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Rate-Dependent Tipping in Human–Ecological Systems

Tipping points are thresholds beyond which ecosystems undergo dramatic and sometimes irreversible regime shifts. Rate-induced tipping (r-tipping) occurs because external changes outpace a system's capacity to adapt. This is especially relevant in socio-ecological systems, where rapid increases in resource exploitation, pollution, or abrupt policy shifts can drive the system away from its basin of attraction, triggering unintended regime shifts. Pollution rates depend on ecological, economic, and social factors, and policy interventions such as fines or incentives can influence them. The rate at which interventions change can trigger r-tipping, shifting the system between ecologically desirable and undesirable states. For example, rapid policy relaxation can lead to abrupt shifts to highly polluted states. On the other hand, sufficiently rapid strengthening of incentives can deliberately induce a shift toward healthy ecosystems, making r-tipping either a risk or a management tool. Oscillation amplitude also affects outcomes in complex ways. Under certain circumstances, only intermediate amplitudes can trigger r-tipping to an ecologically undesirable state; low amplitudes produce no tipping (as expected), but surprisingly, very high amplitudes also avoid tipping. This non-trivial pattern is not yet theoretically understood and highlights a clear direction for further research. I plan to explore how seasonal fluctuations in social, economic, and associated ecological costs affect ecological outcomes. I will model these seasonal effects by allowing associated parameters to oscillate and change in biologically meaningful ways. In addition, I will investigate gradual parameter shifts, such as slowly increasing fines or climate change trends that alter baseline ecological conditions.