This research direction seeks to establish a new theoretical and computational foundation for **industrial ecology**, linking the physical metabolism of materials with their economic, social, and geochemical underpinnings. While traditional **Material Flow Analysis (MFA)** quantifies the stocks and flows of resources, it often treats the system as static and isolated from market forces, behavioural responses, and provenance data. **Opportunities now exist to leverage and unify elements of** isotopic fingerprinting, Bayesian inference, and dynamic systems modelling to construct a holistic framework that can represent how material, economic, and social processes co-evolve over time.

The goal is to move from descriptive MFA toward **predictive, dynamically coupled, and isotopically traceable modelling** of global resource systems. This integration will enable the quantification of how geochemical signatures, market fluctuations, technological change, and social behaviour jointly determine the evolution, stability, and sustainability of metal cycles. The approach will address major gaps in how material flow, provenance, and economic systems are interlinked under the pressures of energy transition, digitalisation, and global policy change.

Possible Technical Directions:

1. **Isotopic Integration into MFA:**
   Develop probabilistic isotope-mixing models that embed isotopic composition data directly into Bayesian MFA formulations. This will allow simultaneous estimation of mass flows and isotopic provenance, linking resource stocks to ore sources and recycling streams. Unlike conventional isotopic tracing or certification studies, this direction formalises isotopic constraints within mass-balance equations, producing a reproducible, uncertainty-aware foundation for material origin verification and system-wide tracing.
2. **Bayesian–Dynamic Coupling:**
   Extend the Bayesian MFA framework to include time-dependent feedbacks and non-linear system behaviour using stochastic differential equations or dynamic Bayesian networks. This will convert static MFA models into tools capable of capturing dynamic transitions such as market-driven recycling, technological substitution, or resource scarcity feedbacks. The novelty lies in combining probabilistic inference with temporal system dynamics to understand how uncertainty, inertia, and behavioural lags shape material system evolution.
3. **Material–Economic–Social Systems Coupling:**
   Integrate dynamic MFA with economic and social models to explicitly represent how resource flows interact with price dynamics, trade networks, and consumption behaviour, with possible cross-constrains from parallel MFA systems. This coupling will make it possible to explore how economic shocks, innovation, and regulation propagate through physical material systems and how various physical systems cross-constrain each other. The approach will use dynamical-systems and network-theory tools to identify equilibrium states, critical thresholds, and resilience properties in coupled resource–economy systems.

Advances in these three areas would enable major progress in **scenario simulation and sensitivity analysis**, providing a physically grounded and probabilistically rigorous basis for exploring alternative futures for key materials such as Cu, Li, Ni, and Al. Together, these directions define a next-generation **science of dynamic resource systems**, in which geochemical, material, and socio-economic processes are modelled as a single, interacting whole—enabling predictive, transparent, and traceable understanding of global resource transitions.

We are looking for pro-active and scientifically curious applicants with an excellent background in the appropriate subject, e.g. data science, engineering, earth or environmental science, chemistry, physics, mathematics, or quantitative ecology, and with the willingness to learn computational methods as needed. Interaction with industry and international collaboration may also be possible (and encouraged) within the scope of the research.

Applicants with a strong academic record and who can demonstrate aptitude for an independent and creative approach to scientific research (or other activities relevant to their background) are more likely to be successful. Students will be strongly encouraged to make projects their own and will be supported through that growth process so do not hesitate to also propose your vision when contacting us.