Complexity Theory, Energy Decline, and Migration

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Introduction

In today's world, migration is not the outcome of individual choice or market incentives. It is increasingly becoming a structural response to ecological, energy scarcity, and systemic imbalance. Across the world, changes in temperature, rainfall patterns, and soil conditions are disrupting food production and water availability, making large swaths of rural land less viable for livelihoods.

In East Africa, prolonged droughts linked to climate change have devastated traditional agriculture and displacing millions (UNHCR, 2023). In South Asia, intensifying heatwaves are rendering some regions uninhabitable during peak seasons, pushing populations toward urban centers or across national borders (World Bank, 2021). Whether within nations or across continents; migration is growing fast as a consequence of interdependent pressures that span ecosystems, economies, and energy systems.

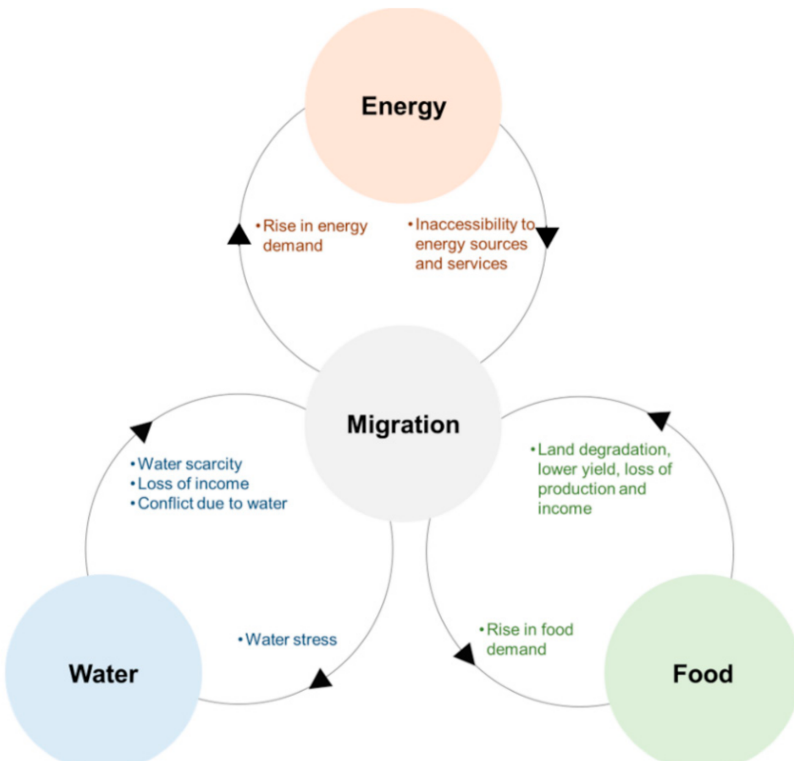

Figure 1: Complexities of Migration and Climate Change

The Figure1 above, shows the interconnected nature of migration and resources creating a self-sustaining loop. As people move from affected regions to large urban cities or more stable countries, the demand for energy-intensive infrastructure increases. Urban housing, food distribution, public transport, and digital services require energy inputs, much of which remains dependent on fossil fuels. Therefore, their collective energy footprint expands due to increased mobility, refrigeration, lighting, and digital connectivity. This intensifies existing infrastructure bottlenecks, driving up costs and triggering social and political friction. Hence, amplifying the scarcity.

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The paradox observed is that improvements in energy efficiency do not reduce total energy consumption instead, they lead to higher overall use as efficiency makes energy services cheaper and more accessible (Jevons, 1865/2001). Shown in Figure 2.

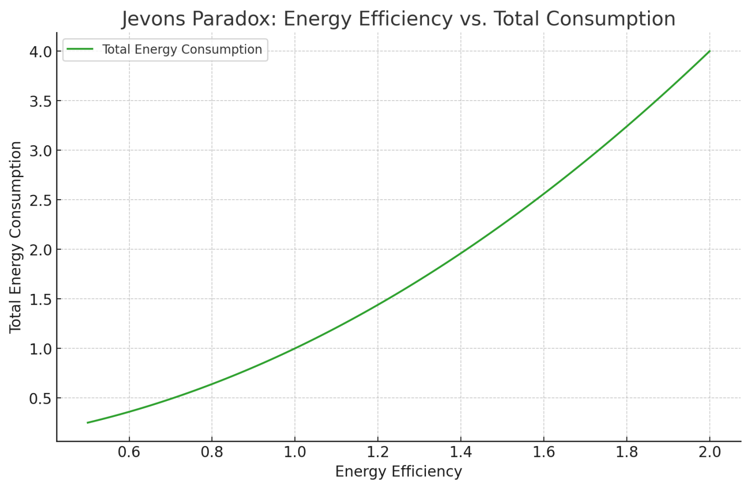

Figure 2: Jevon's Energy And Consuption Paradox

This creates a self-reinforcing loop energy-driven environmental stress displace populations, whose movement increases aggregate energy demand, thereby accelerating resource depletion and further ecological strain. Its further illustrated in the Figure3 below.

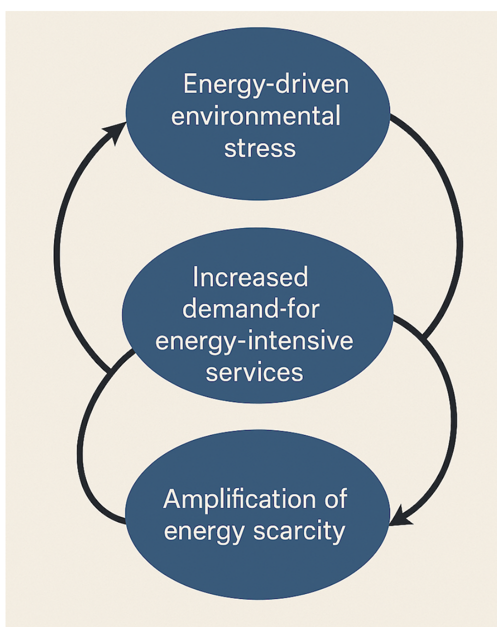

Figure 3: Energy Scarcity And Migration Paradox

Complex Systems Theory

Traditional economic models are rooted in equilibrium and utility maximization. They are ill-equipped at capturing these multi-layered dynamics. Complexity theory, in contrast, frames migration as an emergent behavior within a larger adaptive system where feedback loops, interdependence, and tipping points govern outcomes. Shown in Figure4.

Complexity theory understands systems as evolving networks of interconnected elements that adapt in response to internal and external pressures. It emphasizes uncertainty and emergency patterns that arise from interactions of agents, resources, and environments.

Economies, ecosystems, or migration flows are capable of sudden shifts while remaining sensitive to constraint and creativity. As migration pressures mounts, energy scarcity is both a cause and a result of population displacement. Meanwhile, declining EROI makes it harder to expand services or build resilient systems. Which implies structural limits to growth and adaptation under fossil-fuel dependence.

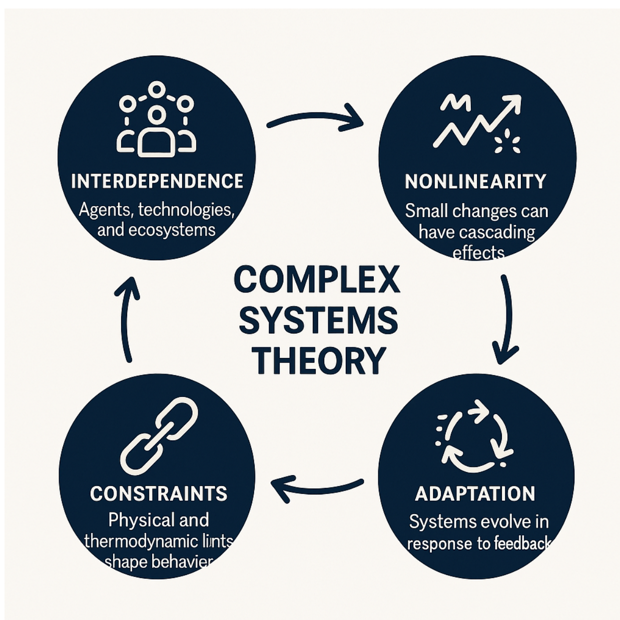

Figure 4: Complex Theory

Limitation of Growth And Roots of Displacement

With fears of fossil-fuel peaking and extraction limitations yielding lower energy returns (EROI), the question of long-term viability becomes central to global development. While technological innovation may offer temporary solutions or efficiency gains, these often mask deeper systemic constraints. As Hubbert's Peak reminds us, fossil fuel extraction follows a trajectory governed by demand, physical and geological limits. Each bounce in production comes at greater ecological, economic, and energetic cost.

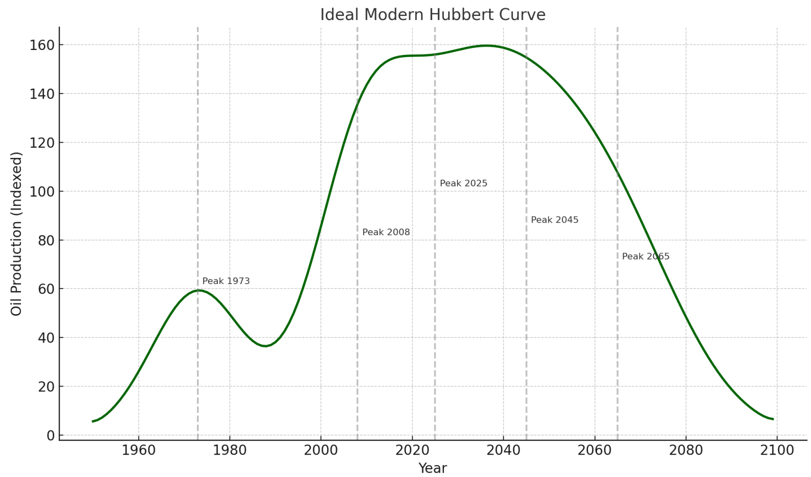

Figure 5: Ideal Hubbert's Curve: *Hubbert's Peak model illustrates the inevitable decline of energy resources, highlighting the structural limits of fossil fuel-dependent economies. As energy returns decrease, migration becomes a necessary response, particularly in regions where energy scarcity disrupts livelihoods. This figure visually demonstrates the energy depletion migration link, reinforcing the inevitability of migration in the face of declining resources.*

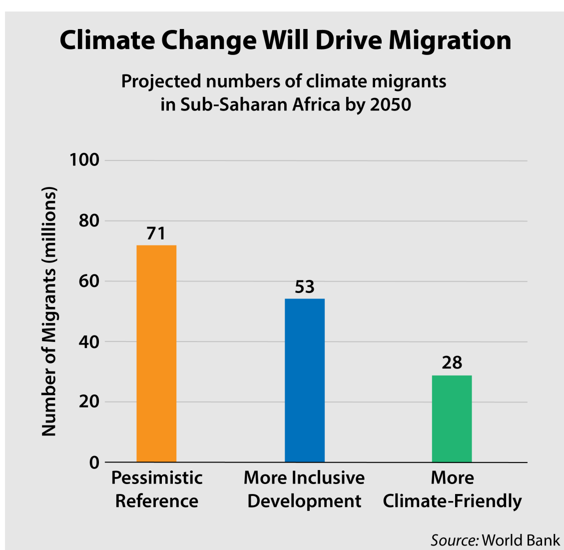

Figure 6: East African migration Trends: *The trends in East Africa clearly reflect how energy constraints and climate instability drive migration. As energy access becomes increasingly unreliable and climate impacts worsen, communities are forced to move. This empirical evidence validates the claim that migration is not only a choice but a structural adaptation to energy and environmental stress.*

These constraints disproportionately impact countries and communities that are already energy-insecure. The regions least responsible for historical emissions such as sub-Saharan Africa and parts of South Asia are now among the most vulnerable to the converging pressures of climate instability and energy scarcity. This energy constraint has profound implications for developing regions, particularly those dependent on imported fuel or global supply chains. In sub-Saharan Africa, for example, energy access remains highly uneven, with rural communities often relying on biomass while cities face frequent grid failures and fuel shortages (IEA, 2022).

As declining EROI shrinks the surplus energy available for infrastructure, healthcare and governance decreases, and people are forced to migrate out of necessity. Migration becomes adaptive behavior in response to its limits. Therefore, migration patterns is a reflection of responses to

structural decline. And just as Jevons foresaw that improvements in efficiency could paradoxically cause resource exhaustion, the current global push for energy efficiency may accelerate the underlying collapse.

Then, roots of displacements are not just political or economic they are also thermodynamic. From Second Law of Thermodynamics :

Entropy Change and Energy Depletion

Definition of Entropy:
Entropy is a thermodynamic quantity that measures the degree of disorder or randomness in a system. It is also a measure of the amount of energy in a system that is unavailable to do work.
Formula for Entropy Change:

$$\Delta S = \int \frac{dQ_{\text{rev}}}{T}$$

Where:

- ΔS is the change in entropy,
- dQ_{rev} is the heat added to the system in a reversible process,
- T is the temperature of the system.

Relation to Energy Depletion and Migration:
As energy resources become depleted (e.g., in the context of fossil fuels), the entropy of the system increases. This is due to the increasing difficulty in extracting and utilizing energy efficiently. In migration systems, entropy increases as the community adapts to external pressures, but not without the cost of higher energy use and decreased economic return, further illustrating the link between energy depletion, economic challenges, and migration resilience.

Systems built on high energy requirement cannot be sustained when cheap energy disappears.

Thus, the illusion of substitution breaks down as every alternative source still require extensive input of materials, land and fossils to function properly. The consequence is a slow and uneven marked by pulses of migration, rising inequality, and institutional fragility.

Recognizing these patterns through complexity theory does not mean giving up on adaptation; it means redefining what resilience looks like. It shifts the conversation from linear progress to cyclical balance, from growth to maintenance, and from extraction to regeneration. Therefore, limitation to growth is not a failure of innovation but a signal for new and comprehensive systems level update.

The theory of energy systems emphasizes that systems naturally maximize energy output, and as energy returns decline, societies are forced to adapt. With diminishing energy quality, migration becomes an inevitable response to the breakdown of local systems (Odum, 1996). Similarly, the concept of entropy explains that economic processes inherently lead to irreversible energy loss, further pushing communities to migrate in search of more sustainable resources (Georgescu-Roegen, 1971). Both perspectives align with the idea that energy depletion and systemic decline drive migration as a natural adaptive behavior.

Therefore, the migration trends observed in East Africa and South Asia are good examples of how **complex systems theory** operates in real-world scenarios. As climate-induced stressors, such as drought in East Africa and heatwaves in South Asia, disrupt local ecosystems and energy systems, they trigger feedback loops that amplify migration patterns. These regions show that migration is not simply an individual choice but an emergent behavior within a larger, interconnected system.

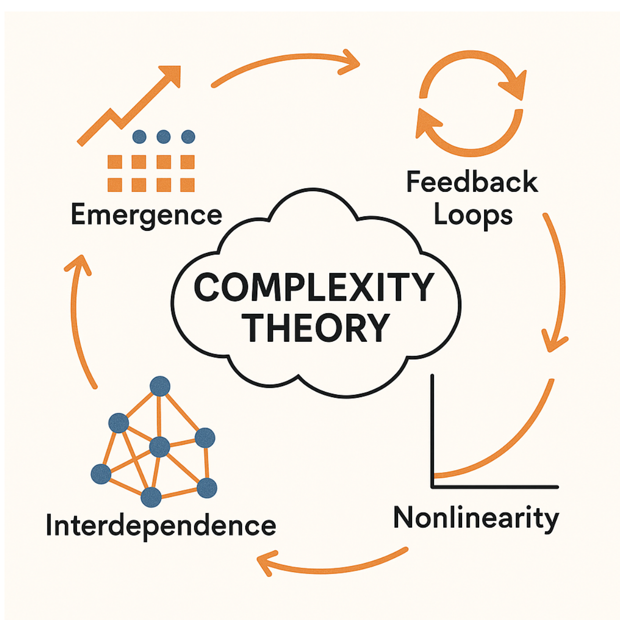

Figure 7: Complex And Non-Linear Relationships

As seen in the Figure 7 above, *energy constraints* and *climate instability* worsen, populations are displaced, further intensifying energy demand in urban centers. This dynamic shows the non-linear and interdependent nature. Where, small change in one part of the system i.e. reduced agricultural productivity can lead to large-scale consequences of mass migration and resource depletion.

Conclusion

Despite the evidence to the contrary, migration is often framed as a problem to be managed, rather than a symptom of systemic dysfunction. Policies treat migrants as external shocks and as isolated as possible from the sources and energy conditions that shaped their displacements.

The second law of thermodynamics offers a scientific light through which we can understand the increasing complex relationships of migration and energy depletion. As resources like fossil fuels become scarcer, entropy increases, making energy extraction and utilization more challenging and inefficient.

In both energy systems and human migration, the rise in entropy signals a shift towards greater uncertainty, highlighting the urgent need for sustainable practices that mitigate disorder and optimize energy use. It's an adaptive strategies of migrant communities to navigate the increasing disorder of the systems.

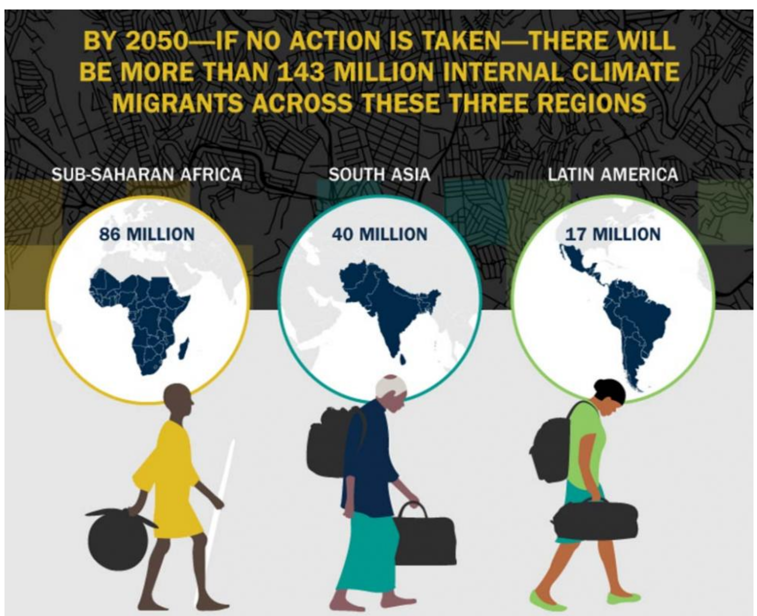

Figure 8: World Bank. (2021). Groundswell: Acting on internal climate migration.

As predicted in the Figure 8, a projected 143 million people across Sub- Saharan Africa, South Asia and Latin America will migrate as a result of climate migration. Understanding these principles and patterns can equip us to better address the intertwined challenges of resource management and migration in a rapidly changing world. As complex as the systems and problems are proving to be, solutions are expected to be as complicated. Building redundant system update with bi-directional growth and accountability feedback loop might help us mitigate and curb the dire consequences of climate changes.

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