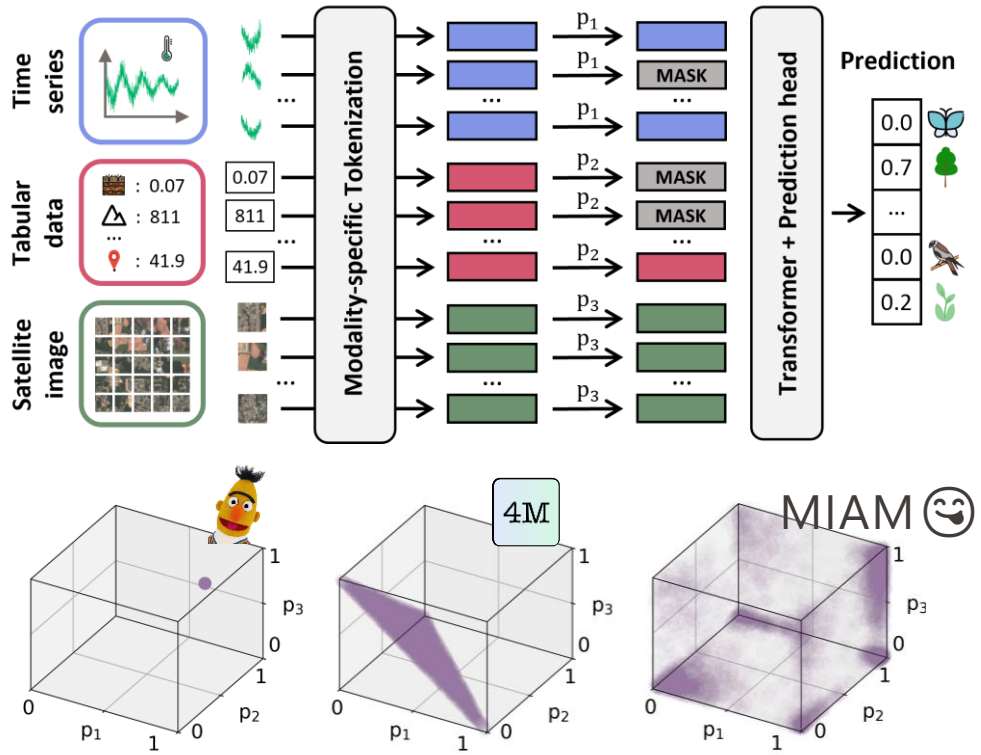
MIAM: Modality Imbalance-Aware Masking for Multimodal Ecological Applications

ICLR 2026

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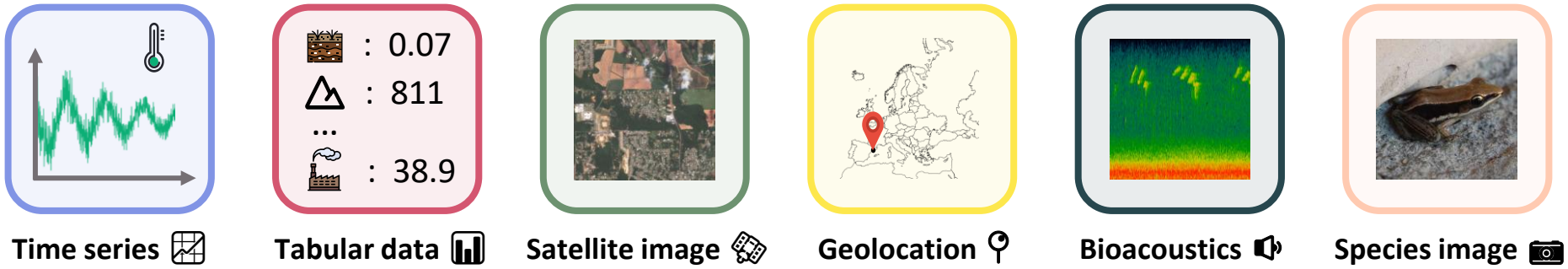
Ecological data are multimodal, but incomplete

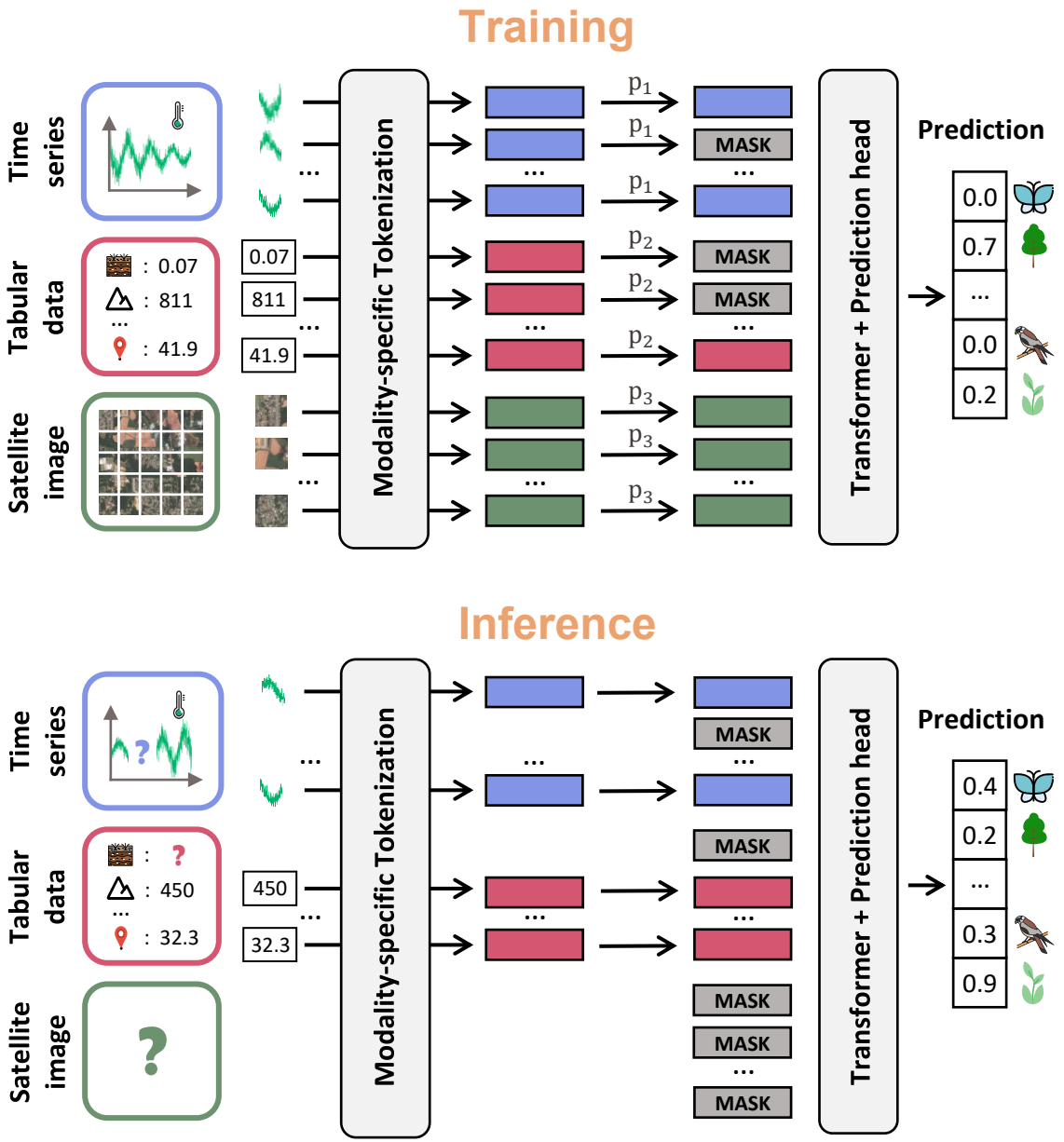


- **Challenge**: Inconsistently available **across space and time**, at multiple levels:
  - **Modality level** — e.g., unavailable satellite image due to cloud cover
  - **Within modalities** — e.g., missing records in a climate time series

- **Objective**: Build models that **work with whatever data are available**
  - Robust to **missing modalities** and **partial observations within modalities**
  - Enable **interpretable input contribution** across and within modalities

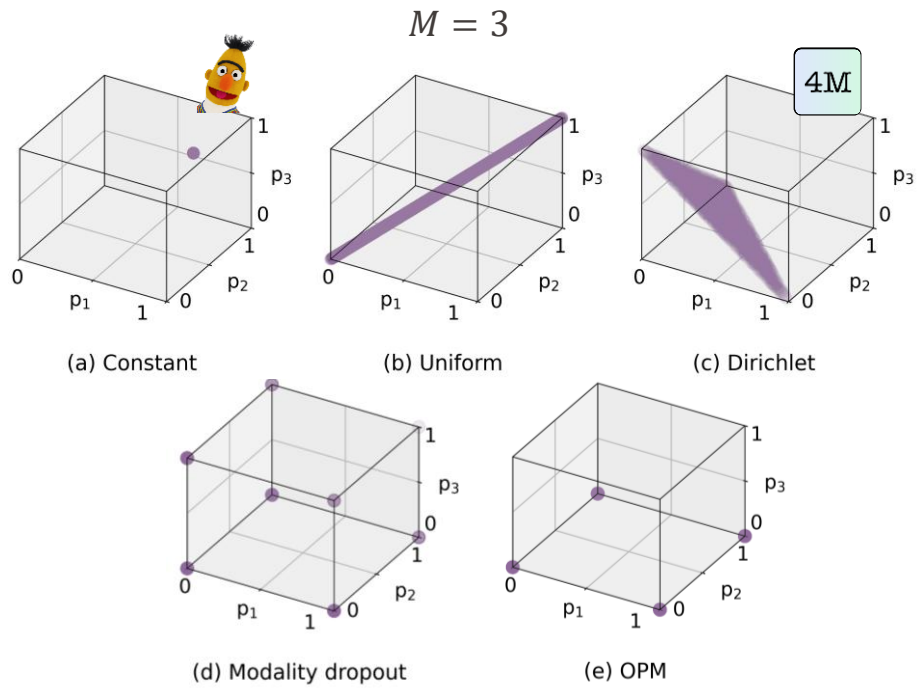
Masking for robustness to missing inputs

- Multimodal **transformer** where each modality is tokenized into tokens
- During **training**, tokens are **randomly masked** at each iteration to expose the model to diverse input subsets
- At **inference**, the model can handle **any subset of tokens**

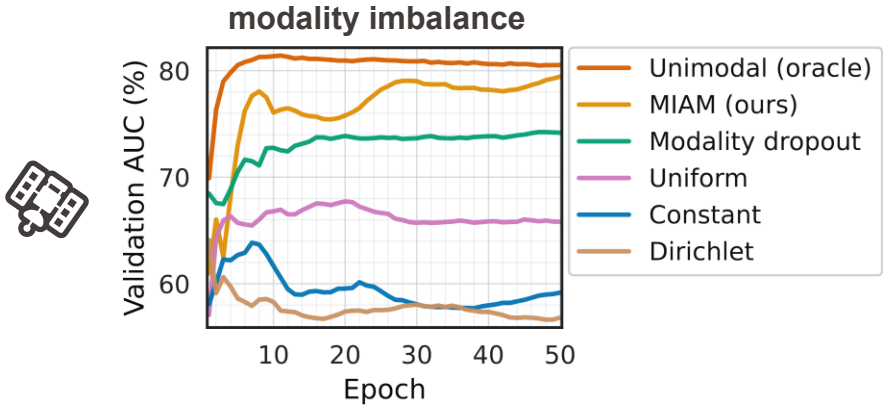


How to effectively mask?

- **Masking strategies viewed as probability distributions** $\mathbf{p} = (p_1, \ldots, p_M)$ over the unit hypercube with M modalities
- Each token of modality m is masked with probability p_m

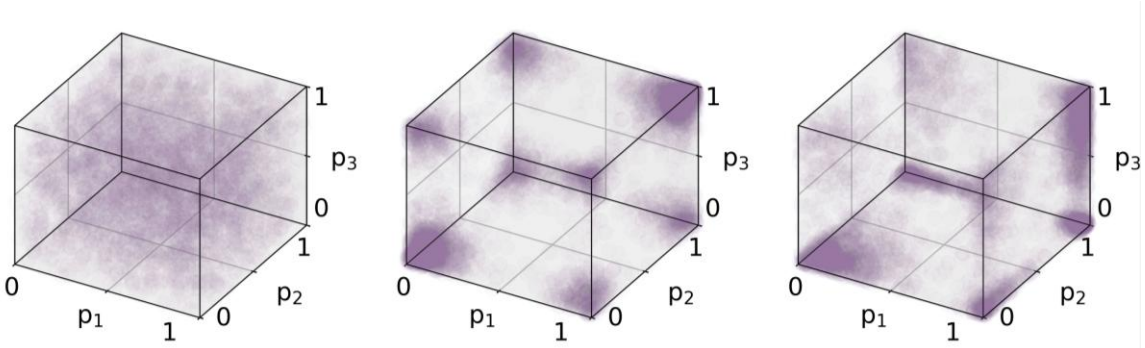


- **Limitations with existing strategies:**
  - Poorly explore the space of input subsets
  - Fixed and uniform
  - **Modality imbalance**, where dominant modalities hinder effective optimization

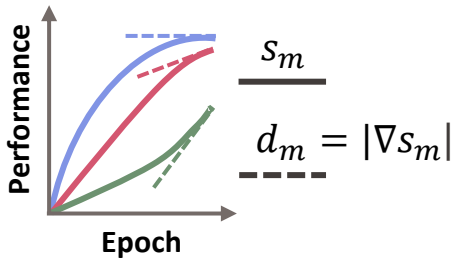


MIAM: Modality Imbalance-Aware Masking

- **Design principles**:
  - Full support
  - Corner prioritization
  - Imbalance-awareness
- Based on a **mixture of product beta distribution**
- **Dynamic score-driven masking**:
  - Modalities that underperform are masked less (unimodal performance s_m)
  - Modalities that are improving are masked less (derivative of unimodal performance d_m)



(f) Uniform hypercube (g) Beta hypercube (h) MIAM



$$s_1\uparrow,\ d_1\downarrow \longrightarrow p_1\uparrow$$
$$s_2\uparrow,\ d_2\uparrow \longrightarrow p_2\rightarrow$$
$$s_3\downarrow,\ d_3\uparrow \longrightarrow p_3\downarrow$$

$$\rho_{s_m} = \frac{s_m}{\left(\prod_{m'=1}^{M} s_{m'}\right)^{1/M}}$$

$$\rho_{d_m} = \frac{d_m}{\left(\prod_{m'=1}^{M} d_{m'}\right)^{1/M}}$$

$$f_c(\mathbf{p}) = \prod_{m=1}^{M} \begin{cases} \text{Beta}\left(p_m;\ 1,\ \kappa \cdot \left(\frac{\rho_{s_m}}{\rho_{d_m}}\right)^{-\lambda}\right) & \text{if } c_m = 0 \\ \text{Beta}\left(p_m;\ \kappa \cdot \left(\frac{\rho_{s_m}}{\rho_{d_m}}\right)^{\lambda},\ 1\right) & \text{if } c_m = 1 \end{cases}$$

$$\text{MixProdBeta}(\mathbf{p}) = \sum_{c \in \mathcal{C}} w_c \cdot f_c(\mathbf{p})$$

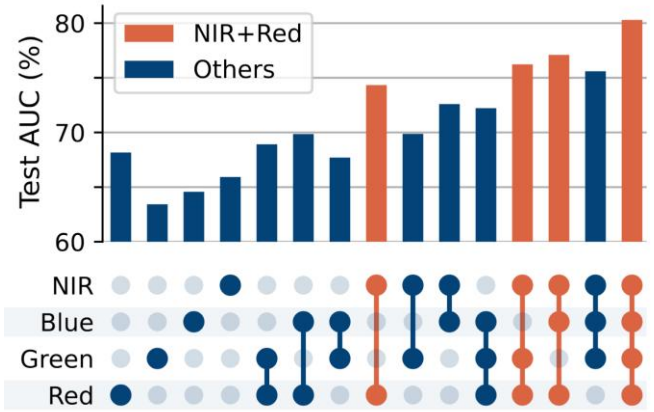
Results

- In **supervised setups**:
  - GeoPlant dataset
  - TaxaBench dataset
- **MIAM outperforms other masking strategies**
  - Especially for dominated modalities
- But also promising in **SSL setups**:

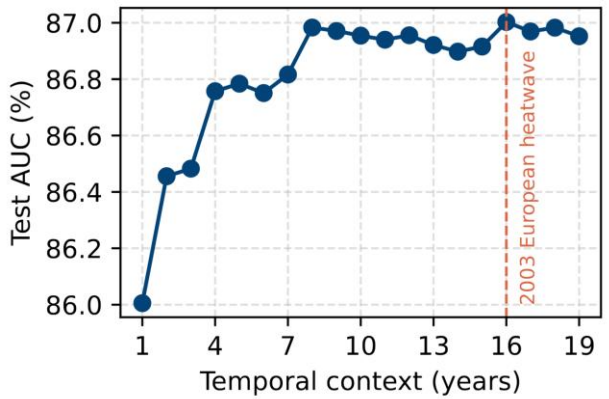
Method	Avg.
Constant	78.3
Uniform	79.3
Dirichlet	77.0
Modality dropout	77.5
OPM	75.3
MIAM (ours)	**79.5**

- It provides **ecological insights**:
  - Spectral bands' importance
  - Extreme event detection

Modality		Input Type											
		Partial Unimodal					Unimodal			Bimodal			All	Avg.
Tabular	BIO1	✔	✔				✔			✔	✔		✔	
	WorldClim		✔				✔			✔	✔		✔	
	Others						✔			✔	✔		✔	
Time series	Clim: 2018			✔	✔			✔		✔		✔	✔	
	Clim: 2000-2018				✔			✔		✔		✔	✔	
	Landsat							✔		✔		✔	✔	
Sat. image	Center patch					✔			✔		✔	✔	✔	
	Others								✔		✔	✔	✔	
Constant		68.6	82.4	84.7	86.7	55.1	83.3	90.0	63.6	90.0	83.3	89.2	87.9	80.4
Uniform		73.3	85.7	**86.3**	**87.2**	61.2	86.9	91.1	65.6	91.6	86.2	**91.8**	**92.0**	83.2
Dirichlet		65.1	82.7	77.8	86.8	54.9	87.5	91.1	58.2	91.8	88.6	91.7	91.4	80.6
Modality dropout		48.7	80.8	77.4	86.4	66.2	88.6	**91.4**	73.2	**92.0**	89.2	91.7	**92.0**	81.5
OPM		68.0	81.9	80.7	85.3	68.1	88.4	90.2	**81.1**	90.7	**89.5**	91.1	91.2	83.8
MIAM (ours)		**78.4**	**86.7**	86.0	87.0	**70.8**	**89.0**	**91.4**	80.1	91.7	**89.5**	91.5	91.7	**86.1**
Oracle (one model per column)		78.0	87.1	87.7	87.6	77.1	89.3	92.2	81.4	92.3	89.7	91.7	92.0	87.2



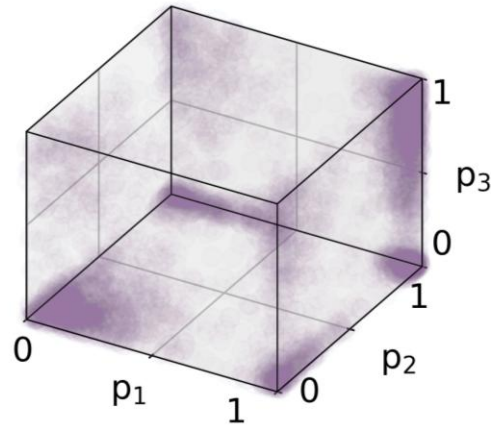
(a) Performance across different spectral band combinations of satellite imagery



(b) Performance with increasing historical climatic context

Takeaways

- **Masking strategy significantly impacts performance**
- Standard masking fails under **modality imbalance**
- We propose **MIAM: Modality Imbalance-Aware Masking**
- Rethinking masking is key for **any-to-any models**

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