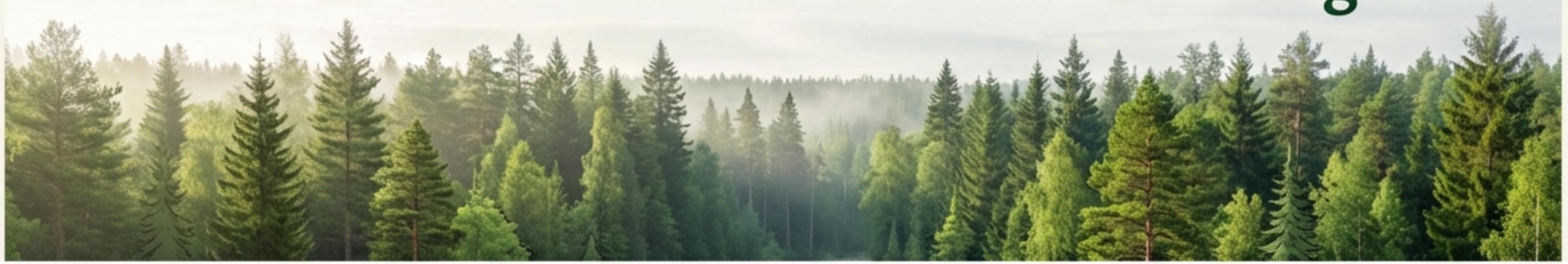


# The Ground Beneath the Trees: Can Forest Growth Predict Road Strength?



An investigative look at using airborne data to forecast forest road trafficability and bearing capacity.

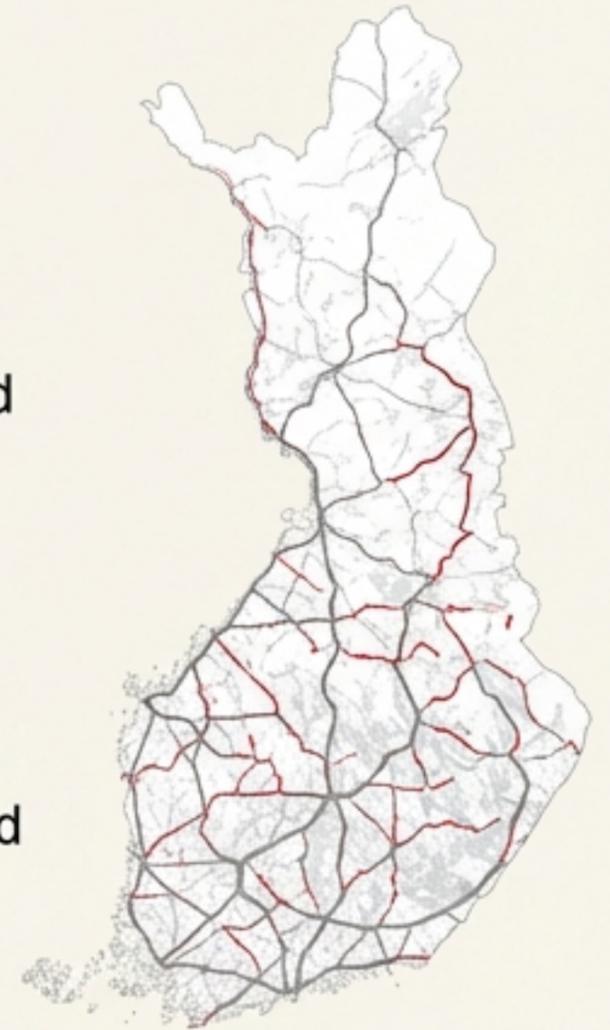
# Why do forest roads fail, and what does it cost us?



Forest roads are the critical link for year-round timber flow, but many have low bearing capacity, especially during thaw seasons, leading to costly bottlenecks.

Finland's network is a prime example: ~160,000 km of forest roads, mostly built between 1960-1990, are now reaching the end of their planned 20-30 year structural life.

(Source: Karjalainen et al., 2025; Uotila & Viitala, 2000)



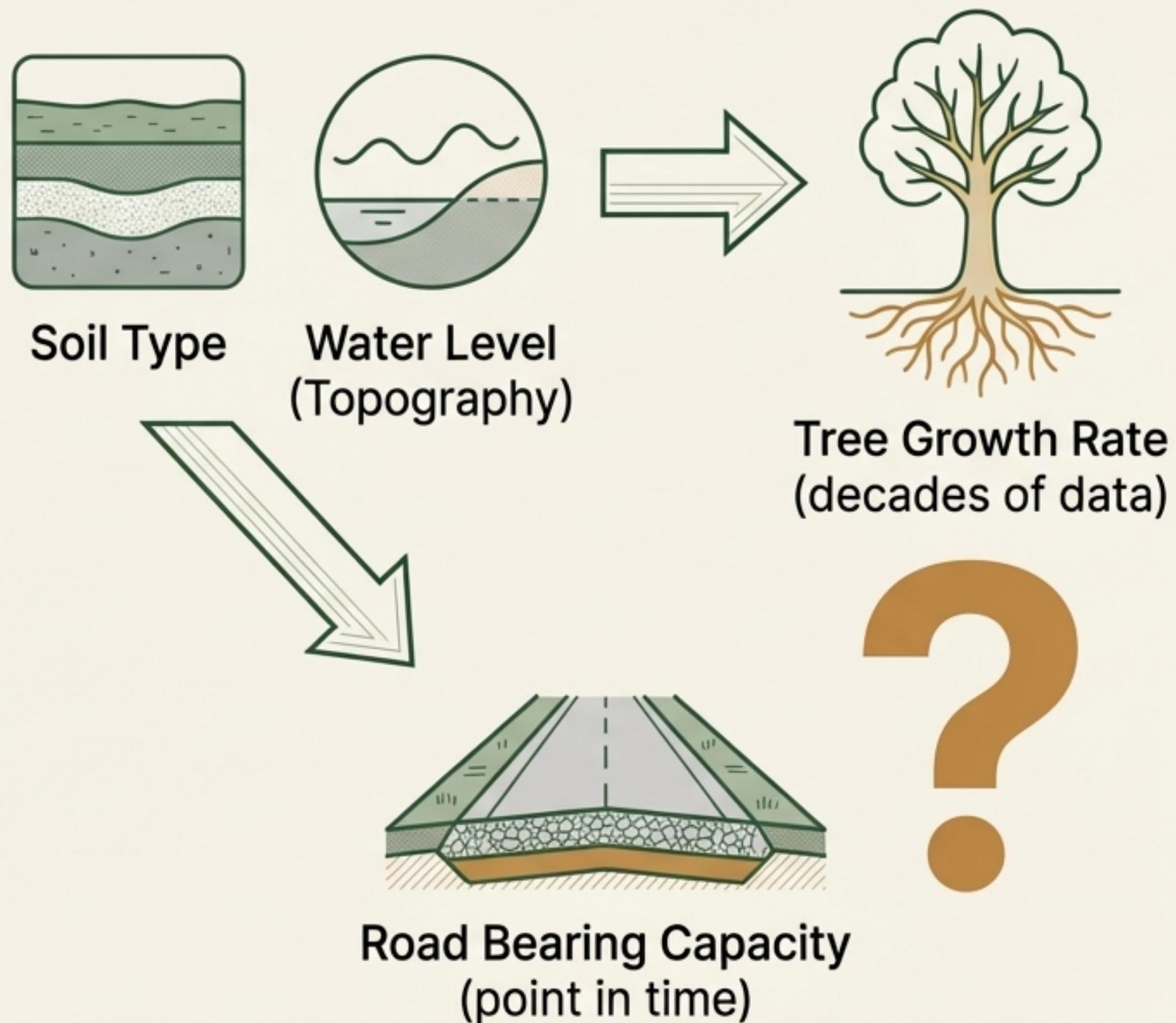
**Seasonal transport inefficiencies due to road failures cost the Finnish forest industry an estimated €70 million per year.**

(Source: Venäläinen et al., 2018, cited in Karjalainen et al., 2025)

**The Core Challenge:** Manually assessing road conditions is slow, expensive, and impractical for an entire network. We need a way to remotely predict failure points before they happen.

# Could tree growth be a natural indicator of soil strength?

- 1. Roads are built from local soil:**  
Forest roads are constructed using materials excavated from the immediate surroundings (the adjacent stands). The roadbed *is* the local soil.
- 2. Soil conditions dictate tree growth:**  
The height and volume growth of trees are directly influenced by the underlying soil type, topography, and moisture conditions.
- 3. Therefore:** Tree growth patterns, which integrate these conditions over decades, might reflect the very soil properties that determine a road's bearing capacity.

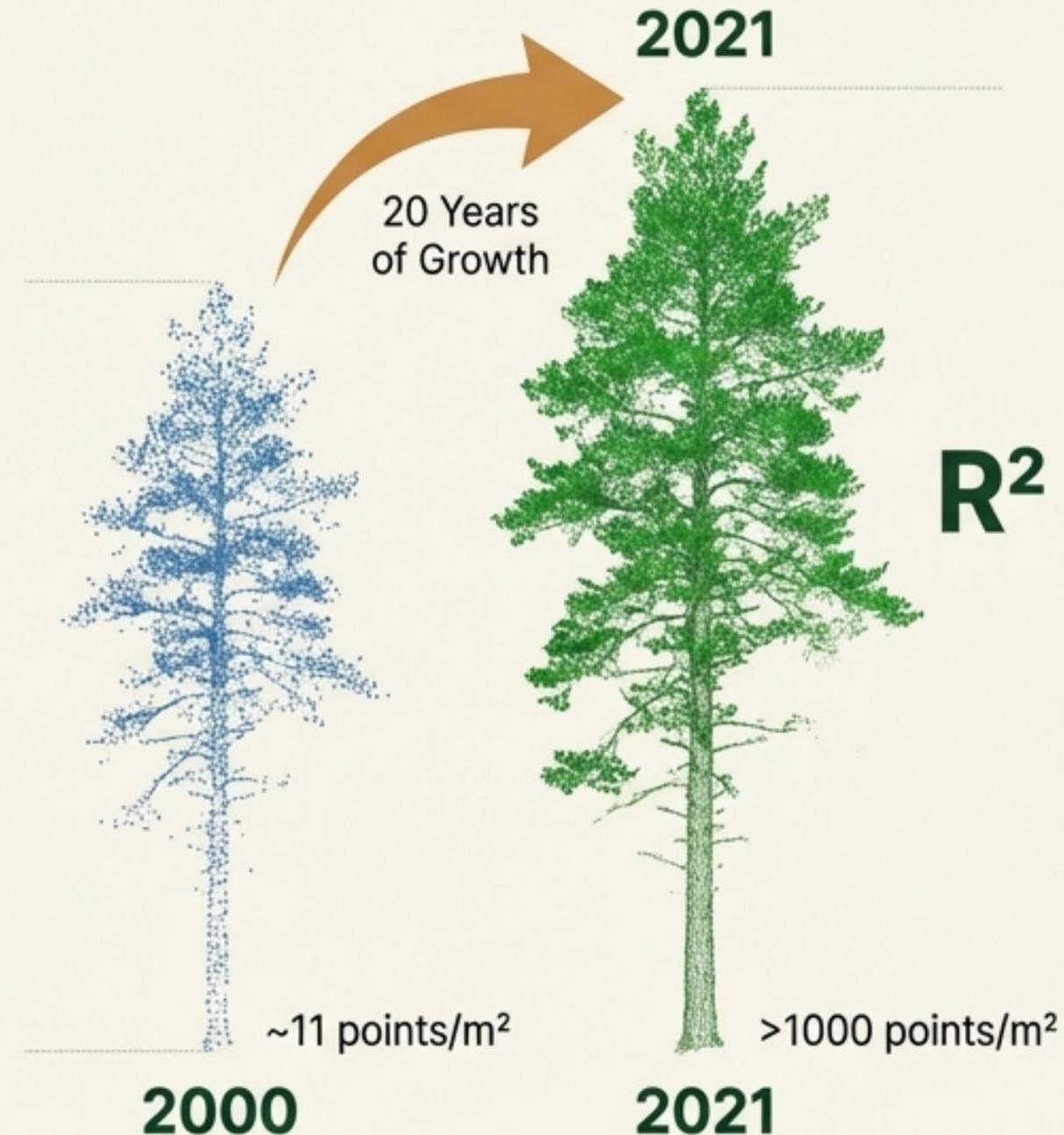


# From 30,000 feet to individual trees: The power of multi-temporal LiDAR.

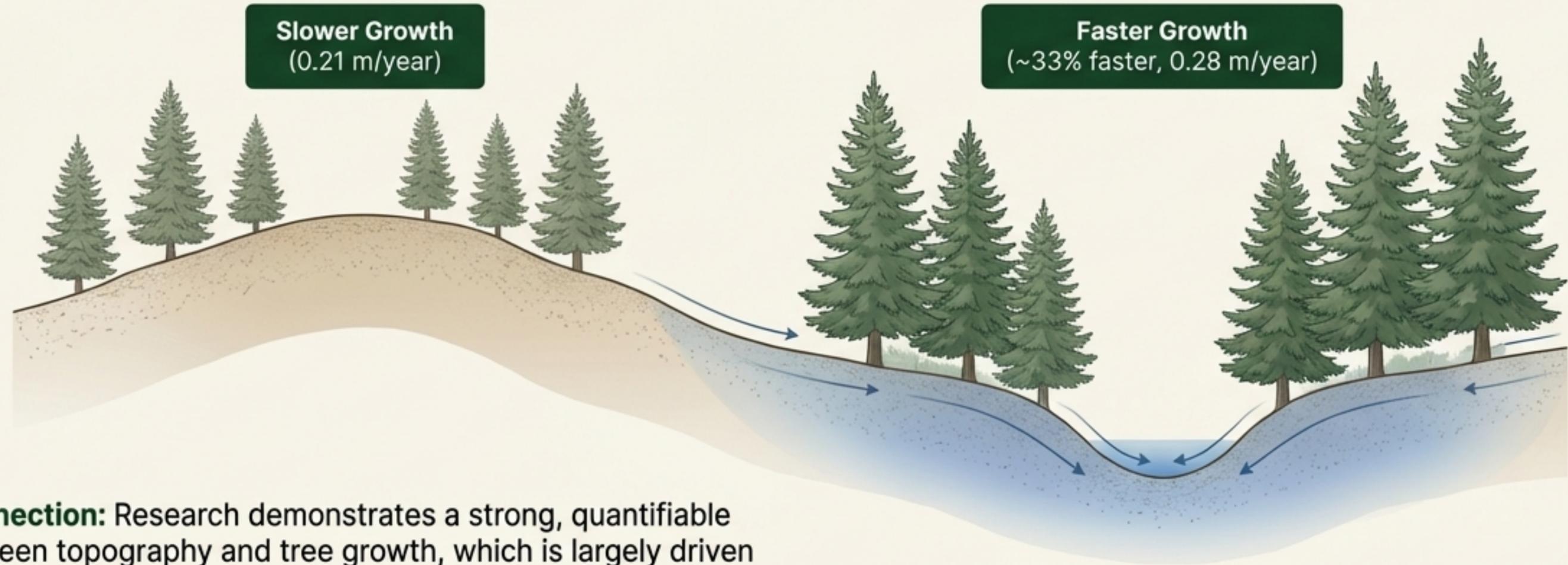
**Core Statement:** Yes, we can reliably measure long-term tree growth from the air. A 20-year study in Finland (Kalkkinen test site) proved the concept. (Source: Soininen et al., 2022)

**The Technology Explained:** Bitemporal Airborne Laser Scanning (ALS/LiDAR) compares 3D point clouds of the same forest from two different points in time (e.g., 2000 and 2021). By linking individual trees between the two datasets, we can directly measure their growth.

**The Evidence (Key Statistic Callout):** The study achieved remarkable accuracy for individual tree height growth, with a coefficient of determination of  $R^2 = 0.90$ . Moderate accuracy was also achieved for DBH ( $R^2 = 0.48$ ) and stem volume ( $R^2 = 0.45$ ) growth. (Source: Soininen et al., 2022)



# How topography shapes both forests and water flow.



**The Connection:** Research demonstrates a strong, quantifiable link between topography and tree growth, which is largely driven by soil moisture availability.

**Evidence from the Field:** A study in Slovenia's karst landscapes found significant differences in silver fir height growth based on topographic position. (Source: Kobal & Hladnik, 2021)

- Trees in sinkholes (wetter, deeper soil) grew ~33% faster on average (0.28 m/year).
- Trees on ridges (drier, shallower soil) grew slower (0.21 m/year).

**The Broader Implication:** The same LiDAR-derived Digital Elevation Models (DEMs) that reveal these topographic positions are also used to model soil moisture through hydrological indices like the **Depth-to-Water (DTW) index**. (Source: Murphy et al., 2007; Karjalainen et al., 2025)

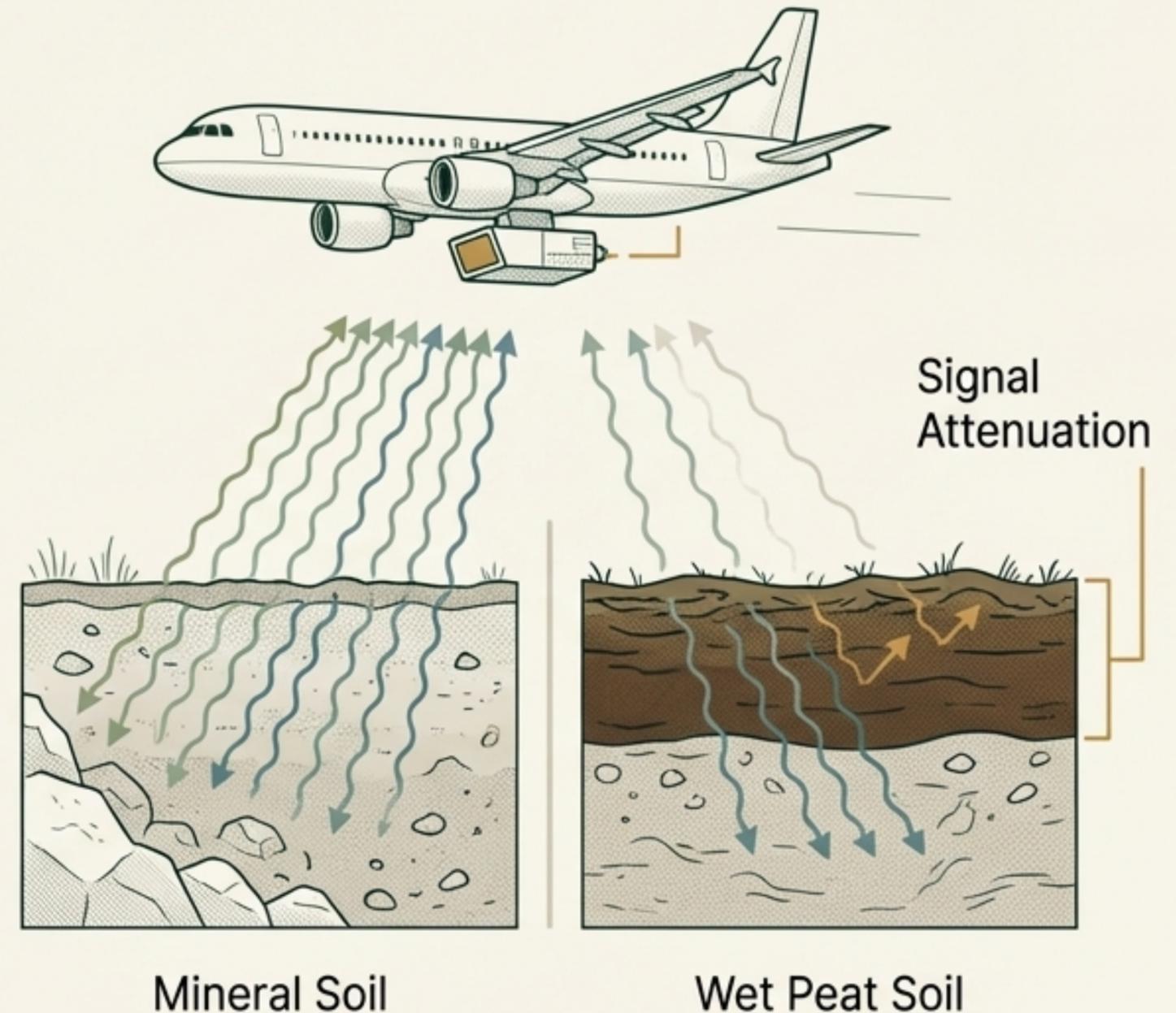
# Can we bypass the trees and measure soil properties from the air?

**The Technology:** Airborne Gamma-Ray Spectrometry (Radiometrics) offers a direct way to map near-surface soil properties.

## The Principle:

- The sensor measures naturally occurring gamma radiation emitted by minerals (K, U, Th) in the top ~40-60 cm soil. (Source: O'Leary et al., 2025; IAEA, 2003)
- High soil moisture and organic matter (like in peat soils) strongly attenuate (block) these gamma rays.
- Therefore, a low gamma-ray signal indicates wet, organic-rich, and potentially weak soils.

**The Proof:** Studies in Ireland successfully used this method with machine learning to delineate peat soils and their transition zones, validated with extensive ground sampling. (Source: O'Leary et al., 2025)



# A direct attempt to predict road bearing capacity from the air.

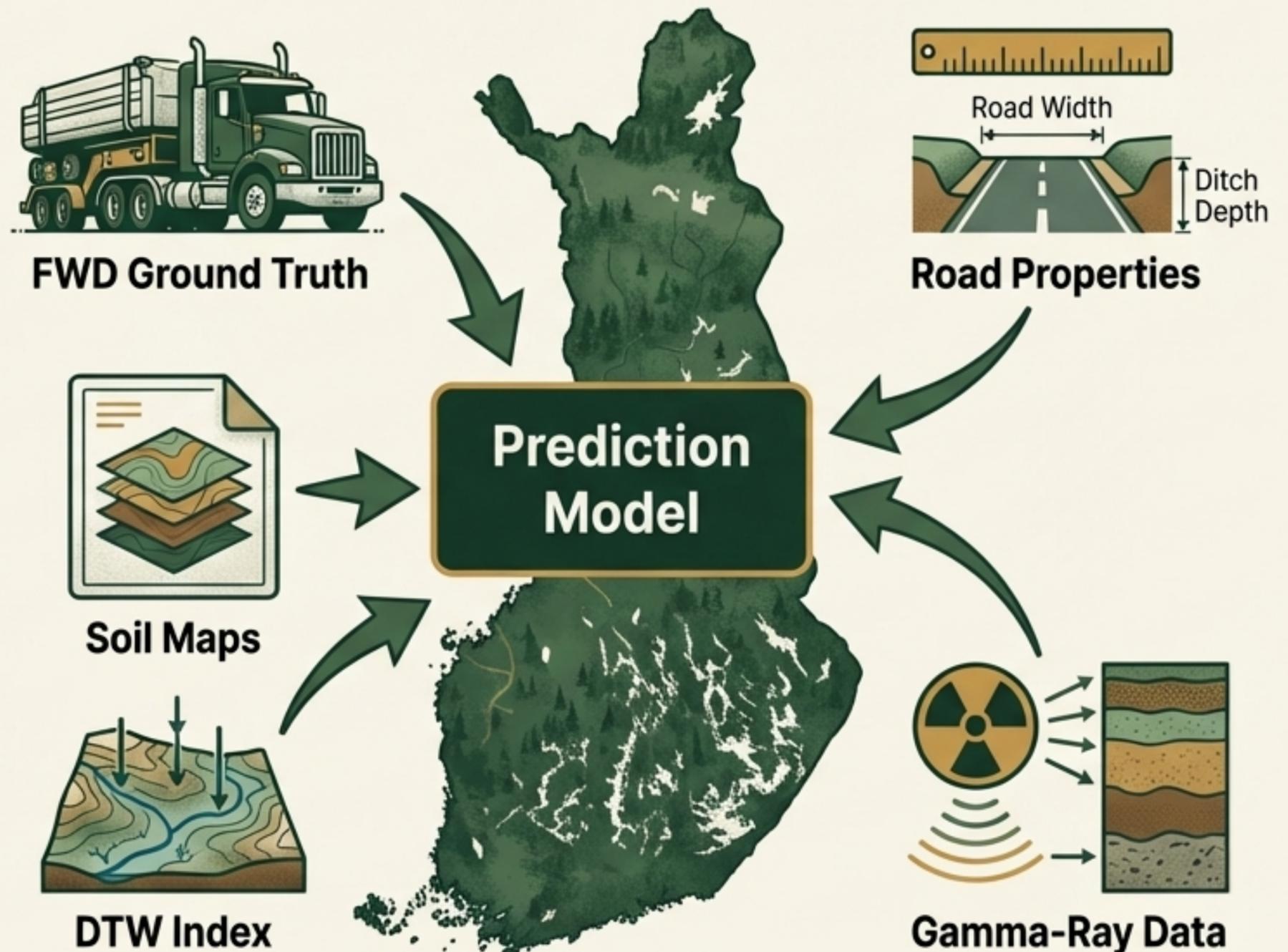
**The Study:** A 2024 study in Finland aimed to predict bearing capacity on 111 forest road plots. (Source: Karjalainen et al., 2025)

**Ground Truth Measurement:** On-site bearing capacity was measured with a **Falling Weight Deflectometer (FWD)**, which provides a quantitative value of surface stiffness (in  $\text{MN}/\text{m}^2$ ).

## **Predictor Variables (The Airborne & GIS Data):**

The model used a combination of remotely-sensed and readily available data to predict the FWD measurements:

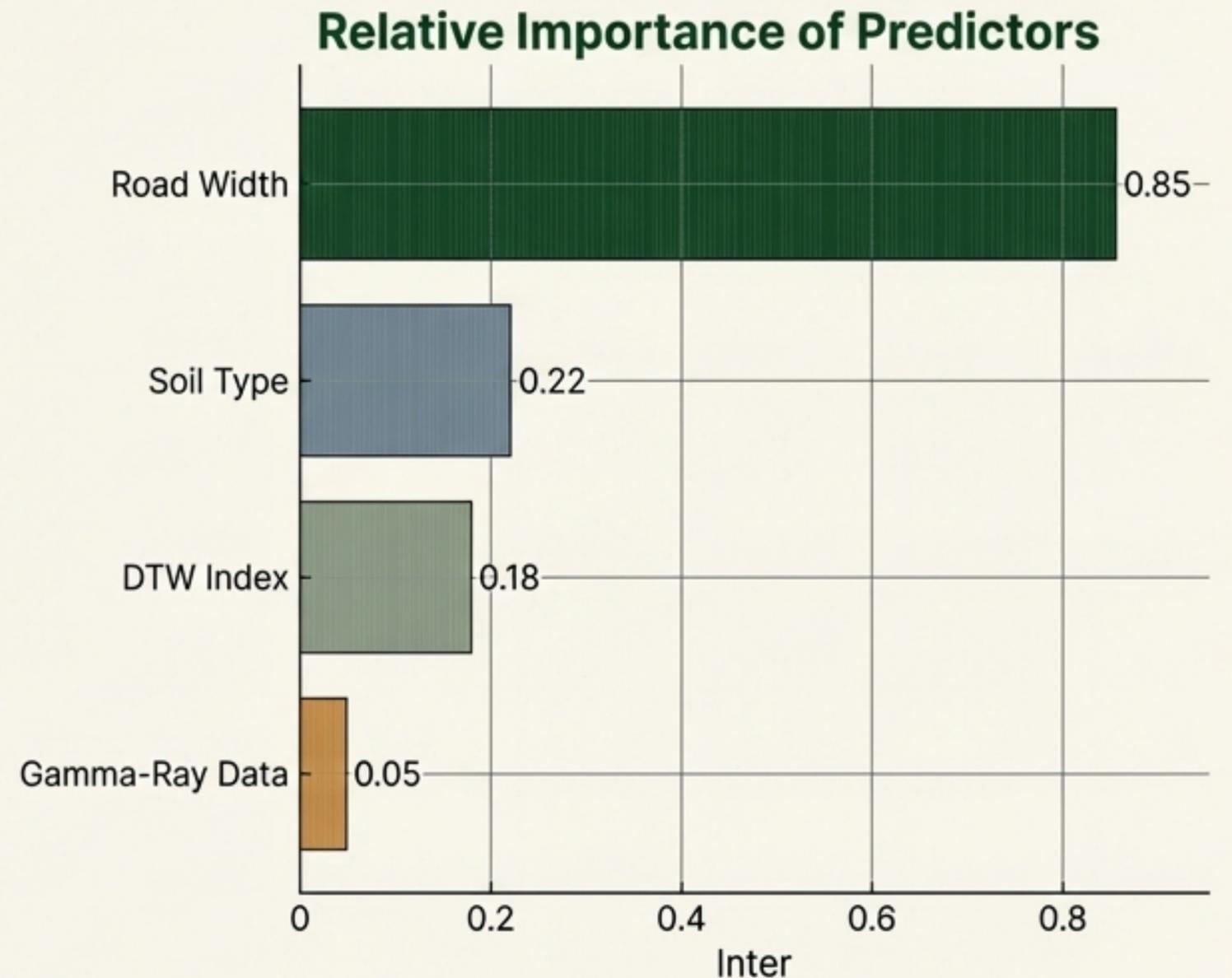
- **Road Properties:** Road width, ditch depth
- **Surrounding Terrain Info:**
  - Existing soil maps.
  - Depth-to-Water (DTW) index from a 2m DEM.
  - Airborne Gamma-Ray spectrometry data.



# What really predicts a weak road? It wasn't the environmental proxies.

- The Dominant Factor: The single most influential predictor of bearing capacity was **road width**. Wider roads consistently showed higher bearing capacity. (Source: Karjalainen et al., 2025)
- The Supporting Cast: Environmental proxies (Soil Type, DTW) provided some information, but their predictive power was limited and often not statistically significant in the final models.
- The Surprise: **Airborne gamma-ray data added very little predictive value** in the final models. (Source: Karjalainen et al., 2025)

**The Overall Result:** The models were only moderately successful, explaining just **25-34% of the variance ( $R^2$ )** in bearing capacity measurements. (Source: Karjalainen et al., 2025, Table 4)

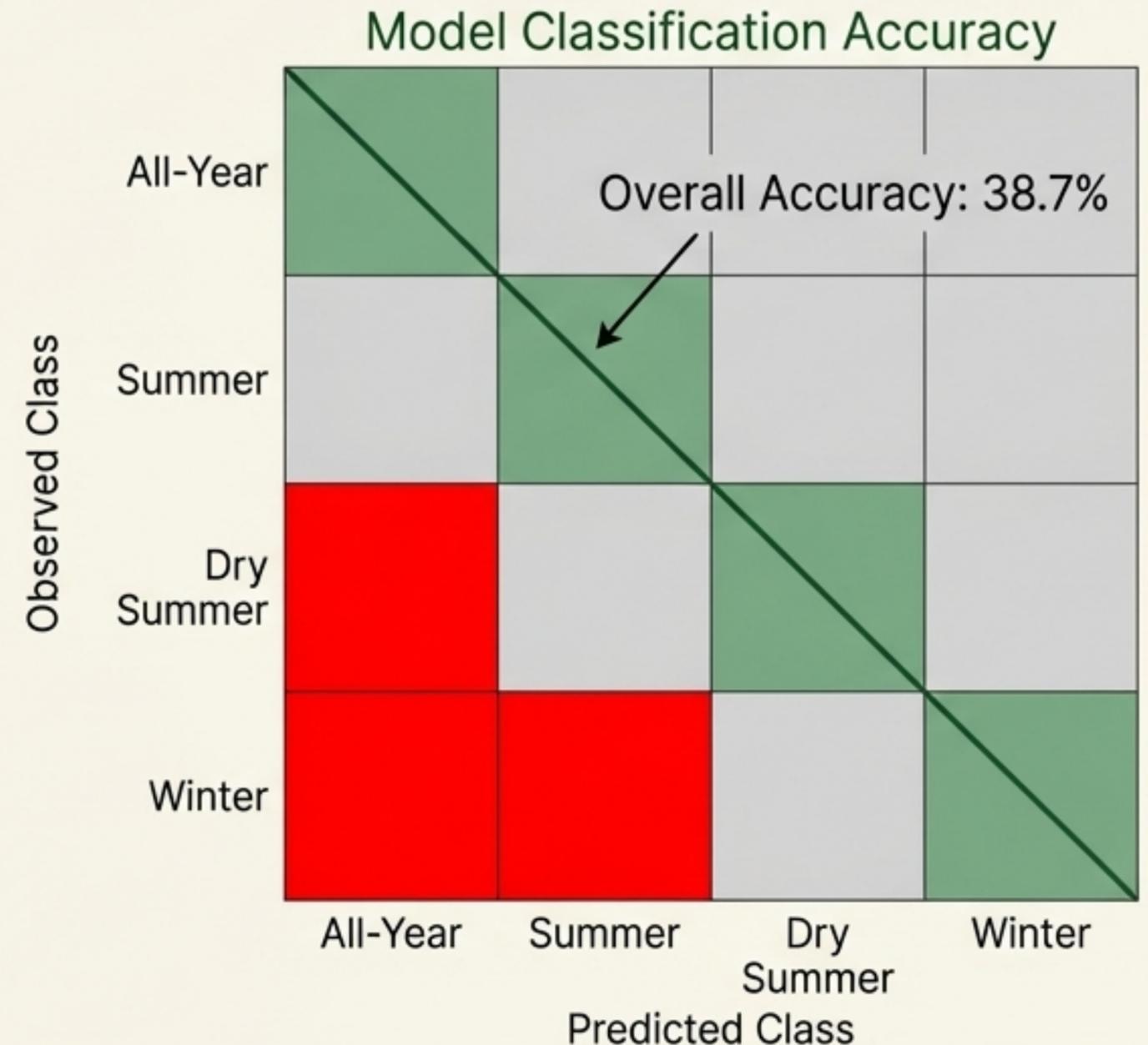


# The challenge of classifying 'Go' vs. 'No-Go'.

**The Practical Test:** The predicted bearing capacity values (MN/m<sup>2</sup>) were converted into practical trafficability classes used by planners (e.g., "All-Year," "Summer," "Winter Only").

**The Sobering Result:** The best model's ability to correctly classify a road's usability was only **38.7%**. (Source: Karjalainen et al., 2025, Table 5)

**The Critical Failure:** The model struggled most with the weakest roads. It had a dangerous tendency to overestimate the strength of low-capacity roads—classifying a "Winter Only" road as "Summer" or "All-Year." This is the most critical error for preventing road damage and logistical disruption.



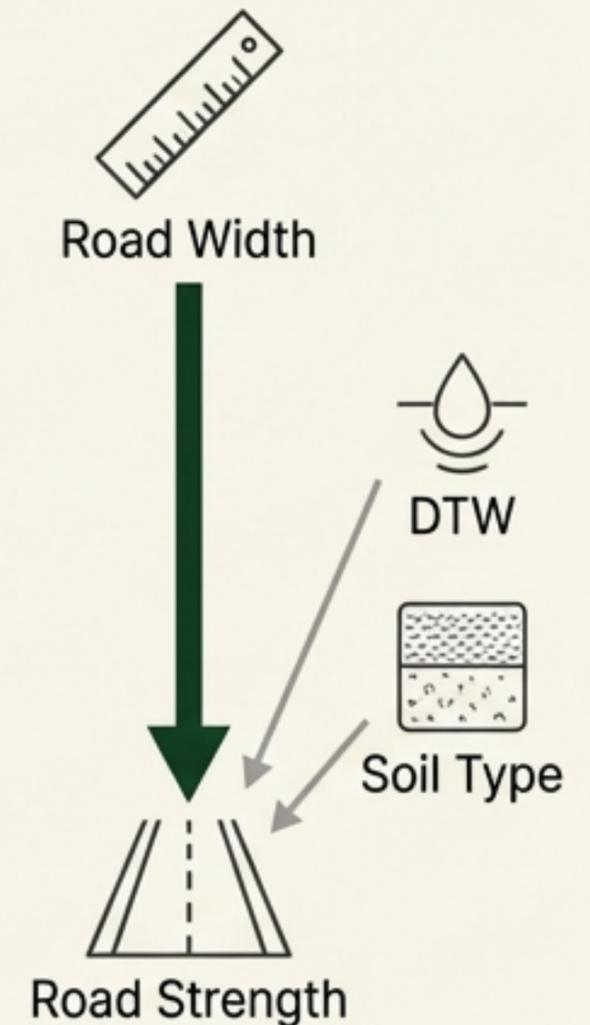
# Connecting the pieces of the puzzle: What have we learned?

- **Confirmed:** We CAN measure tree growth remotely with high accuracy. Multi-temporal LiDAR is a proven technology for this purpose. (Source: Soininen et al., 2022)
- **Confirmed:** Tree growth IS scientifically linked to topography and soil moisture—factors that are directly relevant to soil mechanics and bearing capacity. (Source: Kobal & Hladnik, 2021)
- **Complication:** BUT, in a direct field test, the predictive power of environmental proxies (DTW, soil type, radiometrics) was weak. It was overshadowed by the road's own structural properties, especially its width. (Source: Karjalainen et al., 2025)
- **Conclusion:** The initial, elegant hypothesis is complicated by the messy reality of road construction and performance. The road's design and history may currently have a stronger influence than the natural environment it passes through.

## Hypothesized Link



## Observed Reality



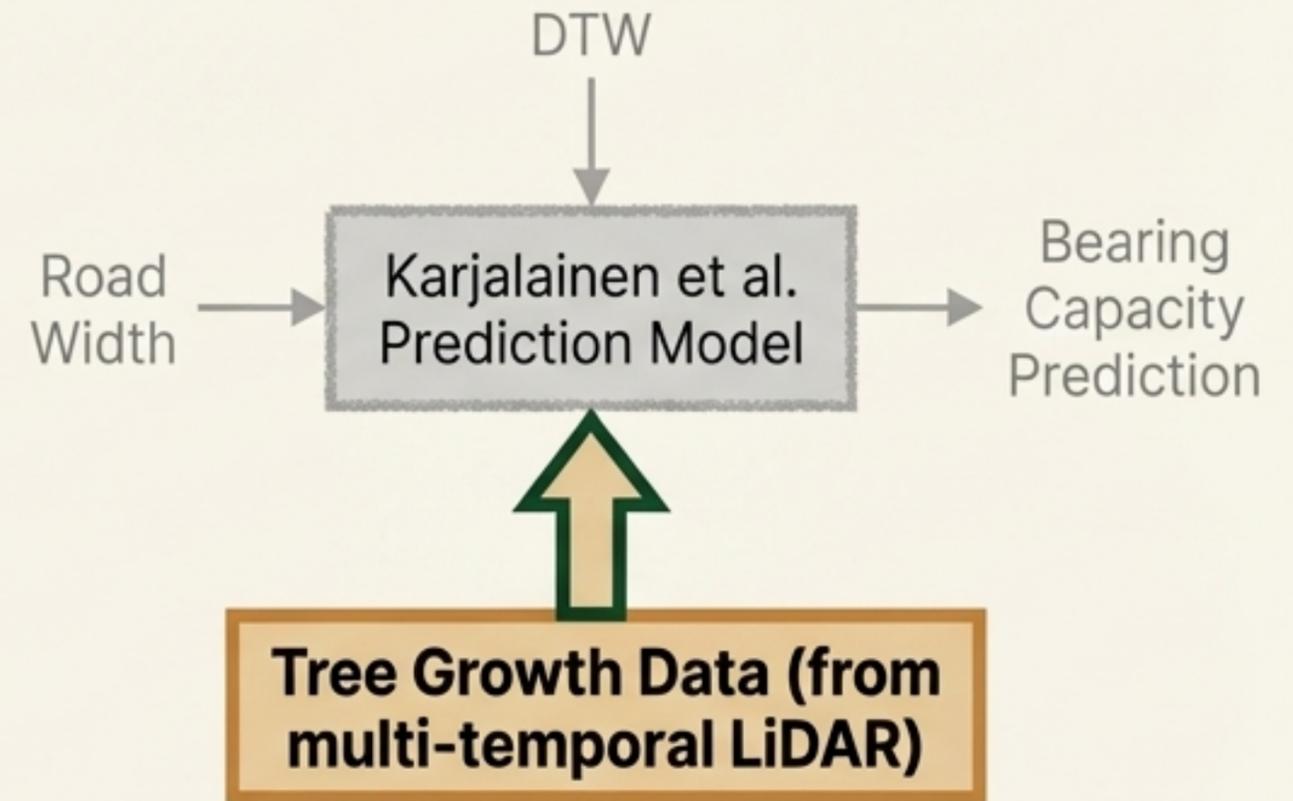
# The missing link in our knowledge.

**The Crucial Observation:** The Finnish study (Karjalainen et al.) tested environmental proxies like DTW and radiometrics, but it **did not include tree growth** from the surrounding stands as a predictor variable.

**The Untested Hypothesis:** The core idea—that the integrated, long-term signal of tree growth is a *better* proxy for underlying soil conditions than instantaneous measures like DTW or surface radiometrics—remains untested.

## The Path Forward: The Missing Experiment

1. **Measure Tree Growth:** Use multi-temporal LiDAR to derive individual tree growth metrics for stands adjacent to roads (Methodology from Soinen et al.).
2. **Measure Road Strength:** Collect on-the-ground bearing capacity data using an FWD (Methodology from Karjalainen et al.).
3. **Test Predictive Power:** Build a new model to determine if tree growth adds significant predictive power above and beyond simple road width and other existing variables.



# Key takeaways from our investigation.



## Prediction is Hard.

Remotely predicting forest road bearing capacity is a complex challenge. For now, simple structural features like road width are the most powerful predictors, while current environmental proxies show only moderate success.



## Technology is Ready.

We possess the airborne technologies (multi-temporal LiDAR, radiometrics) to capture detailed data on both the forest canopy and the ground with unprecedented accuracy. The measurement tools are not the limiting factor.



## Untapped Potential.

The intuitive, scientifically-grounded link between long-term tree growth and soil strength remains a compelling but unproven hypothesis for road trafficability. Directly testing this link is the next logical frontier for forest logistics.