Migrating in a warming world: A deep learning approach to predict pan-American seasonal shifts in the monarch butterfly niche

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Introduction

- **Climate change** is profoundly affecting **ecosystem health**, threatening biodiversity and the essential services ecosystems provide to human wellbeing.
- **Migratory species** are highly impacted by environmental changes and serve as **indicators** of ecosystem functioning. The **intrinsic spatiotemporal connectivity** that characterizes migration makes **mapping** their distribution **challenging**.
- **Species Distribution Models** (**SDM**) can identify a species ecological niche, learning the complex relations between environmental variables and species occurrence. SDMs often treat environmental inputs in a **time-static manner**, not only **neglecting the temporal dynamics** that are pivotal to migratory species but also **limiting their predictive ability**.

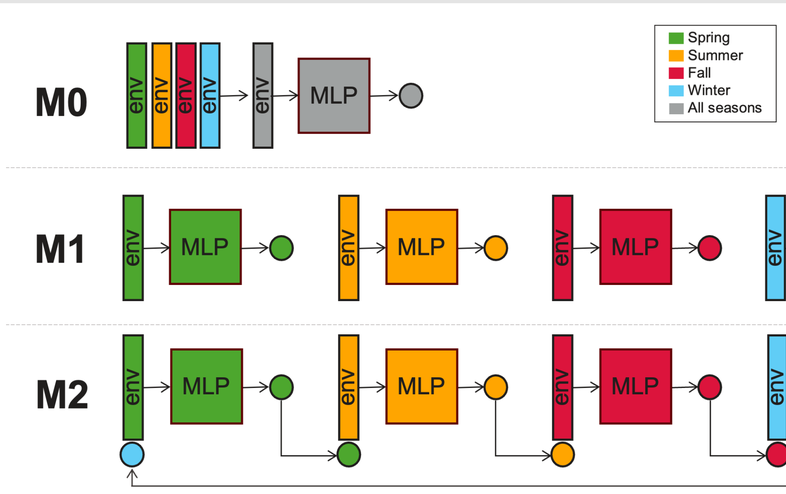
Research goal

We aim to integrate the **temporal dimension** into SDM to generate **dynamic species occurrence probabilities,** enabling:

1) **Tracking of migratory journeys** under current conditions and
2) **Predicting shifts** under **climate change** scenarios.

Materials and methods

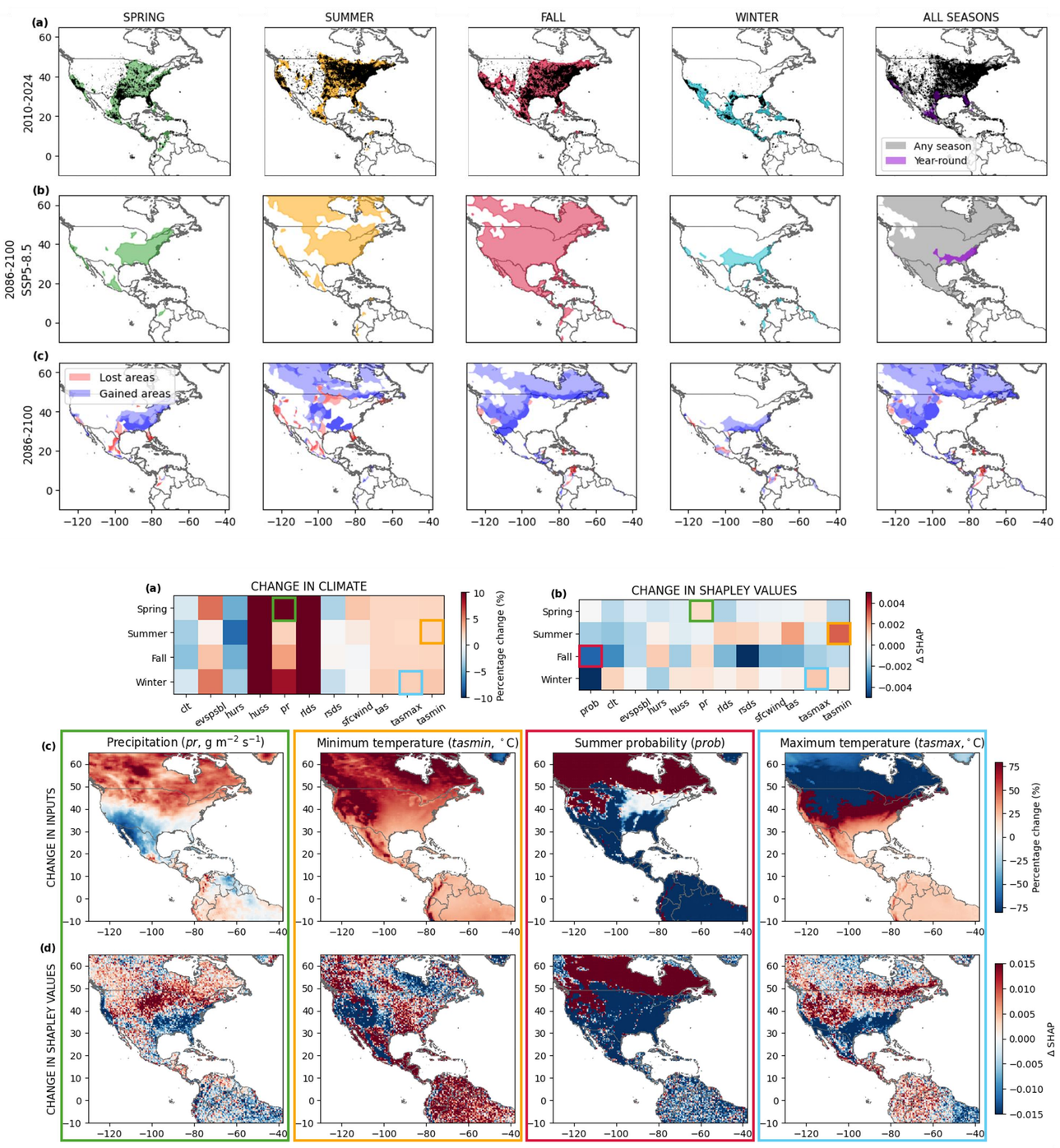
- We select the **monarch butterfly** (*Danaus plexippus*) as study system, a long-term monitored species for biodiversity conservation.
- We use **presence-only data (GBIF)** to train, validate, test, and compare SDM. 11 **monthly climatic variables** are used as environmental descriptors for the past (1990-2004), present (2010-2024), and future (2086-2100) temporal horizons.
- We compare 3 different modeling frameworks: **M0 a time static model**; **M1 seasonal independent models, and M2 seasonal concatenated models** that consider within-season monthly climatic inputs, and the occurrence probability estimated for the previous season.



	Model	AUC_{ROC}	AUC_{PR}	TSS
2010-2024	M0	0.881	0.930	0.683
	M1	0.935 [+6.1%]	0.974 [+4.7%]	0.798 [+16.8%]
	M2	0.944 [+7.0%]	0.978 [+5.2%]	0.805 [+17.9%]
1990-2004	M0	0.874	0.992	0.612
	M1	0.882 [+0.9%]	0.992 [+0%]	0.695 [+13.6%]
	M2	0.898 [+2.7%]	0.993 [+0.1%]	0.713 [+15%]

Results

- **M2** achieves the **best model performance,** better reproduces the present and past niche, and more realistically represents the seasonal distributions of the migratory cycle.
- At the end of the XXI century, we predict a **northwestward shift in the monarch range,** with a significant contraction in California and Mexico, key sites for overwintering that also host resident monarch populations.
- We assess the **difference** ($\Delta SHAP$) **in Shapley values**, **an explainable AI technique** for feature importance, between the future scenarios and the present situation to examine how changes in climatic predictors impact the occurrence of the monarch butterfly. Importantly, we identify the **decrease in precipitation** and an **increase in temperature** as important environmental drivers responsible for the **contraction** of overwintering sites.



Conclusions

- We develop a **time-aware deep learning SDM** that addresses the different role of environmental predictors in time, producing a time-dynamic species occurrence probability, key to follow the journey of migratory species.
- Our predictions hold the potential for **better informing science-based conservation efforts** to face the challenges posed by **global warming.**

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