Impact-based drought detection via interpretable machine learning and causal discovery

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European Geosciences Union General Assembly 2026

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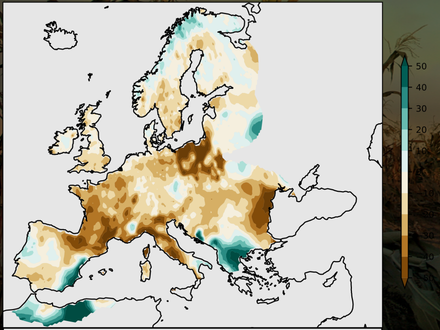
Climate change

- Increasing frequency, duration, severity of droughts

2022 Precipitation Anomaly



Data source: E-OBS Credit: C3S/KNMI Reference Period: 1991-2020

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- Major impacts on agriculture, energy, ecosystems

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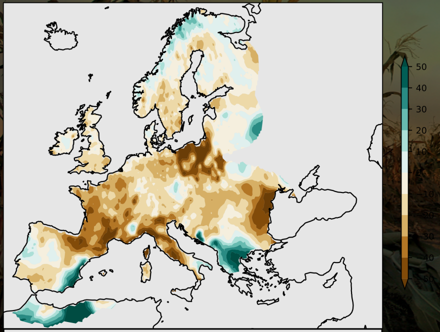

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e.g., SPI, SPEI

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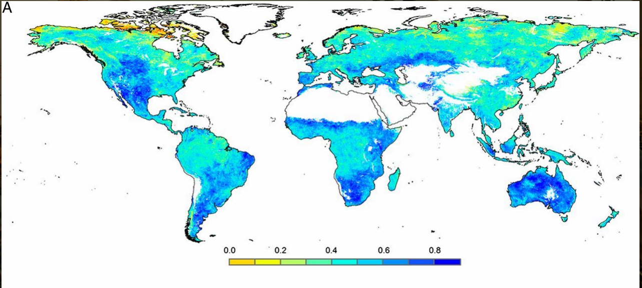

Correlation SPEI–NDVI [Vicente-Serrano et al., 2013]

Contribution: Toward impact-based drought indicators

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👍 Physics aware, human interpretable

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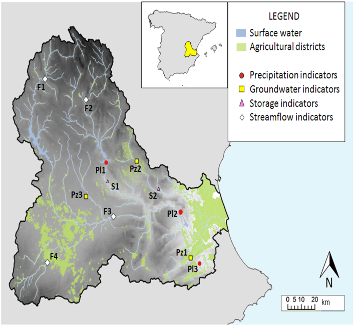

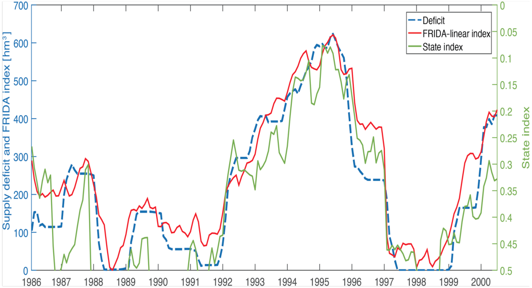

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hydro-climatic drivers $\longrightarrow \widehat{\text{impact}}$

Data: Po River Case Study

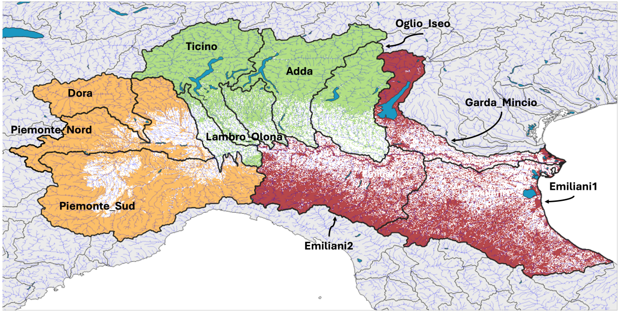
Target: state of vegetation

Vegetation Health Index of cultivated pixels (8-day aggregation)

Candidate drivers

7 temporal aggregations: 8D to 24W

Temperature	991 pixels
Precipitation	991 pixels
Snow depth	53 pixels
Lake water levels	4 lakes

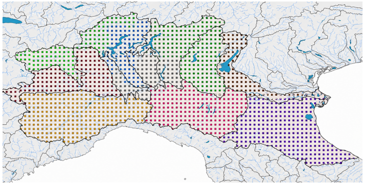


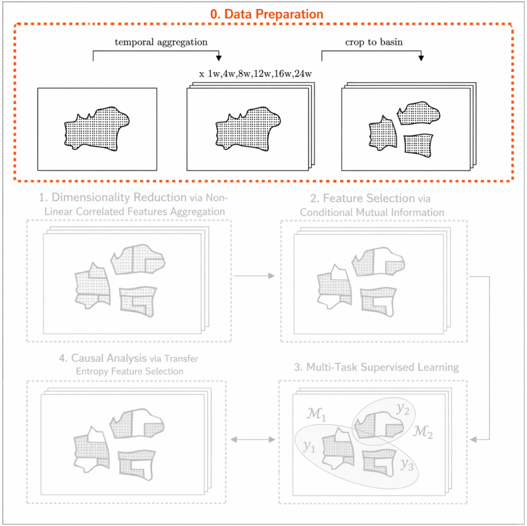
- Tasks: 10 sub-basins, 3 clusters
- Samples: 411 train (2001–2009), 228 validation (2010–2014), 228 test (2015–2019)

Workflow: The DRIER Framework

Input example

Temperature *tg*, 1-week aggregation *1w*, 10 sub-basins





Workflow: The DRIER Framework

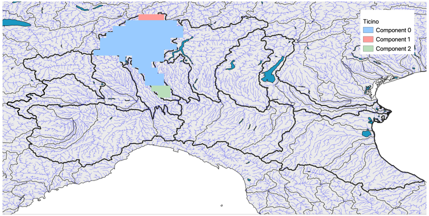
Dimensionality reduction:

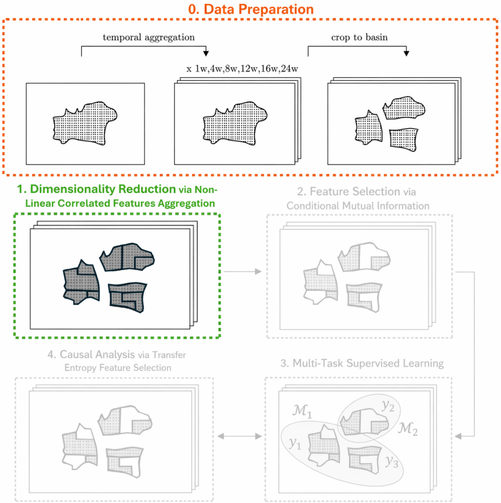
NonLinCFA [Bonetti et al., 2023]

- Principled aggregation:

$$\frac{\sigma^2}{\sigma_f^2(n-1)} \geq R^2_{f,\phi_1\phi_2} - R^2_{f,h(\phi_1,\phi_2)}$$

- Benchmark: PCA
- Example: **Ticino** *weekly temp*





Workflow: The DRIER Framework

Feature Selection:

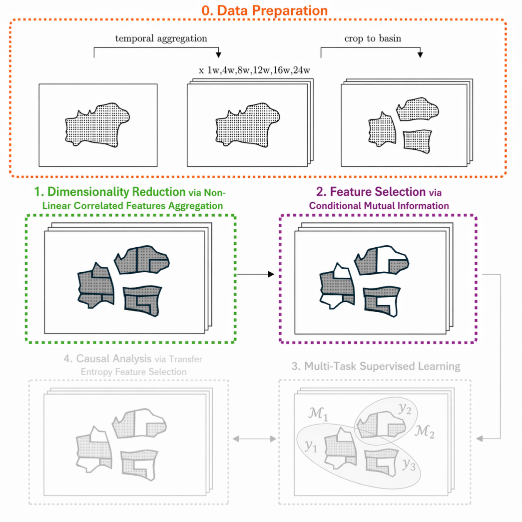
Forward CMI [Beraha et al., 2019]

- Non-linear filter:

$$I(X;Y) := \mathbb{E}_{X,Y}\left[\log \frac{p(X,Y)}{p(X)p(Y)}\right]$$

- Benchmark: wrapper FS
- **Ticino** selected drivers

Temp + Prec	+ Lake + Snow
tg_1w_0	tg_1w_0
rr_4w_0	rr_4w_0
tg_1w_2	snow_1w
	Lugano_1w
	Maggiore_16w



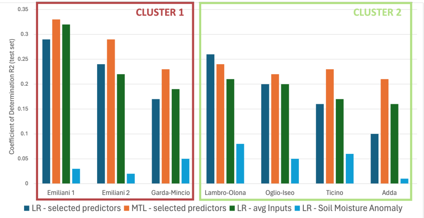
Workflow: The DRIER Framework

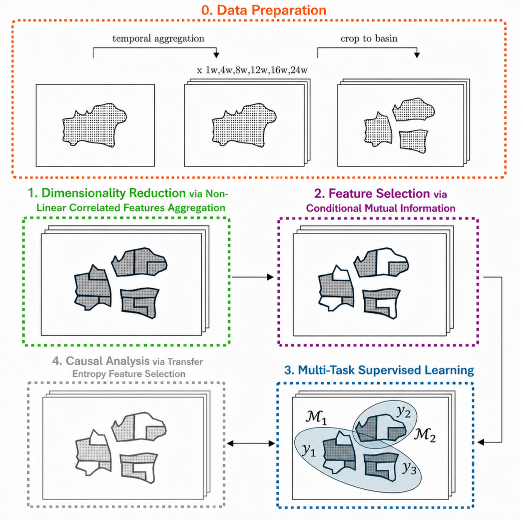
Multi-task linear regression

- Shared cluster-level features:

$$\begin{cases} \hat{y}_1 = \hat{w}_1 x_1 + \cdots + \hat{w}_D x_D + \hat{\beta}_1, \\ \dots \\ \hat{y}_K = \hat{w}_1 x_1 + \cdots + \hat{w}_D x_D + \hat{\beta}_K. \end{cases}$$

- Benchmark: FFNN, RF, SVR
- Coefficient of determination:



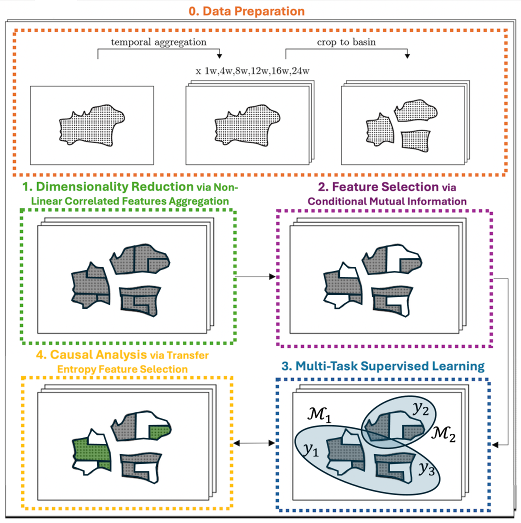


Workflow: The DRIER Framework

Granger-causality inspection

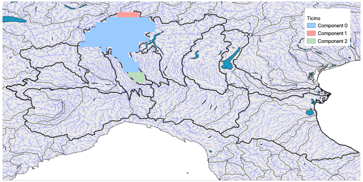
Forward **TEFS** [Bonetti et al., 2024]

- Transfer entropy: $TE(X \to Y \mid Z)$
- Benchmark: PCMCI [Runge et al., 2019]
- Ticino example:

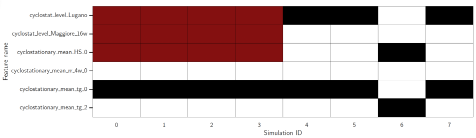


Results Summary

Dimensionality Reduction: from 991x7x2 to 549 features



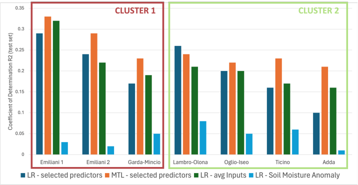
Causal Analysis:



Feature Selection: at most 5 features for each sub-basin

Ticino	Temp + Prec	+ Lake + Snow
	tg_0w_0	tg_0w_0
	rr_4w_0	rr_4w_0
	tg_0w_2	snow_0w
		Maggiore_16w
		Lugano_0w

(Multi-task) linear regression:



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Data-Driven Impact-Based Drought index (Ticino):

$$\widehat{VHI} = -0.35 \cdot tg\_0w\_0 + 0.88 \cdot Lugano\_0w - 0.52$$

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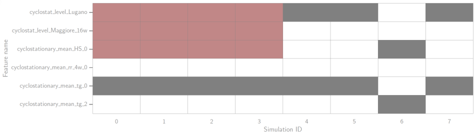

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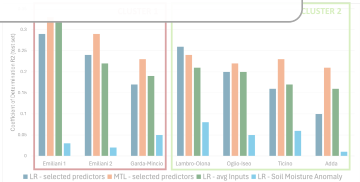

Take-home messages

- Impact based drought indices → 👍 Generalizable across sectors and spatial domains 👎 Need ML experts and users validation

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- Reconstruction performances → 👍 interpretability of all the steps 👎 limits of linear regression
- (Causal) Feature Importance → 👍 relevant information extracted 👎 more variables could be included for improvements

Thank you!

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References

- Beraha, M., Metelli, A. M., Papini, M., Tirinzoni, A., and Restelli, M. (2019).
  Feature selection via mutual information: New theoretical insights.
  In *2019 international joint conference on neural networks*, pages 1–9. IEEE.
- Bonetti, P., Metelli, A. M., and Restelli, M. (2023).
  Nonlinear feature aggregation: Two algorithms driven by theory.
  arXiv preprint arXiv:2306.11143.
- Bonetti, P., Metelli, A. M., and Restelli, M. (2024).
  Causal feature selection via transfer entropy.
  In *2024 International Joint Conference on Neural Networks (IJCNN)*, pages 1–10.
- Runge, J., Nowack, P., Kretschmer, M., Flaxman, S., and Sejdinovic, D. (2019).
  Detecting and quantifying causal associations in large nonlinear time series datasets.
  Science advances, 5(11):eaau4996.
- Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Beguería, S., Trigo, R., López-Moreno, J. I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., et al. (2013).
  Response of vegetation to drought time-scales across global land biomes.
  Proceedings of the National Academy of Sciences, 110(1):52–57.

References (cont.)

Zaniolo, M., Giuliani, M., Castelletti, A. F., and Pulido-Velazquez, M. (2018).
Automatic design of basin-specific drought indexes for highly regulated water systems.
Hydrology and Earth System Sciences, 22(4):2409–2424.