Evaluating real-world super-resolution of hyperspectral images

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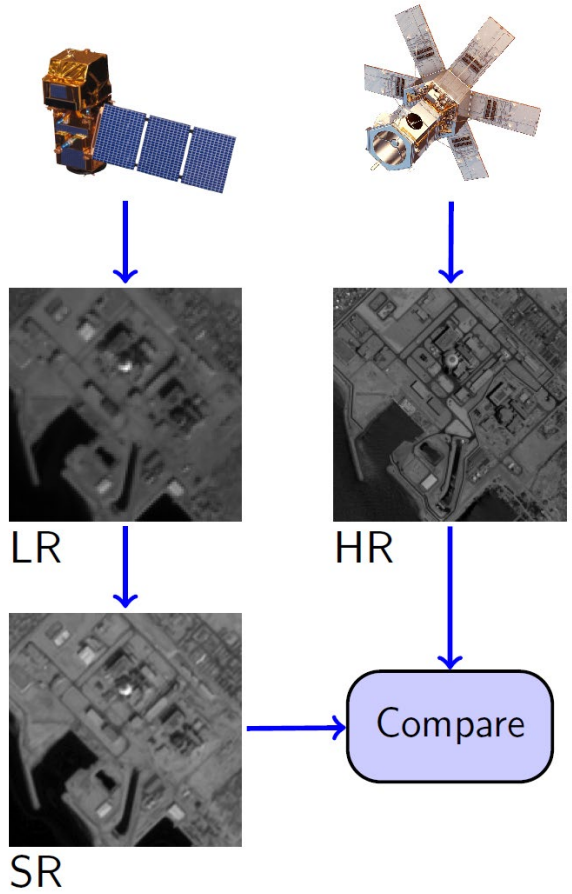
Introduction: evaluation of SR outcome

- Reference-based evaluation procedure:
  - LR images coupled with HR reference
    - LR image(s) simulated by downgrading an HR reference
    - LR and HR images captured independently (real-world data)
  - super-resolved image compared with HR reference
    - SR quality assessed based on the similarity
  - limitations:
    - SR performed from simulated data – over-optimistic results
    - challenging to compare SR output with HR reference
    - unknown value of SR data for specific applications

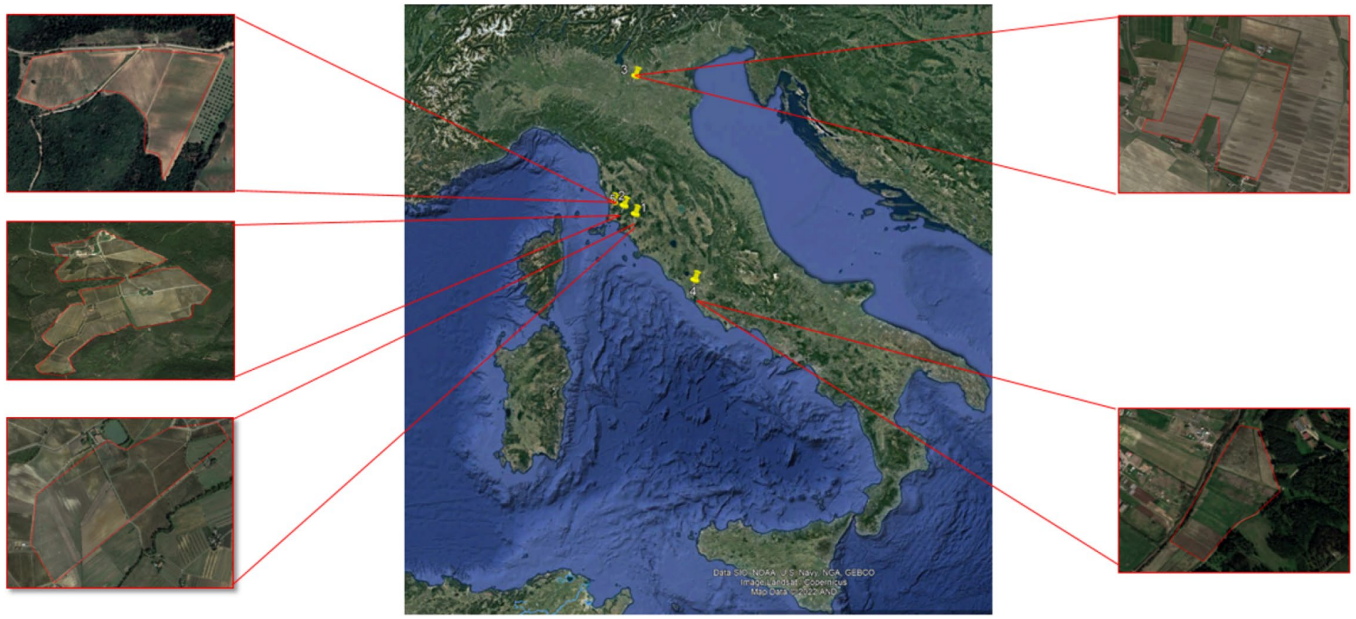


Introduction: goal of our study

- Application-related evaluation of HSI SR
  - three categories of HSI SR:
    - single-HSI SR
    - pansharpening
    - MSI-HSI fusion
  - three test cases:
    - precision farming test case to validate single-HSI SR and pansharpening
    - water quality test case to validate single-HSI SR and pansharpening
    - air pollution test case to validate MSI-HSI fusion
- Project funded by European Space Agency (KP Labs and GEO-K)
  - PIGEON: Hyperspectral Image Super-Resolution in the Wild (2022-23)

Test cases: precision farming

- Precision farming: soil nitrogen estimation (g/kg)
  - ground-truth measurements provided by Italian Council for Agricultural Research (CREA)
  - 87 samples (2019–2022) from 5 images
  - corresponding PRISMA images
    - original (30 m GSD)
    - enhanced (up to 5 m GSD)
  - maximum two-weeks temporal difference

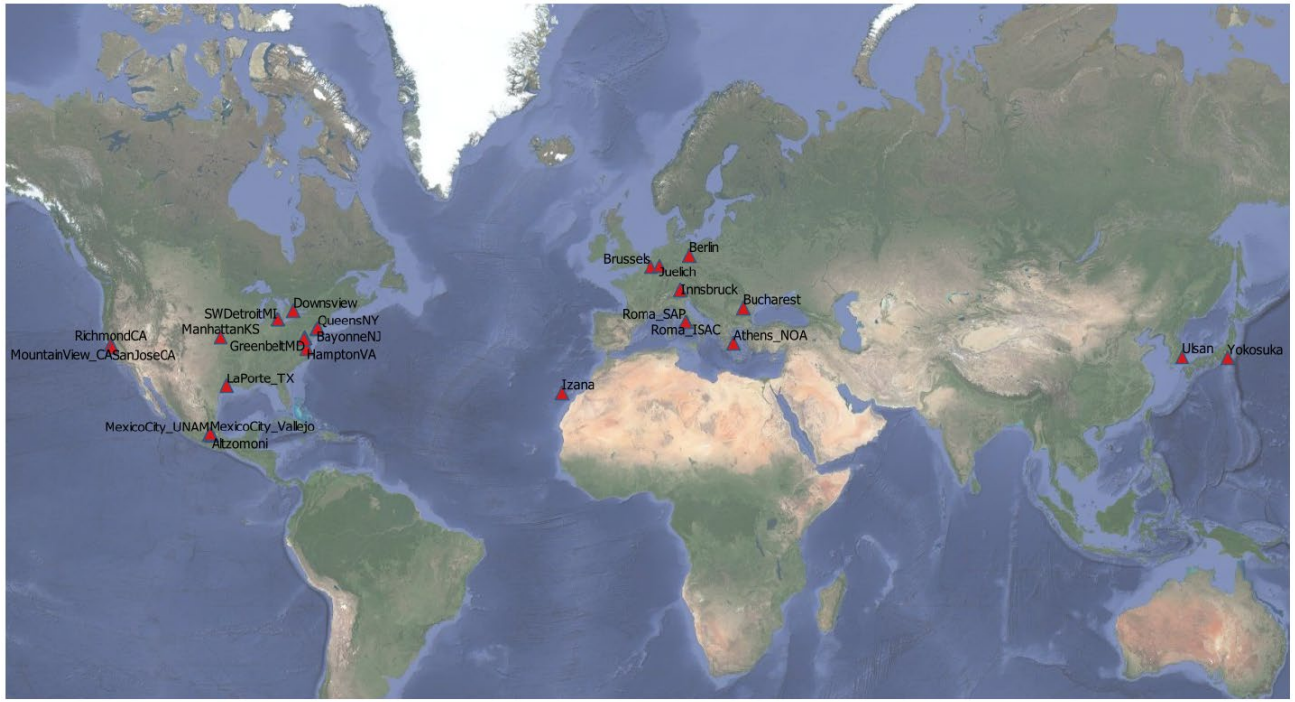


Test cases: water quality

- Water quality: chlorophyll-a level (mg/m^3)
  - Sentinel-3 considered as a ground truth
  - estimation from PRISMA bands
    - original (30 m GSD)
    - enhanced (15 m GSD)
- Coastal and inland waters
  - 12 coastal sites (270 samples)
  - 10 inland sites (290 samples)

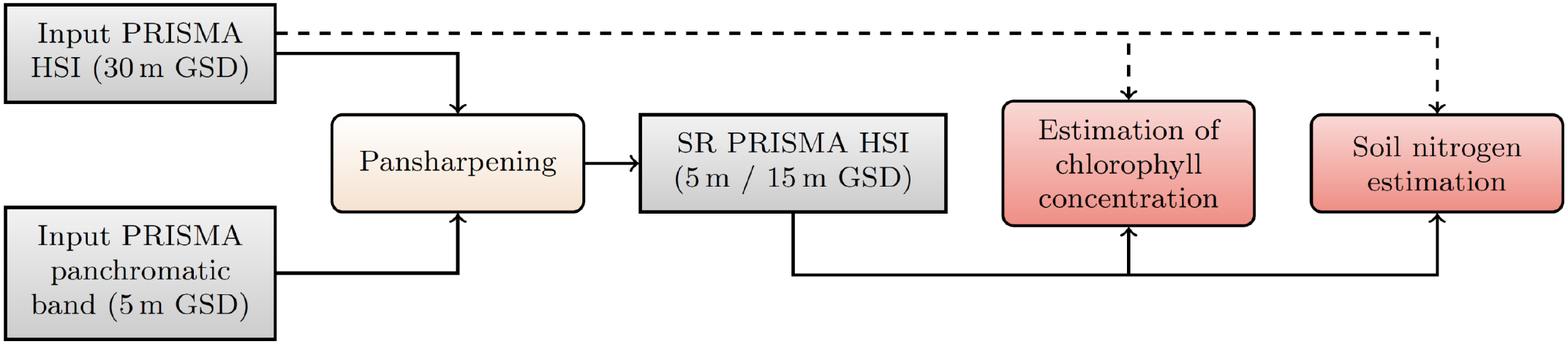
Test case: air pollution

- Air pollution: nitrogen dioxide (NO_2) column estimation (mol/m²)
  - TROPOMI data
    - original (3.5 km x 5.5 km)
    - enhanced (500 m GSD)
- Ground truth data:
  - Pandonia Global Network (PGN)
  - 354 samples
- 76 TROPOMI-PRISMA image pairs



Evaluation: pansharpening

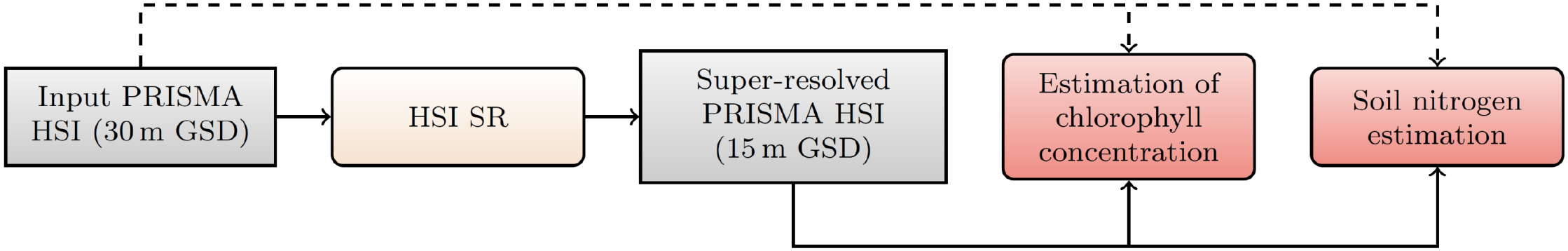
- Method: HyperTransformer (Bandara and Patel, 2022)
  - trained from data simulated from 70 PRISMA L2D VNIR
- Assessment strategy:
  - original PRISMA HSI – 30 m ground sampling distance (GSD)
  - pansharpened HSI (5 m GSD)
  - pansharpened HSI, downsampled to 15 m GSD



W. G. C. Bandara and V. M. Patel, "HyperTransformer: A textural and spectral feature fusion transformer for pansharpening," in Proc. IEEE/CVF CVPR, 2022, pp. 1767–1777.

Evaluation: single-HSI SR

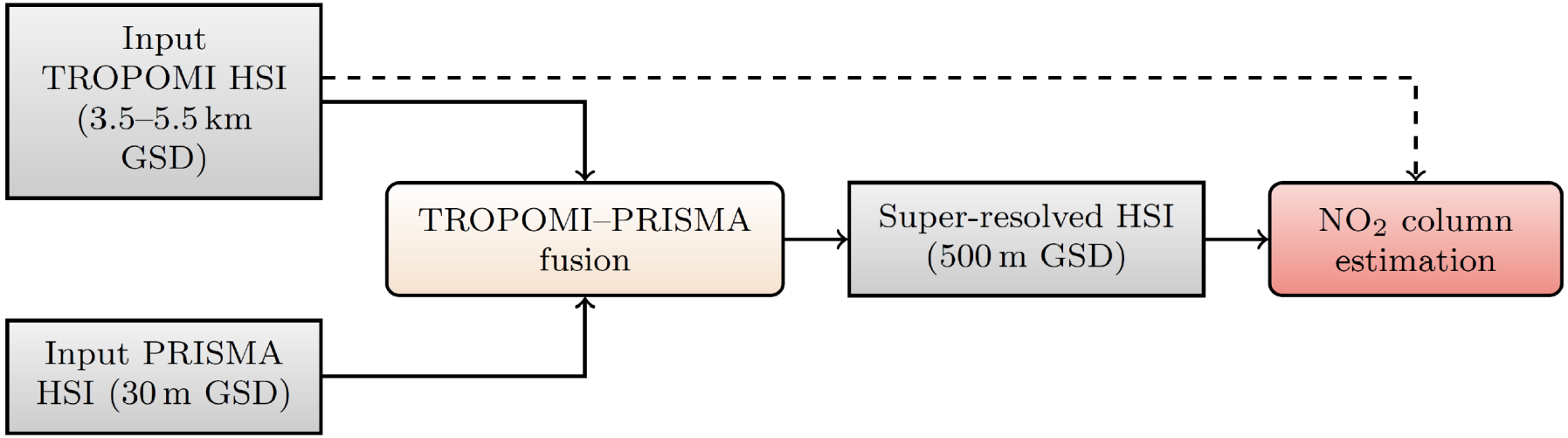
- Single-image SR: bidirectional 3D quasi-recurrent network (Fu et al., 2021)
  - trained from data simulated from 10 PRISMA L2D images
- Assessment strategy:
  - original PRISMA HSI – 30 m GSD
  - resolution of the spectral bands enhanced 2x (15 m GSD)



Y. Fu, Z. Liang, and S. You, "Bidirectional 3D quasi-recurrent neural network for hyperspectral image super-resolution," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 14, pp. 2674–2688, 2021.

Evaluation: TROPOMI-PRISMA fusion

- HSI-MSI fusion with FusionNet (Xie et al., 2019)
  - TROPOMI: high spectral resolution (in 405-500 nm), but low spatial resolution (3.5–5.5 km GSD)
  - PRISMA images: 11 bands in the range – source of HR information (up to 2 h difference)
  - consistency loss component added
- Assessment strategy:
  - original TROPOMI data
  - super-resolved data (500 m GSD)



Q. Xie, M. Zhou, Q. Zhao, D. Meng, W. Zuo, and Z. Xu, "Multispectral and hyperspectral image fusion by MS/HS Fusion Net," in IEEE/CVF CVPR, 2019, pp. 1585–1594.

Experimental validation

- Application-independent validation
  - tests for the simulated data
  - for original images (real-world):
    - SR outcome downsampled back to original dimensions (consistency check)
- Application-related validation
  - three test cases

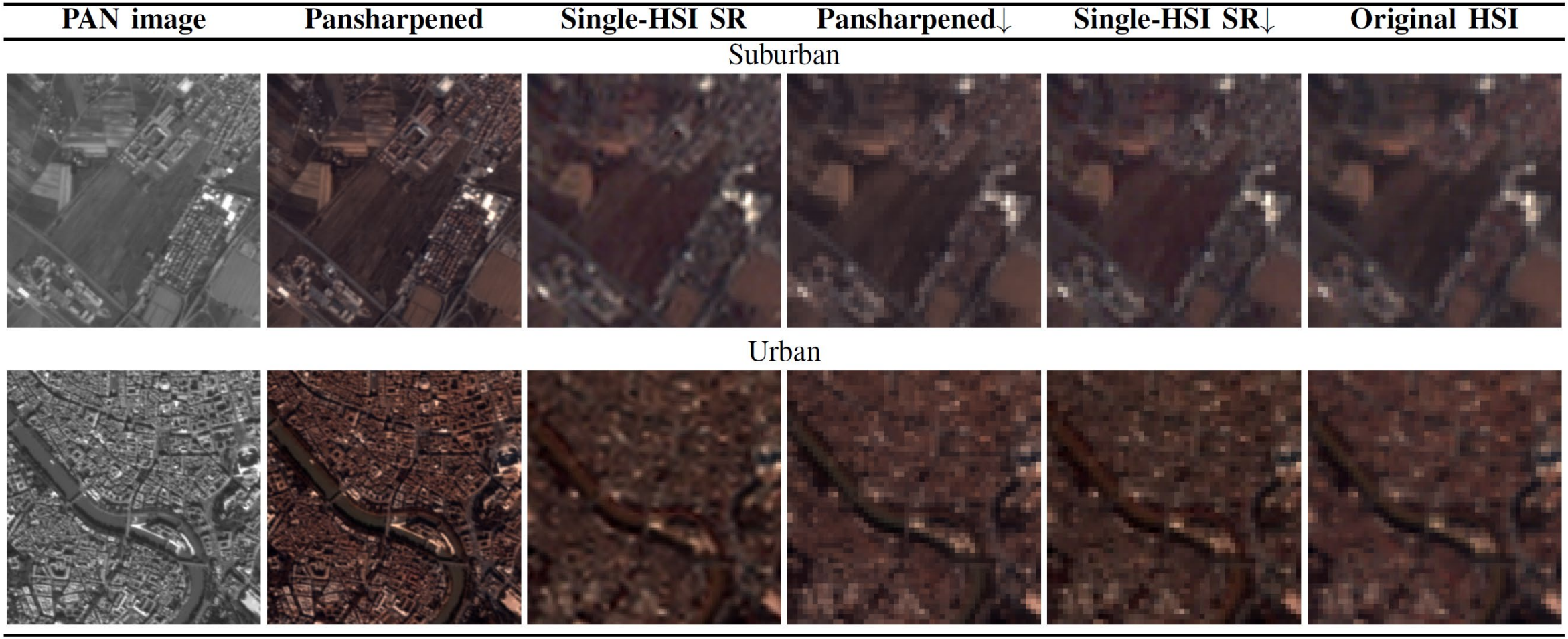
Experimental validation

- Application-independent validation: quantitative results

Model	Upsampling ratio	PSNR↑	SSIM↑	SAM↓
Simulated data				
Single-HSI SR (Bi-3DQRNN)	2×	48.85	0.995	0.333
Pansharpening (HyperTransformer)	6×	33.80	0.923	0.105
Fusion Net	32×	34.40	0.967	3.048
Original data (consistency check)				
Single-HSI SR (Bi-3DQRNN)	2×	48.52	0.996	0.294
Pansharpening (HyperTransformer)	6×	36.44	0.972	0.104
Fusion Net	32×	32.08	—	0.847

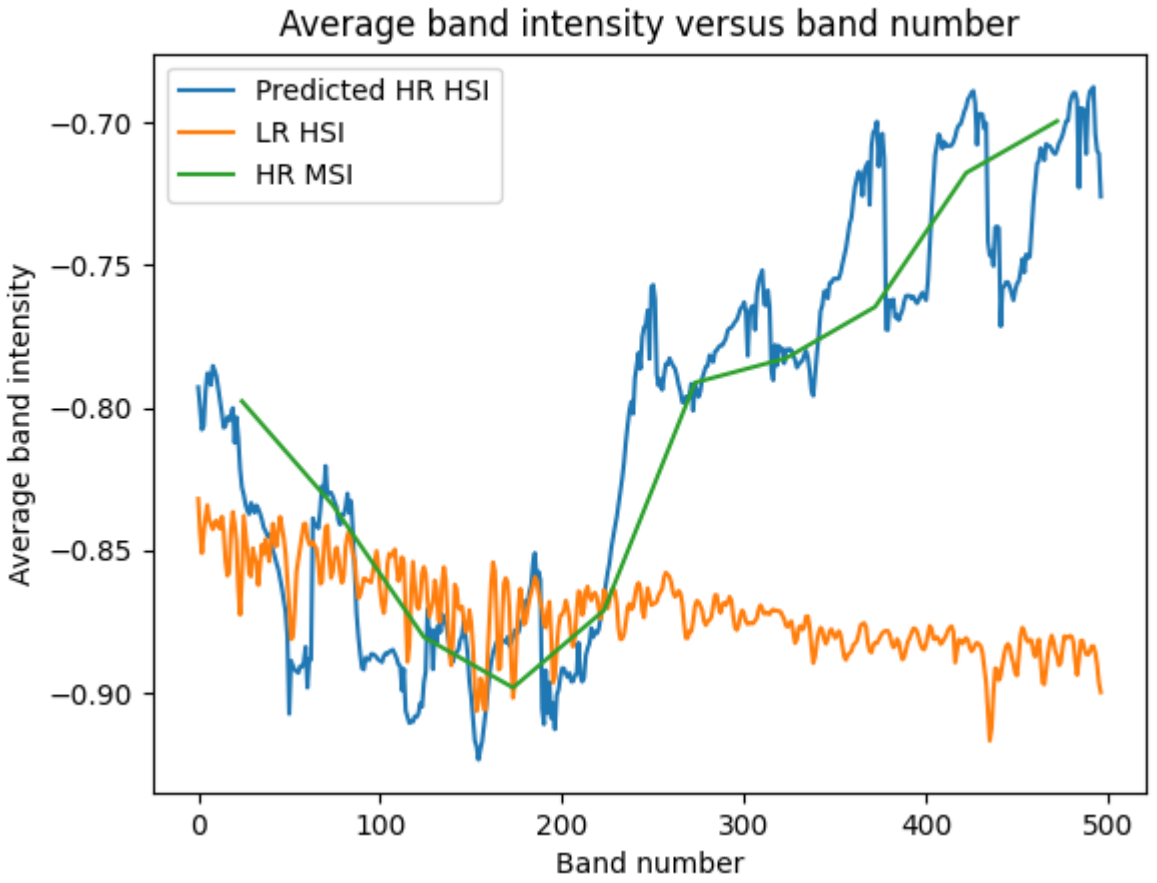
Experimental results

- Qualitative results: pansharpening vs. single-HSI SR



Experimental results

- Fusion Net trained without consistency loss



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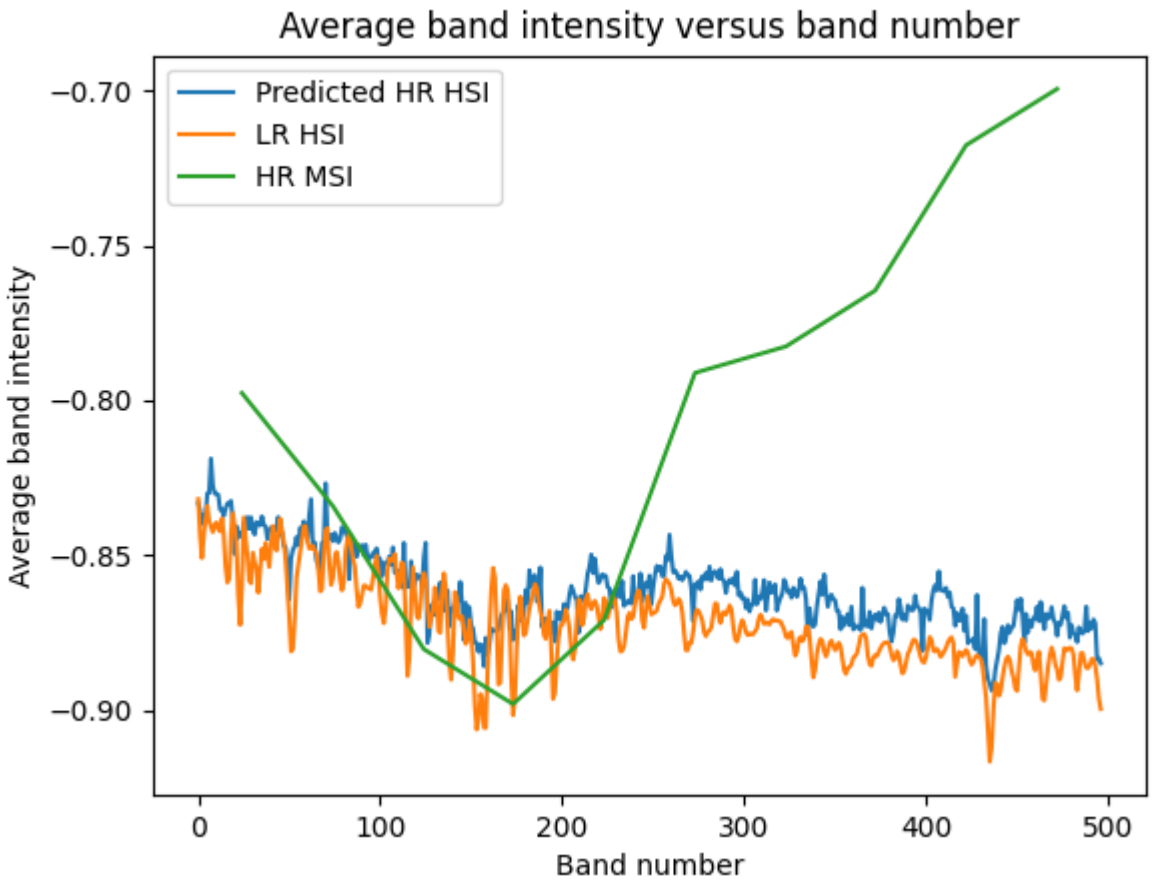
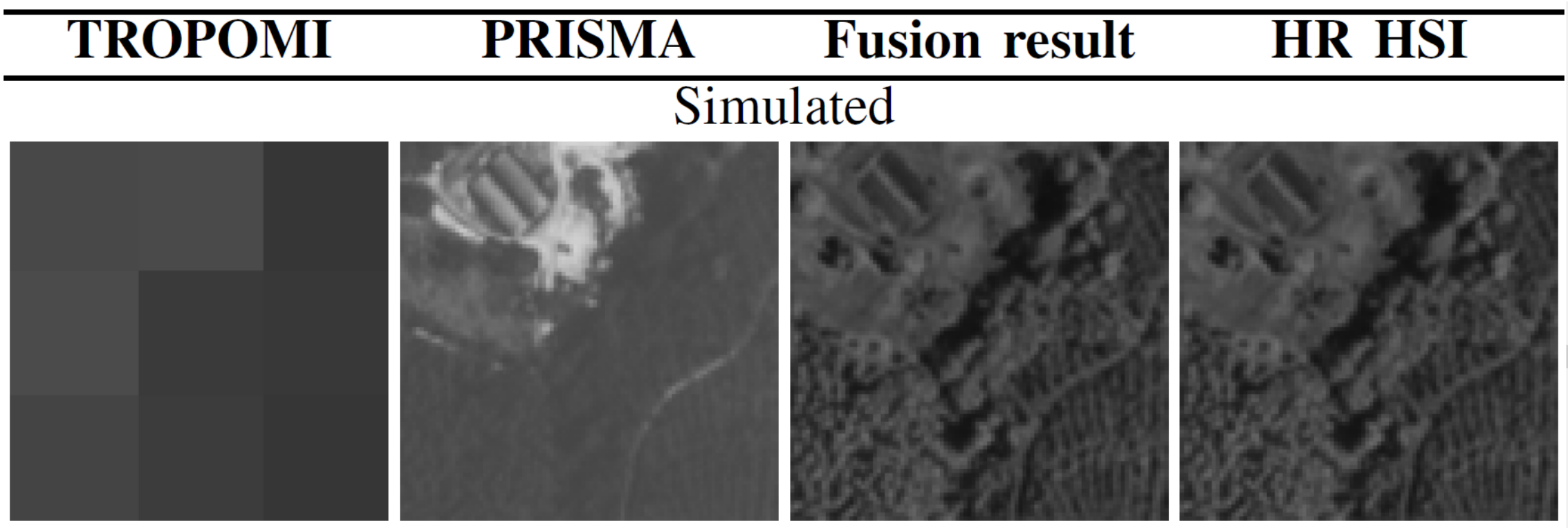


Experimental results

- TROPOMI-PRISMA fusion

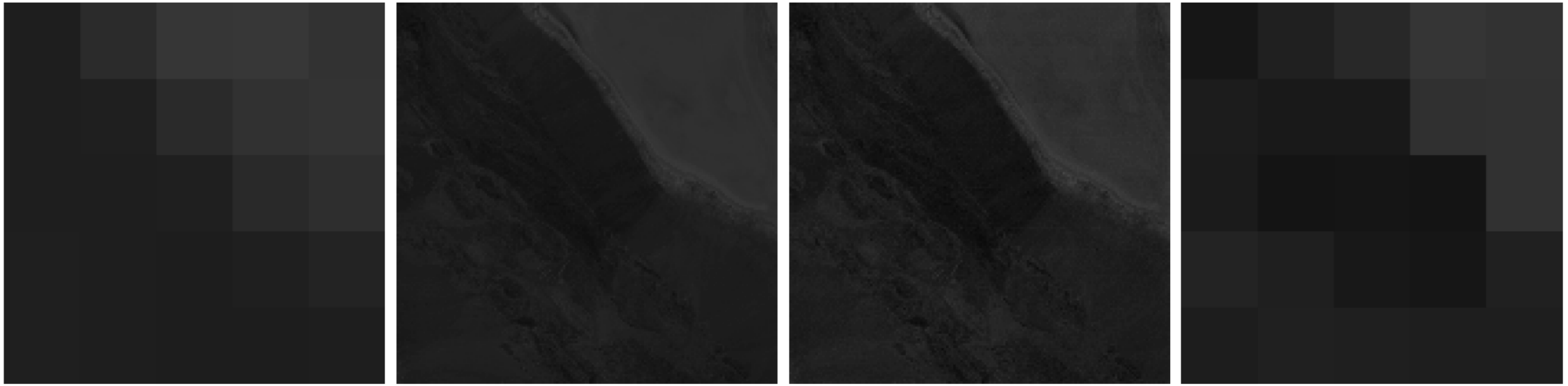


Experimental results

- TROPOMI-PRISMA fusion

TROPOMI	PRISMA	Fusion result	Fusion result↓

Real-world



Experimental results

- Quantitative results: single-HSI SR and pansharpening

Data	GSD	RMSE↓	MAE↓
Precision farming			
Original	30 m	$3.8 \cdot 10^{-3}$	$4.6 \cdot 10^{-2}$
Single-HSI SR	15 m	0.018	0.11
Pansharpened	15 m	0.015	0.055
Pansharpened	5 m	$2 \cdot 10^{-3}$	$3.2 \cdot 10^{-2}$
Inland water quality			
Original	30 m	1.704	1.184
Single-HSI SR	15 m	0.619	0.469
Pansharpened	15 m	1.193	0.848
Coastal water quality			
Original	30 m	0.094	0.064
Single-HSI SR	15 m	0.164	0.108
Pansharpened	15 m	0.174	0.097

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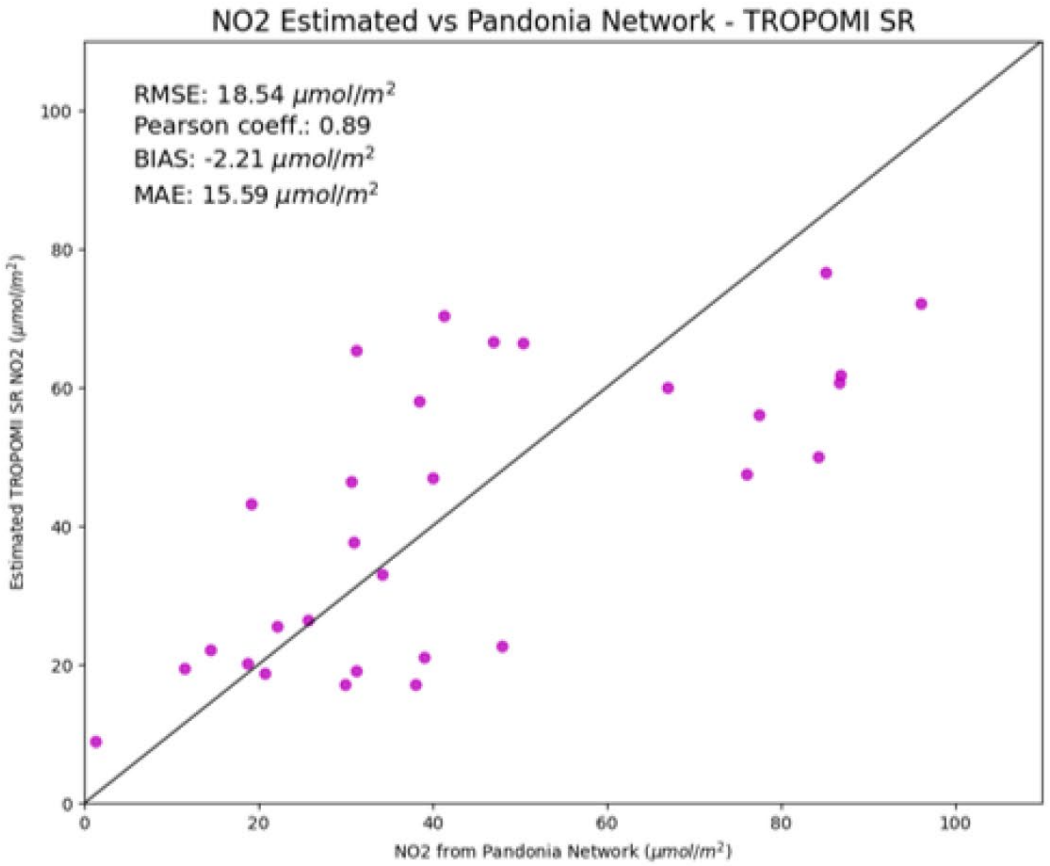
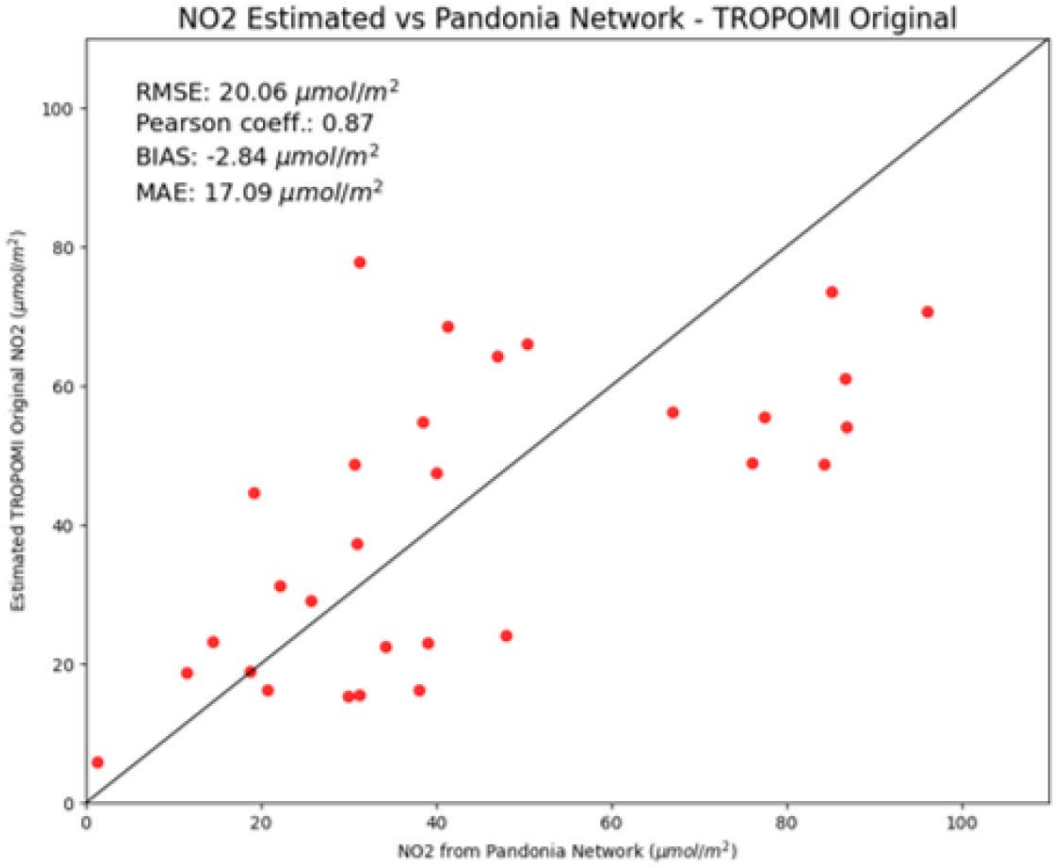
Experimental results

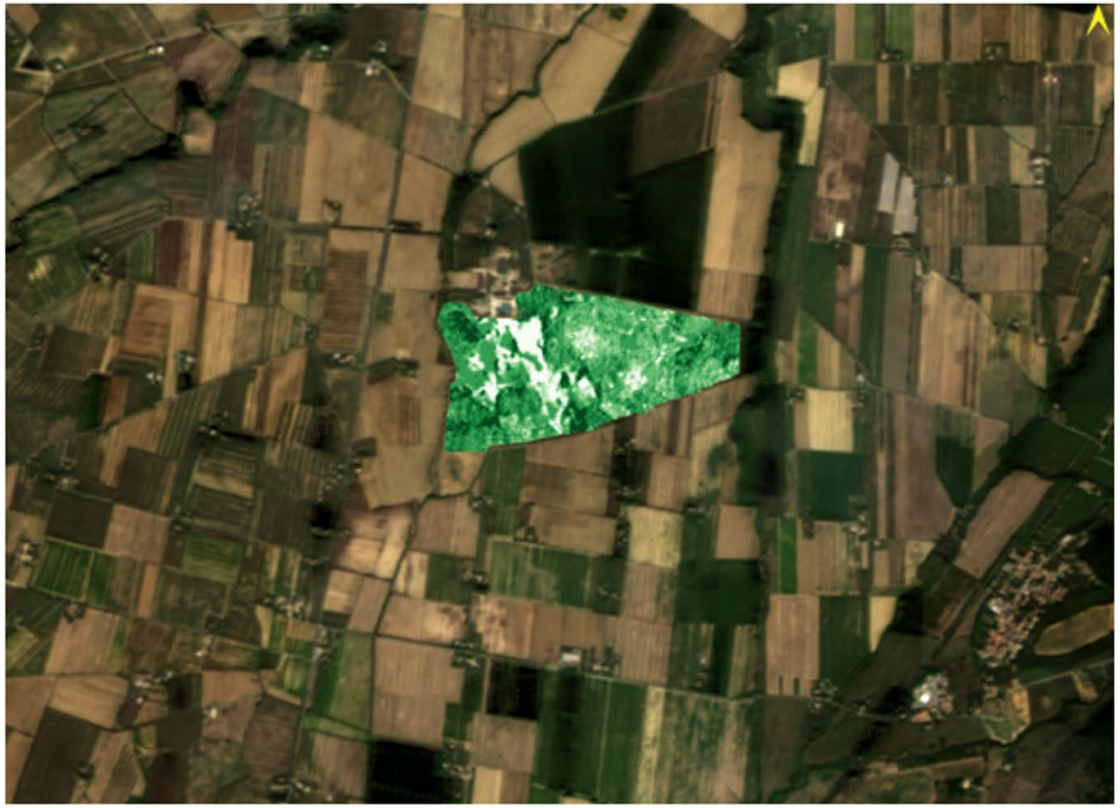
- Air pollution: scatter plots and quantitative results





Experimental validation

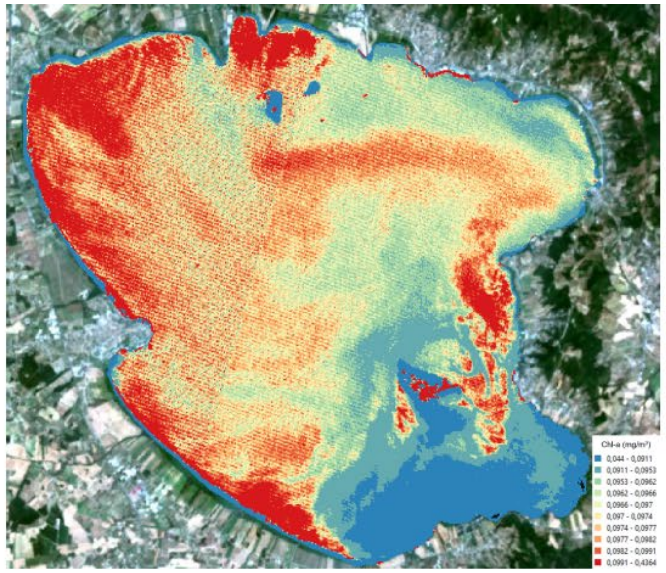
- Precision farming: qualitative results



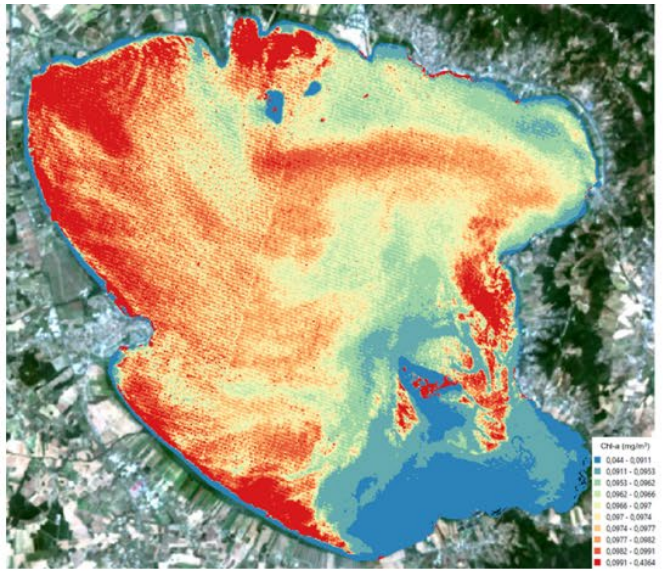
Experimental validation

- Water quality: qualitative results (Trasimeno lake)

color image



estimation from original image

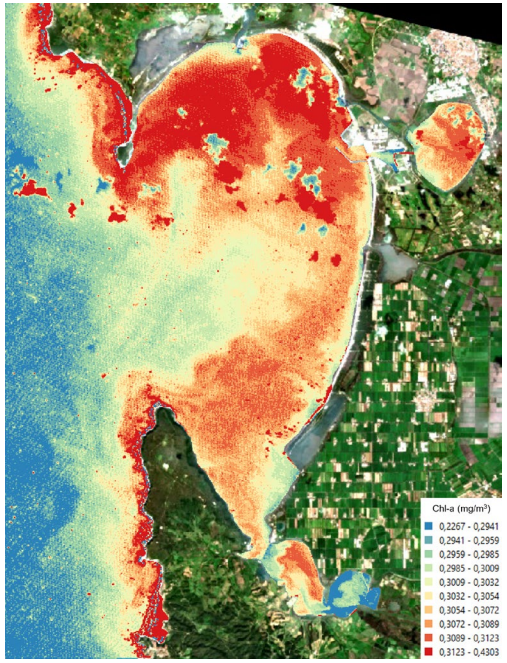


estimation from super-resolved image

Experimental validation

- Water quality: qualitative results (Sardinian coast)

color image



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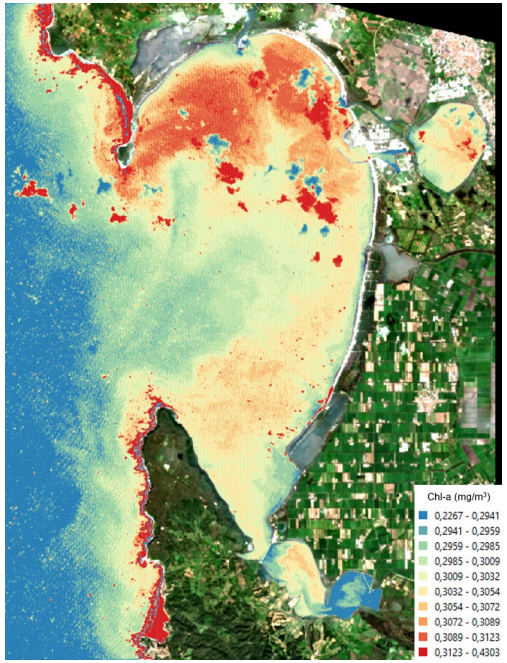
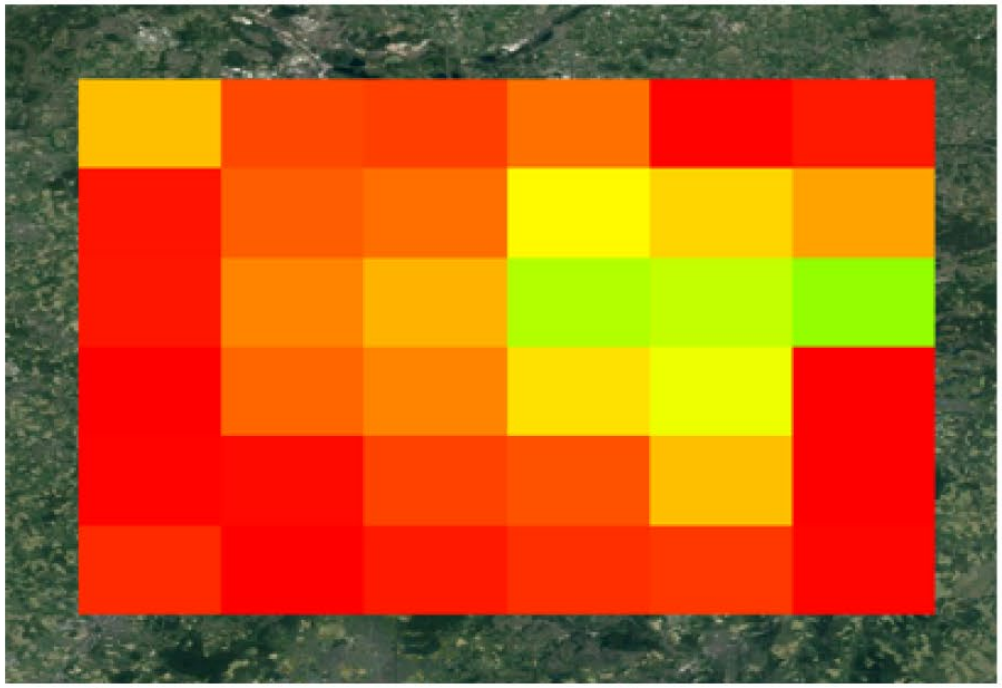
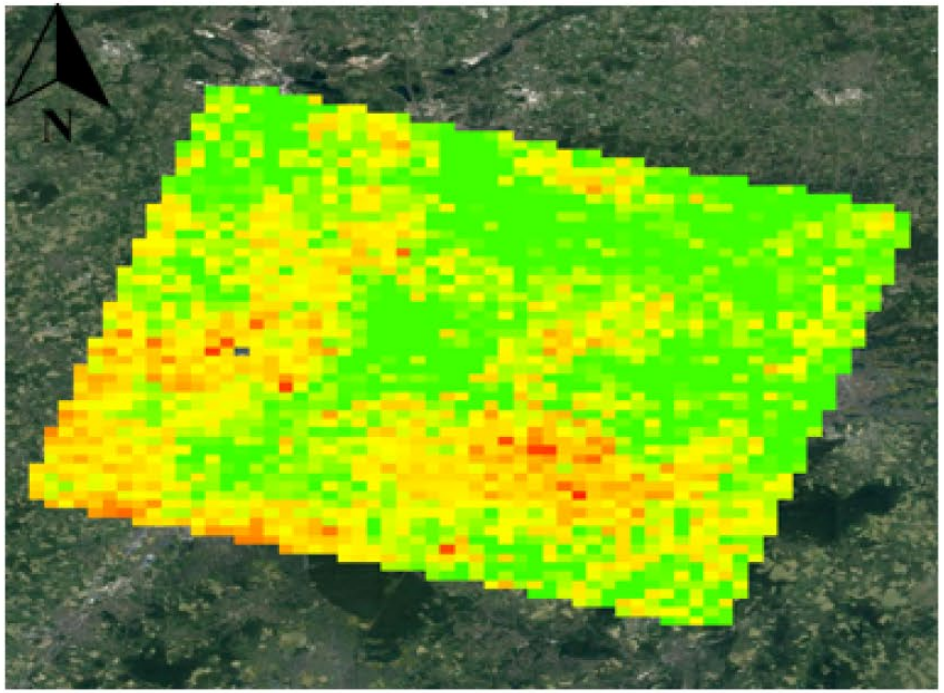


estimation from super-resolved image

Experimental validation

- Air pollution
  - qualitative results





Conclusions and future work

- Value of super-resolved HSI products
  - positively verified by the domain experts
    - well aligned with the quantitative results
  - enhanced for techniques which involve data fusion
    - pansharpening, MSI-HSI fusion
  - lower enhancement for single-HSI SR
- Future work
  - improved consistency for single-HSI SR
  - single-HSI SR trained from real-world SR

KP LABS
Mission Complete

GEO-K

Silesian University of Technology

Thank you!

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