

Digital Earth Twin's Systemic Integration and Transformational Pathways

Operationalizing Safe and Just Earth System Boundaries for Cities and Businesses Using DestinE

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Presented at EGU26 – Vienna, Austria – 2026

Introduction

This supplemental material expands on the conceptual and operational components presented in the EGU26 poster presentation.

The research explores how Safe and Just Earth System Boundaries (ESBs) can be operationalized at city and business level through the integration of Earth-system monitoring, translation protocols, waste-system analysis, and Digital Earth Twin infrastructure.

Using the Marrakech Prefecture and the ECOMED waste-management system as a case study, the framework connects environmental pressures, circular economy pathways, and Earth-system state monitoring to support systemic decision-making and future scenario capability.

The work aims to contribute toward practical operationalization of ESBs through near real-time environmental monitoring and cross-scale translation processes.

ESB Translation Framework

The framework translates global Earth System Boundaries into operational indicators at city and business scale.

The research integrates:

- Earth-system ceilings

- Social foundation floors
- State-pressure relationships
- City and business allocation logic
- Circular economy pathways
- Earth-system monitoring infrastructure

The framework connects:

1. System activities
2. Environmental pressures
3. Earth-system state conditions
4. Operational indicators
5. Decision-making pathways

The Marrakech and ECOMED case study is used to demonstrate how waste-management systems generate pressures across climate, freshwater, biosphere, and infrastructure domains.

Earth System Boundaries and Translation Logic

The framework operationalizes selected Earth System Boundaries and social foundation domains.

Earth-System Ceiling Domains

- Climate
- Freshwater
- Biosphere
- Biogeochemical Flows

Social Foundation Floor Domains

- Water Access
- Energy Access
- Food Access
- Infrastructure Access

Global ESBs are translated to city-level indicators and further allocated to specific city and business activities.

The framework applies state-pressure logic:

- System activities generate pressures
- Pressures influence Earth-system state conditions
- State conditions are monitored through indicators and Earth-system datasets

Proxy-based operationalization is used where direct measurements are unavailable.

DestinE Integration

The research integrates DestinE Earth-system data infrastructure to support environmental monitoring and future scenario capability.

DestinE contributes:

- Earth-system state monitoring
- Near real-time environmental indicators
- Future projection capability
- What-if scenario potential
- Systemic monitoring pathways

Example environmental dimensions include:

- Atmospheric conditions
- Water availability
- Ecosystem condition
- Climate-related indicators

The integration demonstrates how Digital Earth Twin infrastructure can support operational sustainability assessment and systemic planning.

Marrakech / ECOMED Case Study

The Marrakech Prefecture and ECOMED waste-management system are used as a case study for operational translation.

The case demonstrates how waste-management activities influence:

- Climate pressures
- Water-system pressures
- Biosphere pressures
- Infrastructure conditions
- Circular economy performance

The analysis identifies systemic pressures linked to:

- Methane emissions
- Waste leakage
- Water stress
- Nutrient imbalance

- Infrastructure gaps

The framework evaluates whether current system conditions operate within or outside a safe and just corridor.

Results suggest that Marrakech currently operates outside several safe and just boundary conditions, particularly across climate, freshwater, and biosphere-related domains.

Circular Economy and Waste-System Logic

The framework integrates Waste Management System Development Stage Concept (WMS-DSC) logic toward circular economy pathways.

The analysis evaluates:

- Recycling rates
- Resource recovery
- Composting potential
- Waste-system infrastructure
- Circular economy transition stages

The framework demonstrates how circular economy interventions may reduce environmental pressures and support movement toward safer operational corridors.

Limitations

Several limitations currently exist within the framework.

These include:

- Proxy-based operationalization
- Incomplete direct measurements
- Limited data availability at city/business scale
- Early-stage integration across Earth-system domains
- Uncertainty in operational thresholds and allocation methods

The work therefore represents an early-stage operational framework demonstrating feasibility and integration potential.

Future Work

Future work aims to:

- Improve direct indicator measurement
- Expand cross-domain Earth-system integration
- Strengthen allocation methodologies
- Improve uncertainty assessment
- Integrate additional DestinE datasets
- Develop dynamic what-if scenario simulations
- Support operational governance and planning systems

The broader objective is to contribute toward actionable Earth-system governance and operational sustainability planning using Digital Earth Twin infrastructure.

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EGU26 Poster QR Code: Poster , Abstract , Supplementary Material, CV
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