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FROM CLOUD TO CLIENT: Web-native, in-browser EO DataCube exploration & analytics using Zarr

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PARIS LODRON UNIVERSITY SALZBURG | Z_GIS | Interreg Danube Region | SpongeCity

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SpongeCity – Interreg Danube Project

- **Project:** SpongeCity (2024–2026) tackles urban heat, flooding, and water scarcity in the Danube Region with nature-based solutions.

- **Toolbox:** EO data powered decision-support toolbox to helps pilot cities assess risks, plan sponge city measures, monitor and share solutions across the Danube Region.

- **User base:** Municipal decision-makers, stakeholders, institutions with limited infrastructure, local communities and general public.

Requirements

Sustainable & transferable

- Many municipalities across countries → hard to harmonize infrastructure & budgets;
- Need solution without complex backend systems.

Exploration + analysis

- Must support interactive EO data exploration *and* analytical functions in one environment.

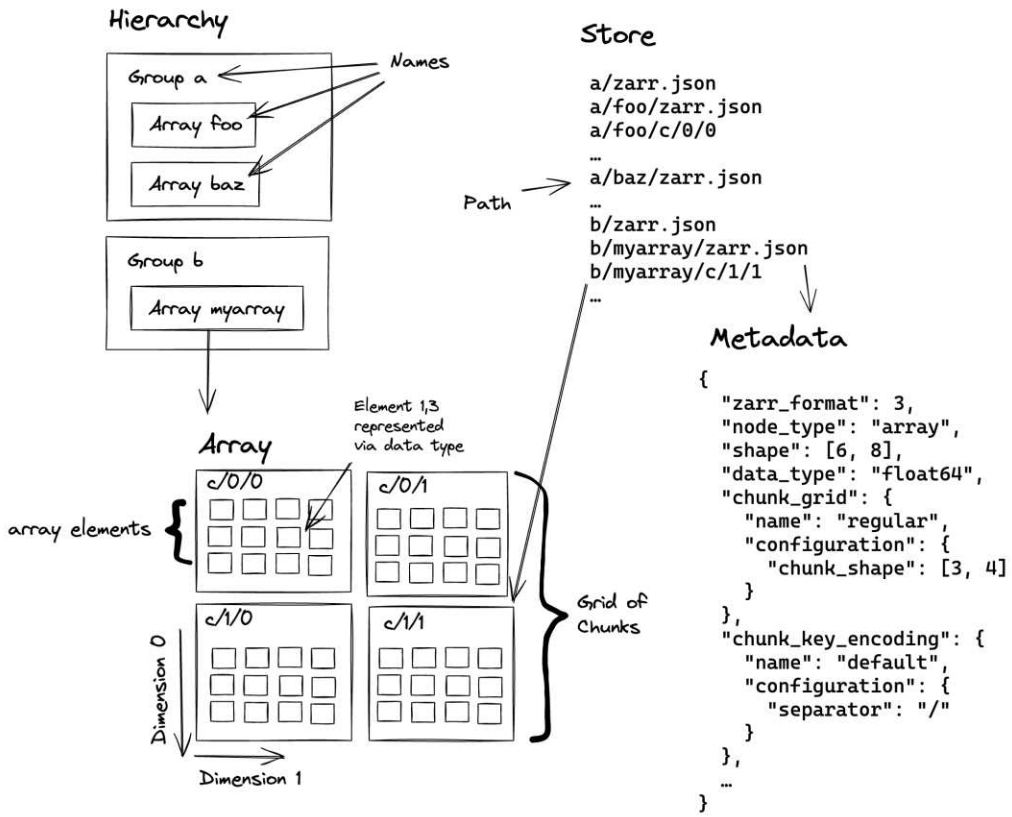
Accessible everywhere

- Toolbox should run on standard laptops or tablets, no installation required.

Challenge, Formulation & Solution

"Can we enable EO analytics to run fully in the browser (no backend systems) while remaining responsive and usable for municipalities, communities, and educators?"

- Data Format: Zarr
- Map Visualization: OpenLayer
- Analytics: Web Workers (WebGPU, WebGL, WebAssembly, ONNX)



What is **Zarr**?

- Open format for **multi-dimensional arrays**
- Stores data in **compressed chunks** (small blocks)
- Fetch only the **subset you need** (object storage friendly)
- Simple **JSON metadata** (shape, dtype, coords)
- Designed for **parallel/cloud access**
- **GeoZarr** extends Zarr with geospatial conventions

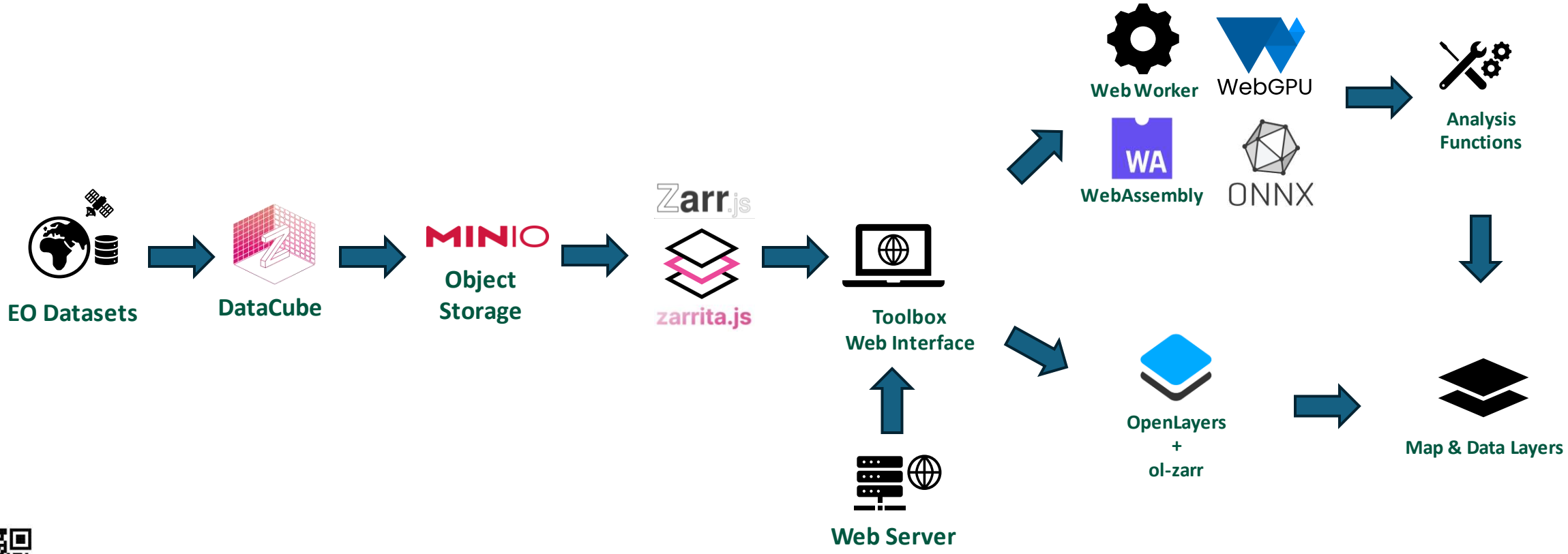
https://zarr-specs.readthedocs.io/

Zarr Structure

- Hierarchical multi-resolution pyramids per zoom (…/zNN/).
- Coordinate arrays (x, y, time) enable index math in the browser.
- values[time, band, y, x], chunked ~[1,1,256,256] to favor tile-sized spatial reads.
- Precomputed statistics (per-timestamp) for autoscaling.

```
Dataset (zgroup)
+-- Zoom Levels (zgroup: 0, 1, 2, ..., n)
    |-- times (zarray)
    |-- statistics (zarray)
    |-- values (zarray: [time, band, y, x])
    |-- y (zarray)
    +-- x (zarray)
```

System Architecture



ol-zarr
https://github.com/nyinyinyanlin/ol-zarr

Performance Test (Pécs, Hungary test case)

- Scope:
  - Pécs municipality, Hungary 163 km² (and 378 km² for UHI)
  - 21 ECOSTRESS (70 m) and 27 SIAM (10 m) acquisitions (Jan–Jun 2024).

- Devices: Laptop (Chrome) & iPad (Safari); 40/10 Mbps link.

Table 1. Performance metrics for browser-based EO analytics in SpongeCity Toolbox (Pécs, Hungary test case)

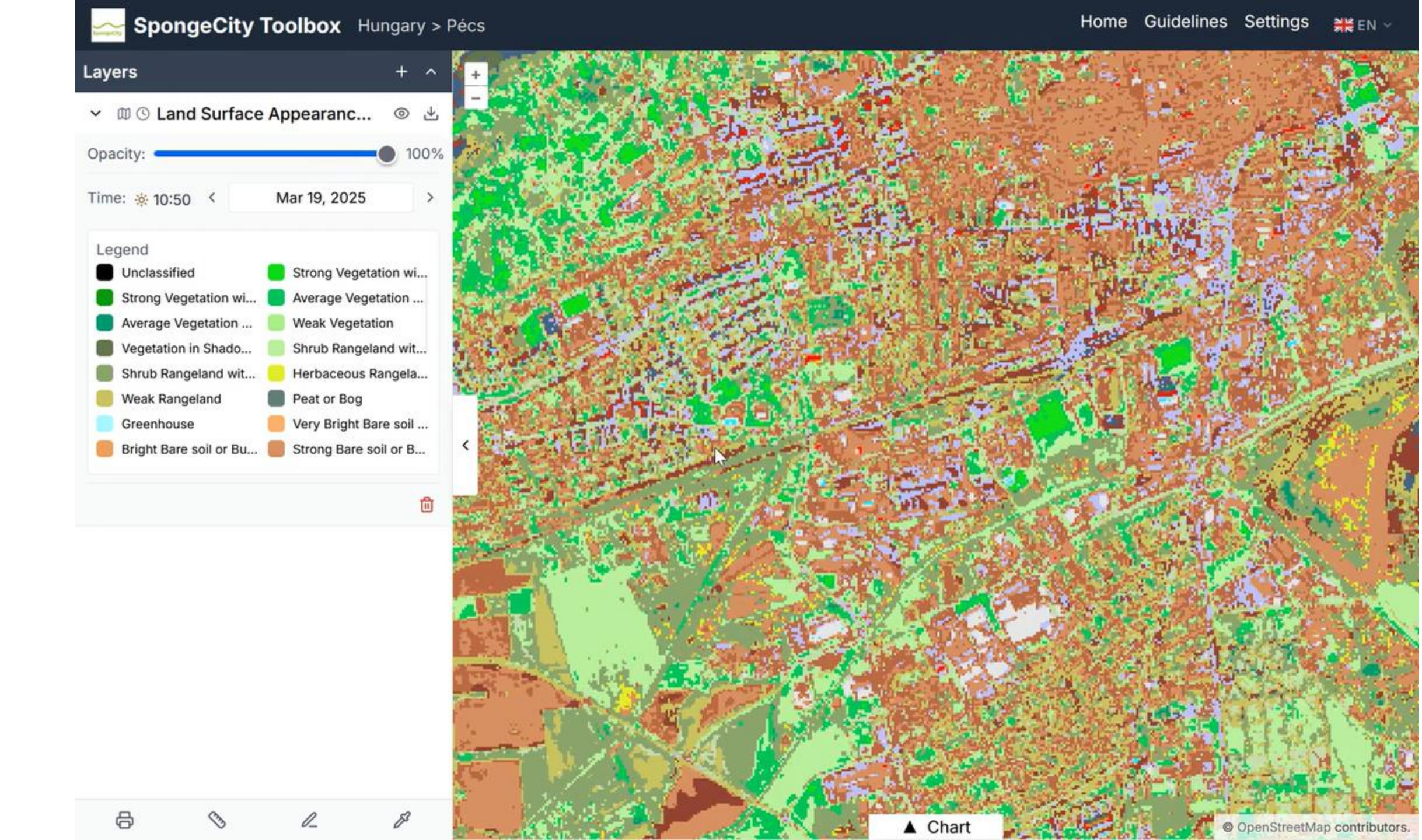
Analysis	Dataset	DType/Res	Time Steps	Area (km²)	Time (seconds)			Data (MB)		Bandwidth (MB/s)	
					Total	Retrieval	Process	Compressed	Uncompressed	Avg	Peak
iPad Performance - No Cache / Cached											
Urban Heat Island	ECOSTRESS LST	F32/70m	21	378	3.4 / 2.1	1.8 / 0.4	1.6 / 1.6	5.8	9.5	0.41 / 2.99	6.82 / 20.45
Distribution	SIAM™ Categories	U8/10m	27	163	252.0 / 5.9	249.0 / 1.9	4.0 / 4.0	43.9	84.6	0.48 / 2.90	2.40 / 9.76
Zonal Statistics	SIAM™ Greenness	F32/10m	27	163	125.2 / 120.8	123.2 / 118.9	2.0 / 1.9	513.0	338.5	1.11 / 0.91	123.97 / 134.34
Occurrence	SIAM™ Mixed	Mixed/10m	27	163	175.0 / 170.1	173.6 / 168.6	1.0 / 1.0	43.9	84.6	0.50 / 2.90	3.42 / 9.76
Desktop Performance - No Cache / Cached											
Urban Heat Island	ECOSTRESS LST	F32/70m	21	378	2.3 / 1.0	2.1 / 0.9	0.2 / 0.2	5.8	9.5	0.55 / 1.22	4.65 / 14.31
Distribution	SIAM™ Categories	U8/10m	27	163	27.7 / 19.0	13.8 / 5.7	13.9 / 13.2	43.9	84.6	0.30 / 1.61	2.72 / 13.95
Zonal Statistics	SIAM™ Greenness	F32/10m	27	163	141.6 / 16.3	138.6 / 14.7	2.9 / 1.6	513.0	338.5	1.03 / 2.24	19.32 / 2.63
Occurrence	SIAM™ Mixed	Mixed/10m	27	163	142.5 / 18.2	139.1 / 15.4	3.2 / 2.7	43.9	84.6	0.27 / 1.47	3.01 / 11.85

SpongeCity

Toolbox Demo

https://spongecity.zgis.at

(Development in progress)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Mar 19, 2025
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Herbaceous Rangela...
Weak Rangeland
Peat or Bog
Greenhouse
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Strong Bare soil or B...
Chart
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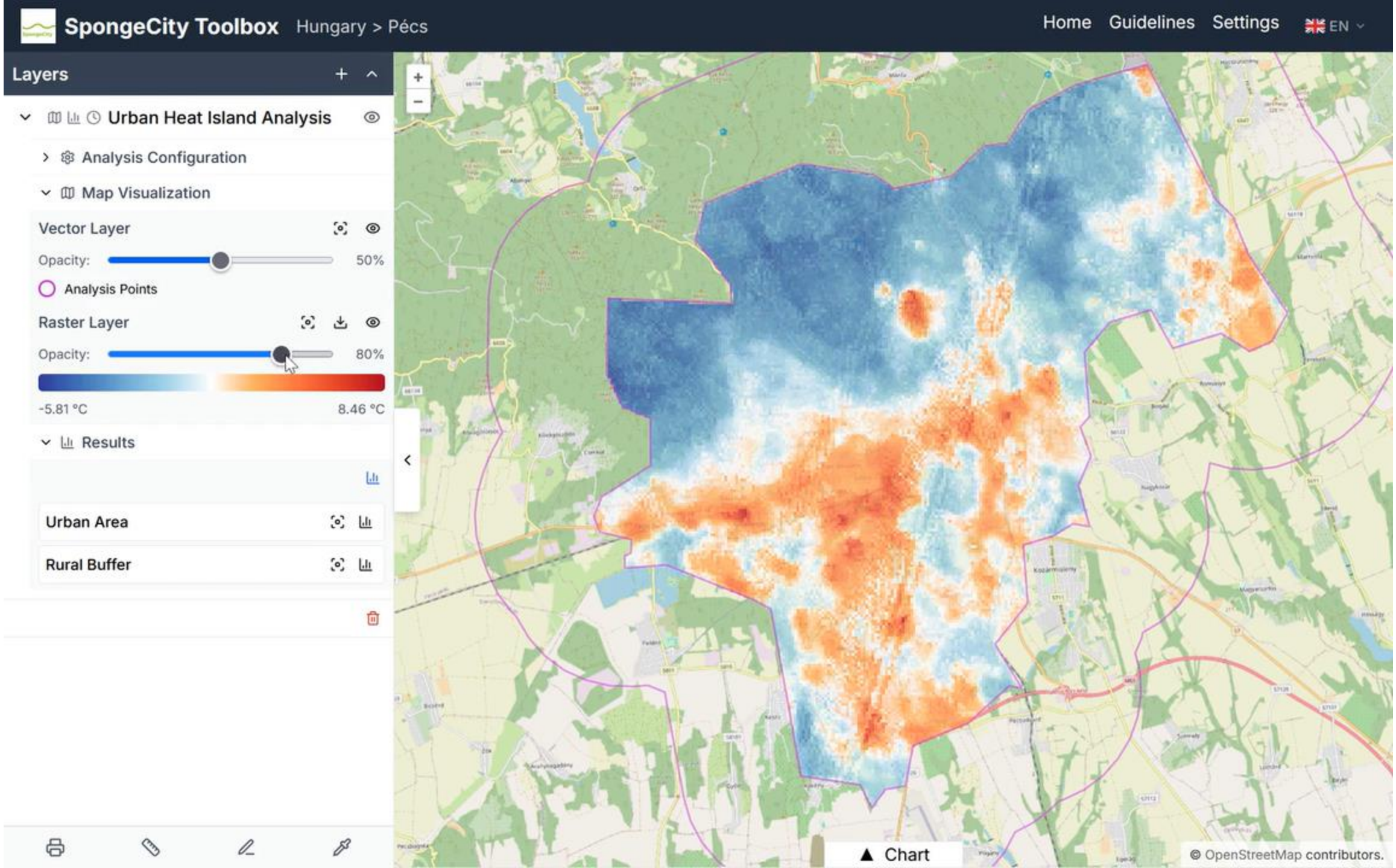
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Urban Heat Island Analysis
Analysis Configuration
Map Visualization
Vector Layer
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Analysis Points
Raster Layer
Opacity:
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8.46 °C
Results
Urban Area
Rural Buffer
Chart
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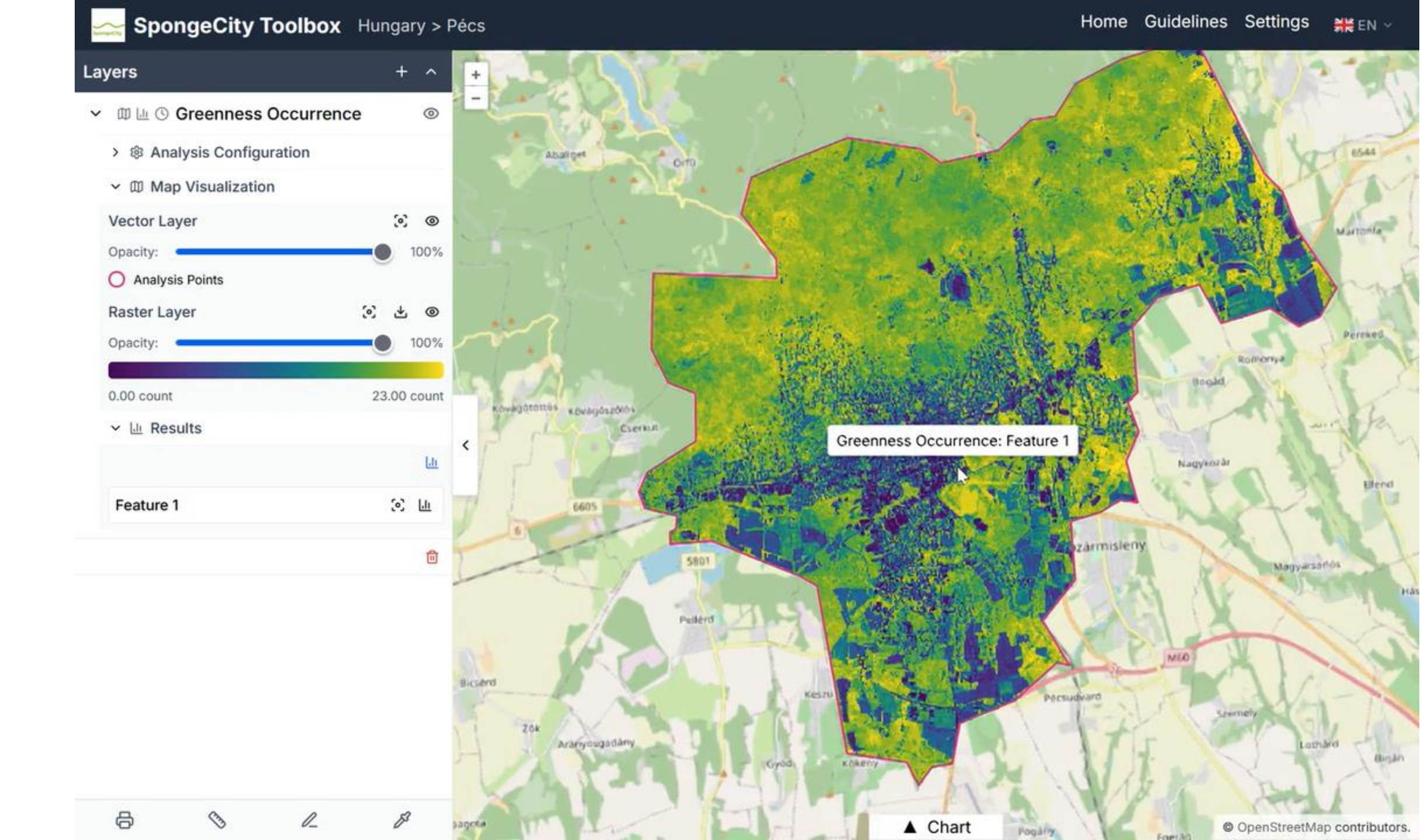
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Results
Feature 1
Greenness Occurrence: Feature 1
Chart
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Discussion

- Chunking trade-off: spatial slices are fast; long time-series fetch many chunks
- Browser memory & heap limits (~400–500 MB) constrain analysis size
- First-load vs. cached: initial latency before cache warms up
- Analytics scope: targeted functions feasible; generic frameworks still server-side
- Device & browser variability: performance differs across platforms
- Multi-dataset integration still a challenge: different CRS, extents, and resolutions complicate analysis

Conclusions & Next Steps

- **Where this fits**: City-scale EO exploration & targeted analytics directly in the browser — fast, zero-infrastructure, FAIR by design.
- **What it promotes**: Open standards (Zarr, GeoZarr), reproducibility, and accessible tools for municipalities, educators, and communities.
- **Limits today**: First-load I/O, browser memory ceilings, single-dataset scope (same CRS/extent/resolution).
- **What's next**: WebGPU kernels, temporal-chunk strategies, multi-dataset fusion, Discrete Global Grid System (DGGS), PWA/offline support and hardening ol-zarr.

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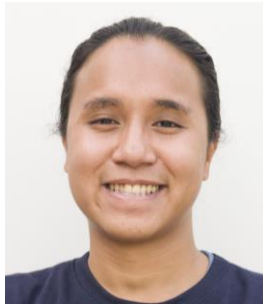

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Thank you for your attention.

Backup (for Q&A)

A. COG vs Zarr bullets (OGC ER)

- COG = single GeoTIFF, great for linear access, broad ecosystem.
- Zarr = chunked store, strong for multi-dimensional & cloud object storage.
- Trade-off: simplicity vs multidimensional scalability.

B. Performance table (selected rows)

- Desktop (no-cache → cached)
  - SIAM Categories 10 m (163 km²): 27.7 s → 19.0 s
  - Greenness 10 m (163 km²): 141.6 s → 16.3 s
  - ECOSTRESS 70 m UHI (378 km²): 2.3 s → 1.0 s

Backup (for Q&A)

C. Key web enabler: COOP/COEP headers

- Required for SharedArrayBuffer + WASM threads.

MDN: set ***Cross-Origin-Opener-Policy: same-origin*** and ***Cross-Origin-Embedder-Policy: require-corp***

D. WebGPU + ONNX Runtime

- MDN & Chrome: WebGPU now stable in Chrome/Edge.
- ONNX Runtime Web shows 10×–20× inference speedups vs CPU JS backends.
- Clear path for browser-native ML on EO DataCubes.

Backup (for Q&A)

E. Datasets & areas

- Pécs 163 km²; UHI buffer 3 km (378 km²); 21× ECOSTRESS (F32/70 m), 27× SIAM (U8/F32/10 m).