MULTIFUNCTIONAL LANDSCAPES

DIGITAL TRANSFORMATION

# Digital Twins applications: linking earth observation, models, and decision-making for Multifunctional Landscapes

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December, 2025

# Contents

# Abstract

Digital twins (DTs) are virtual replicas of physical systems that stay synchronized with real-world. In agriculture, water, and environmental management, DTs range from hybrid, periodically synchronized bio-physical models used for planning and forecasting, to full, continuously updated virtual systems supporting real-time operational decisions. This document presents empirical evidence of DTs applications to characterize where they are already creating value, why hybrid DTs dominate over full real-time twins, and how we can design fit-for-purpose implementations of DTs). It also summarizes recent evidence from operational deployments and reviews across water resources, agriculture, biodiversity, and climate services, serving as a starting point for exploring how the concept of DTs can be integrated into the science and practice of the Multifunctional Landscapes Science Program (MFL SP). We analyze enabling data infrastructures (e.g., Digital Earth Africa), emerging basin-scale twins (e.g., the Limpopo River Basin), and the combination with high-resolution climate twins (Destination Earth). It also proposes a practical taxonomy tailored to different characteristics, clarifies the distinction between hybrid and full DTs, and provides ready-to-use typologies by function, scale, data intensity, and decision context. We emphasize that hybrid DTs often deliver most of the value at lower cost where data are sparse and decisions are not time-critical, while full DTs add operational value when minutes-to-hours decisions change outcomes (e.g., pressurized water networks, floods, controlled environments). The taxonomy aligns with recent reviews and case studies and is intended for researchers and implementers in LMICs. We integrate findings from sectoral reviews, African community-scale pilots, water-utility cases, and digital foundations policy analyses. We outline priority use cases for MFL—transboundary allocation and drought management, smart irrigation, flood early warning, and biodiversity management—. The paper concludes with a research and learning agenda for development partners and policy makers.

## Acknowledgments

This work benefitted from discussions with colleagues in the CGIAR Digital Transformation Accelerator. Any errors are the authors’. The views expressed are those of the authors and do not necessarily reflect those of IFPRI, Alliance Bioversity International-CIAT or CGIAR.

# 1.Introduction

Across low- and middle-income countries, constrained water availability, climate variability, and ecosystem degradation increasingly challenge food, land, and water systems. Digital twins (DTs) offer a way to synchronize observations, models, and operations in a single environment to support timely, evidence-based decisions. Unlike static dashboards, DTs continuously ingest data, update system state, and enable interactive *what-if* scenario exploration from field to basin scales.

Digital twins are virtual constructs that mirror natural or engineered systems and remain synchronized through data connections to support monitoring, simulation, and decision-making (Heluany & Gkioulos, 2023). In natural-resource domains, canonical architectures encompass a physical entity, bi-directional communication, a virtual entity with modeling and simulation, data management, and services (Heluany & Gkioulos, 2023). In agriculture, water, and environmental systems, DTs are attractive because they can fuse physics-based models with sensor and remote-sensing data to improve planning, operations, and resilience. However, their value depends on foundational enablers—connectivity, compute, interoperable data, and skills—that remain uneven, particularly in LMICs, where policy interest aligns with broader digital public infrastructure (DPI) agendas emphasizing connectivity, compute, interoperable data, and skills (World Bank, 2024; World Bank, 2025).

The integration of DTs in rural contexts has been slower than in other fields due to the complexity of living systems (Pylianidis, et. al., 2021). Unlike manufacturing, where inanimate objects are used, agriculture faces the challenge of modeling plants and animals that have non-deterministic biological processes and dynamic behaviors that are difficult to predict. Early studies integrating digital twins in rural contexts were driven by the need to manage complex systems by providing control over physical entities. DTs facilitate the decoupling of physical flows from planning and control, allowing farmers to manage operations remotely based on real-time data and act when deviations are expected (Pylianidis, et. al., 2021). Key drivers to integrate DTs in rural contexts include the optimization of crop production to reduce time and costs, the advancement of environmental sustainability through efficient resource utilization, and the creation of safer working conditions (Pylianidis, et. al., 2021; Purcell, et. al., 2023). Furthermore, DTs act as a *virtual laboratory* where *what-if* simulations allow stakeholders to evaluate the impact of interventions and predict future states without the costs, risks, or disruptions associated with physical experimentation (Purcell, et. al., 2023).

While the concept of DTs has potential in agriculture their implementation is still in its early stages of maturity, characterized by a gap between research and commercial deployment. Although formal adoption began around 2017, most current agricultural applications remain at a conceptual or prototype level. Systematic reviews indicate that while some sectors like agricultural machinery and supply chains show higher maturity, many DTs are partially integrated *digital shadows* where data flows only from the physical entity to the virtual model, rather than being fully autonomous, bi-directional systems (Pylianidis, et. al., 2021; Purcell, et. al., 2023).

# 2. Definition and types of Digital Twins

The taxonomy organizes DTs choice across five dimensions—type, function, scale, data intensity, and decision context—providing a fit-for-purpose design scaffold for LMIC implementers. From static and calibrated models to hybrid, near-real-time hybrids, full, and autonomous twins, maturity and cost rise with data and control intensity. In practice, most fielded DTs in natural-resource domains are hybrid, with full twins concentrated where real-time control is intrinsically valuable.

We define hybrid DTs as process-based models (e.g., hydrology, hydraulics, crop growth) periodically fed by earth observation and high-resolution spatial data to support planning and forecasts, while full DTs are continuously synchronized, often bidirectionally combined systems for near-real-time control. In LMIC agriculture, water, and environmental management, hybrid twins dominate because telemetry is sparse, connectivity intermittent, and many decisions are seasonal or weekly rather than minute-to-minute. Full twins add value when rapid operational actions drive outcomes—e.g., flood routing, 24/7 pressurized water networks, or greenhouse control. A modular stack underpins both approaches: (i) Data layer (earth observation, sensors, administrative/utility data); (ii) Model layer (physics-based models, Machine Learning/Artificial Intelligence, emulators); (iii) Twin core (state synchronization, scenario engine, uncertainty); (iv) Experience layer (dashboards, APIs, copilots). Design principles emphasize open standards, FAIR assets, offline-first synchronization, and co-design with basin organizations, utilities, irrigation agencies, and farmer groups.

Hybrid DTs combine process-based models—e.g., crop growth, hydrology, and hydraulics—with intermittent observational inputs such as satellite indices, weather-station data, and episodic sensor uploads, which suit seasonal, spatially distributed decisions (Tagarakis et al., 2024; Zhang et al., 2025). They are designed to model or mimic bio-physical simulations and are ideal for seasonal decisions and spatially distributed systems where continuous telemetry is impractical. Full DTs require high-frequency telemetry and exact matched data input for minutes-to-hours decisions such as pressurized water networks, early flood warning, or controlled environments. They are continuously synchronized, often bidirectionally linked systems, supporting real-time monitoring, early warning, and automated or semi-automated control.

The main characterization of DTs model typology can be drawn along control intensity and data intensity, shown in Figure 1.

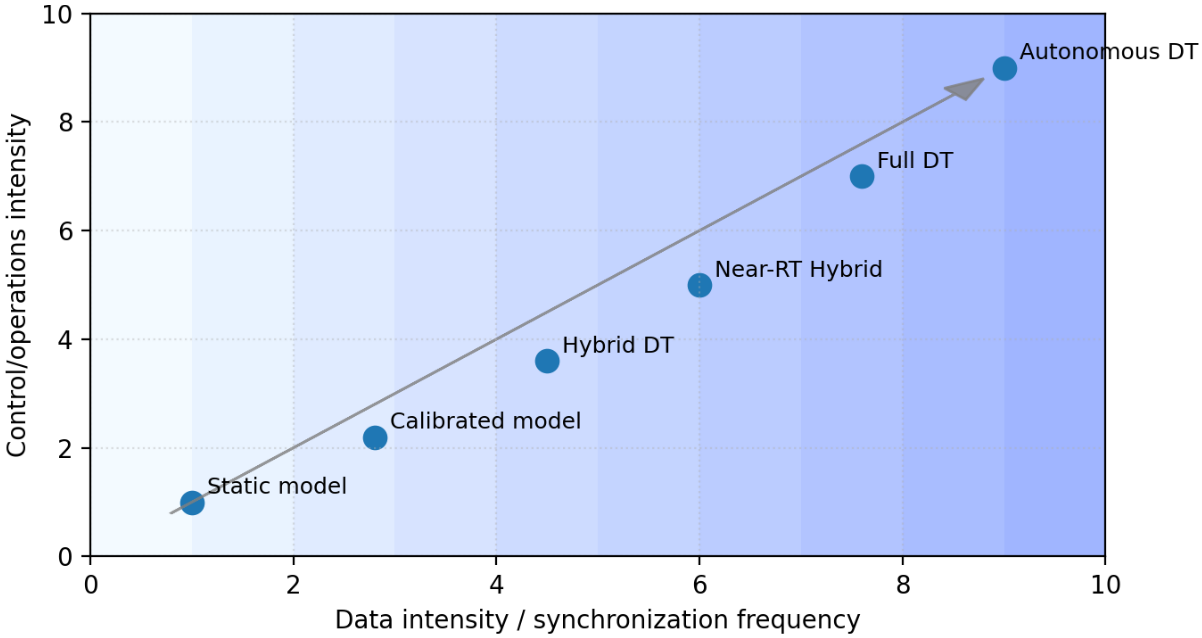

**Figure 1. Characterization of model types by data and control intensity**

Since DTs choice follows data intensity, most LMICs implementations sit at medium intensity (satellite + weather stations), favoring hybrid twins with periodic updates. Adding telemetry enables progressive upgrades toward full twins in critical operations. Other important characteristics are associated with each typology, summarized in **Error! Not a valid bookmark self-reference.**.

Hybrid and full twins complement each other across planning and operations. Evidence from water utilities and sector reviews indicates most fielded DTs in natural resource systems are hybrid, with full twins concentrated where real-time control matters (e.g., 24/7 water distribution). DT models are characterized by the use of different technological components and data technologies, listed in Table 2.

**Table 1. DTs typology**

| DT type | Data | Core Models | Purpose | Temporal Resolution | Use Cases | Maturity |
|---|---|---|---|---|---|---|
| **Static digital model** | None | Physics-/empirical | Baseline analysis | One-off | Watershed planning; land-use scenarios | High |
| **Calibrated model** | One-time / infrequent | Process-based | Improved accuracy | Annual | Crop yield potential estimation | High |
| **Hybrid digital twin** | Periodic, unidirectional | Process + ML/rules | Scenario analysis; forecasting | Daily → seasonal | Irrigation planning; drought analysis | Medium–high |
| **Near-real-time hybrid** | Frequent, unidirectional | Physics + analytics | Early warning | Hourly → daily | Flood forecasting; soil-moisture stress | Medium |
| **Full digital twin** | Continuous, bidirectional | Integrated cyber-physical | Real-time operations | Minutes → sub-hourly | Smart irrigation; pressurized water | Low–medium |
| **Autonomous twin** | Continuous + control | AI + control logic | Automated management | Seconds → minutes | Controlled environments | Low |

### Table 2. Digital Twin technology components

| Technology | Description | Example application |
|---|---|---|
| **Sensor Technologies** | Devices collecting real-time data on crops, soil, and environment | Soil moisture sensors, weather stations |
| **IoT Technologies** | Networked devices and sensors for real-time data collection and automation | Smart irrigation, livestock tracking |
| **Artificial Intelligence** | Algorithms analyzing data to provide predictions and recommendations | Disease prediction, yield optimization |
| **Data Analytics** | Tools and methods for extracting insights from agricultural data | Trend analysis, anomaly detection, decision support |
| **Data Sources** | Origins of agricultural data (sensors, satellites, UAVs, systems) | Crop monitoring, yield prediction |

DTs for descriptive purposes can be delivered by both hybrid and full twins (with different refresh rates) (see Table 3). Predictive and exploratory roles align with hybrid twins that leverage models fed by satellite and sparse sensors. Prescriptive and adaptive roles require high-frequency synchronization and, often, control loops—hallmarks of full twins.

### Table 3. Functional typology

| Function | Description | DTs type |
|---|---|---|
| **Descriptive** | Mirrors current system state | Hybrid / Full |
| **Predictive** | Forecasts system evolution | Hybrid |
| **Prescriptive** | Recommends actions | Full |
| **Adaptive** | Updates strategies dynamically | Full |
| **Exploratory** | Tests counterfactual scenarios | Hybrid |

Table 4 shows that, as spatial scale increases, hybrid DTs become more feasible due to satellite coverage and the high cost of dense telemetry. Full twins are practical at small, sensor-dense scales and in select, highly instrumented subsystems within larger systems.

### Table 4. DTs type by scale

| Scale | Examples | DTs type |
|---|---|---|
| **Plot / greenhouse** | Soil moisture; micro-climate | Full |
| **Farm** | Rotations; irrigation scheduling | Hybrid |
| **Scheme / command area** | Canal networks; pumping | Hybrid → Full |
| **Watershed / basin** | Hydrology; allocation | Hybrid |
| **Landscape / ecosystem** | Land-use; erosion; degradation | Hybrid |

Decision time horizon is the strongest predictor of DTs type (Table 5). Hybrid twins support anticipatory strategic and seasonal decisions; full twins are required for rapid operational and emergency decisions.

### Table 5. DTs type by scope

| Context | Horizon | DTs type |
|---|---|---|
| **Strategic planning** | Years | Hybrid |
| **Climate adaptation** | Seasons | Hybrid |
| **Resource allocation** | Weeks–months | Hybrid |
| **Operational control** | Hours–days | Full |
| **Emergency response** | Minutes–hours | Full |

# 3.DTs applications

This synthesis draws on reviews and gray literature on DTs in agriculture and water, case documentation from Southern Africa’s Limpopo basin, and program notes. We triangulate reported outcomes with independent satellite services (e.g., evapotranspiration products) and summarize maturity, value propositions, and constraints.

Systematic reviews document rapid growth in agricultural and forestry DT applications since 2018 but also show that most fielded systems are hybrid with partial data combination, reflecting data and governance constraints typical in LMICs. (Tagarakis et al., 2024; Zhang et al., 2025). Emerging methods embed reinforcement learning within DTs loops for irrigation and greenhouse control, indicating potential efficiency gains as sensing and control mature in LMICs (Goldenits et al., 2024).

Water utilities have demonstrated measurable gains from DT-guided network re-engineering in India: reduced non-revenue water, and lower emissions via optimized pumping—enabled by a connected hydraulic twin and scenario testing.

Operational case work demonstrates engineering-consistent gains from hydraulic twins—lower non-revenue water, energy savings via optimized pumping, and faster design cycles—particularly where telemetry and staff training are in place. These strategies are transferable to African utilities confronting chronic water shortage and intermittent supply.

At watershed and landscape scales, DTs typically operate as hybrid systems, periodically fed by gauges and satellite data to support allocation, drought planning, and land-degradation strategies (Mazzetto, 2024). Urban DT briefs and reviews stress governance, standards, and staged deployment from single-system to multi-system integration—issues central to rapidly urbanizing African cities (UNDP, 2025; Mazzetto, 2024). Table 6 reports some examples of DT applications.

**Table 6. DT applications**

| Project | Country/ Region | Theme | Notes |
|---|---|---|---|
| **Smart Farming Digital Twin** | Finland | Prototype farm DT; real-time field infrastructure; Python package (TwinYields) | https://www.luke.fi/en/projects/twinyields ; https://twinyields.github.io/intro.html |
| **Mandarins Digital Twin** | South Korea | Agricultural DT using mandarins as a model crop | https://www.nature.com/articles/s41467-024-45725-x |
| **Landscape DT for area-wide IPM** | Australia | Prototype multi-actor landscape-scale DT for IPM/AWM; pathway to real-world application | https://research.csiro.au/agroecology/projects/digital-twin-of-an-agricultural-landscape-for-area-wide-integrated-pest-management/ |
| **Biodiversity Digital Twin (BioDT)** | EU | Prototype biodiversity DT to push predictive understanding; HPC/AI & FAIR data | https://biodt.eu/ |
| **Urban community planning** | Ghana | Hybrid | Twin tracked micro e-commerce; small-n limits |
| **Smart cities & infrastructure** | Pan-Africa (policy/brief) | Hybrid → Full | Governance/standards/DPI emphasized |
| **Manufacturing readiness** | South Africa & SSA | Hybrid → Full | Skills and interoperability key |

| | | | |
|---|---|---|---|
| **Limpopo River Basin** | Botswana,<br>Mozambique,<br>South Africa,<br>Zimbabwe | Real-time, data-driven integrated monitoring and modelling (LIMIS) with a basin DT | https://www.cgiar.org/news-events/news/digital-twin-handover-limpopo/ |

Transboundary water: The Limpopo River Basin DT (Garcia Andarcia et al. 2024) integrates a near real-time hydrological model, seasonal forecasts, and reservoir monitoring within an interactive portal being trialed by the Limpopo Watercourse Commission.

*Box 1. The Limpopo River Basin Digital Twin: Co-Designing a Transboundary Decision Environment*

Partners developed a prototype basin twin for near real-time monitoring, forecasting, and scenario testing, including environmental flows and drought monitoring. The platform is being refined based on LIMCOM feedback and data-sharing arrangements among neighboring states. Lessons include the importance of institutional ownership, phased delivery aligned to user priorities, and clear data-governance protocols.

Continental backbones: Digital Earth Africa's Waterbodies Monitoring Service (2024) identifies over 700,000 water bodies across Africa, updates weekly, and exposes an API—reducing data-engineering costs for basin implementers.

Irrigation and water-use efficiency: Reviews indicate that DTs, combined with machine learning, can support optimization of irrigation scheduling and reduce water use without compromising yields; robust satellite-based evapotranspiration datasets (e.g., OpenET) have been independently validated against flux towers, strengthening DTa inputs.

Water and wastewater utilities: Sectoral reviews report DT-enabled gains in predictive maintenance, process optimization, and downtime reduction, while noting challenges in data interoperability, cybersecurity, and financing operation and management of digital infrastructure.

Ghana community-scale DTs are open-access case integrating aerial mapping, built-environment inventories, and micro-surveys to support a micro e-commerce intervention; treated firms increased online transactions (Cordes et al., 2024). City-scale urban DT briefs and reviews stress platform governance, interoperability, and staged deployments—from single-system to multi-system integration—as financing and data governance mature (UNDP, 2025; Mazzetto, 2024). For manufacturing: the African experience highlights Internet of Things–DTs integration, standards, and skills development to avoid pilot lock-in and achieve cross-organizational gains (Onu et al., 2024; Mezgebe et al., 2025). On digital foundations, the World Bank reports emphasize the "four Cs" (connectivity, compute, context/data, competency/skills) to close the Artificial Intelligence/digital divide and enable scalable, equitable DTs (World Bank, 2024; World Bank, 2025; UNDP, 2025).

So far, applications have followed a hybrid model, although they have been designed for upgrade paths; exploiting existing telemetry, choosing open standards, bundling with DPI investments, and centering equity in monitoring and governance. Evaluation designs lied on stepped-wedge cluster randomized trial design to implement and test a water-related intervention in different district metered areas, cluster randomization for irrigation scheduling, difference-in-differences for corridor twins, and full cost accounting (UNDP, 2025).

Research prioritized randomized or quasi-experimental rollouts, lifecycle cost and full cost accounting, interoperability and resilience benchmarks under intermittent connectivity, scalable data combination with sparse sensing, and participatory governance and ethics for community-scale twins (Tagarakis et al., 2024; UNDP, 2025). Africa-specific DT applications remain limited, and the existing applications are based on pilots or high-income contexts. Future work should strengthen independent evaluation, long-term sustainability, and distributional analyses (Mazzetto, 2024; Cordes et al., 2024).

Hybrid DTs offer an immediately practical choice for agriculture, water, and environmental management across LMICs, with full twins adding operational advantages where real-time decisions matter. Interoperable architectures, operator-centric validation, inclusive governance, and rigorous evaluation—backed by investments—are decisive for moving from promising pilots to equitable, system-level gains. Basin allocation and drought management integrate satellite (surface water extent, evapotranspiration), streamflow and groundwater telemetry, and hydrologic models to quantify trade-offs among irrigation, urban supply, and ecosystems; stress-test rules under climate storylines. Smart irrigation for smallholders embeds soil moisture, crop status, and weather forecasts; apply rule-based or reinforcement-learning controllers; deliver advisories through low-bandwidth channels (USSD/WhatsApp). Flood early warning and adaptation planning build compound-flood twins linking rainfall runoff, river hydraulics, storm surge, and exposure; evaluate nature-based and gray interventions. Biodiversity and ecosystem services use biodiversity DTs to explore habitat/species responses to land-use and climate change and link to agricultural DTs for pollination/pest control trade-offs.

# 4. Conclusion and implications for Multifunctional Landscapes

In agriculture, water, and environmental management, hybrid DTs often provide the optimal balance between value and feasibility, while full twins add operational control where real-time decisions materially change outcomes. The taxonomy presented here offers a practical guide for classifying, designing, and evaluating DTs efforts in LMICs contexts and can be paired with rigorous impact evaluation as systems mature.

Complexity of living systems represents the most significant challenge for agricultural digital twins compared to their industrial counterparts. Unlike the manufacturing sectors, which deal with predictable, human-made components, agriculture must model biological entities—such as plants and animals—that exhibit non-deterministic behaviors and interact with highly dynamic environmental factors like weather and soil health. This biological variability makes achieving high-fidelity synchronization between the physical and virtual worlds exceptionally difficult, requiring advanced data-driven modeling and artificial intelligence to capture the nuances of a living *physical twin*.

Digital twins offer a *virtual laboratory* for environmental sustainability, yet their implementation must be guided by robust social and ethical frameworks to avoid negative systemic impacts. By allowing farmers to perform *what-if* simulations, this technology can drastically reduce waste, optimize resource use, and predict the impact of climate change without the risks of physical experimentation. However, researchers warn that if not developed in an open and equitable manner, these systems could lead to market centralization and wealth inequality, where only large-scale, commercial farmers can afford the high investment and technical expertise required, potentially displacing smaller family-run farms and traditional industry knowledge

There are several recommendations for DT applications in Multifunctional Landscape: -starting with a small scope and existing data streams, then expanding data requirements and inputs:

- Using open standards to reduce vendor lock-in and planning for model validation/maintenance.
- Prioritizing foundational enablers—connectivity, computation, data interoperability, and skills—within broader digital public infrastructure programs.
- Prioritizing connectivity (reliable electricity + internet), compute (affordable cloud or sovereign data centers), context (locally relevant datasets and standards), and competency (skills) alongside DT pilots (World Bank, 2024; World Bank, 2025)
- Starting with financing small, bounded twins that leverage existing telemetry and satellite data; adopting open, interoperable architectures, data models and APIs across utilities and city departments to prevent vendor lock-in and facilitate replication across districts and countries.
- Embedding equity and safeguards by tracking distributional outcomes (service reliability in poorer wards, smallholder inclusion).
- Using results-based financing or sequential funding disbursement linked to verified key performance indicators.

- Promoting regional knowledge platforms and peer learning on standards, benchmarks, and reference implementations to reduce duplication and cost.
- Maximizing the economics sustainability and minimize the governance failure of the model implements.

All these key factors would ensure DTs deliver value to Multifunctional Landscapes, and they should be complemented with lesson learned from research on: 1. evaluating impact of DT-enabled irrigation on water productivity, equity, and gender outcomes; 2. modeling risk governance for public-sector twins; 3. designing data combination methods for soil moisture and stream flows in regional basins; 4. studying socio-technical adoption and change management; 5. designing interoperability between climate/biodiversity DTs and basin/agricultural twins for landscape trade-offs.
Public-sector DTs require transparent documentation of data rights and privacy, uncertainty quantification, assurance processes for models, and clear lines of accountability for decision use. Procurement should prioritize open standards and portability; cybersecurity and continuity-of-operations plans are essential.

Finally, DTs can increase decision-making efficiency, improve cross-border coordination, and enable proactive resource management. However, piloting and scaling responsibly in countries of interest to Multifunctional Landscapes hinges on co-design with institutions, investment in data and human capital, and interoperable, open architectures that keep annual costs manageable.

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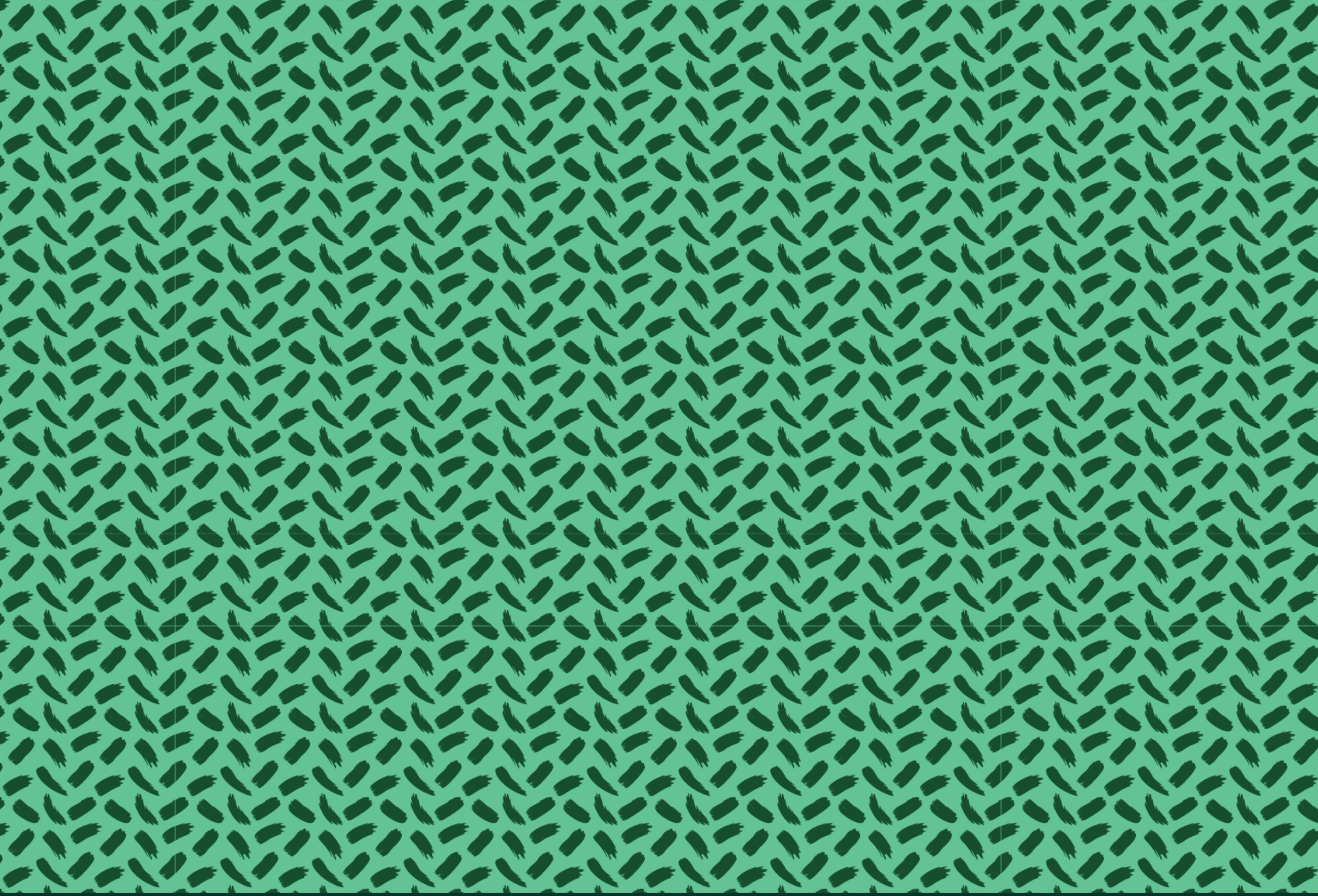

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