

## Fringe 2026

University of Krakow, Poland | 15-19 June

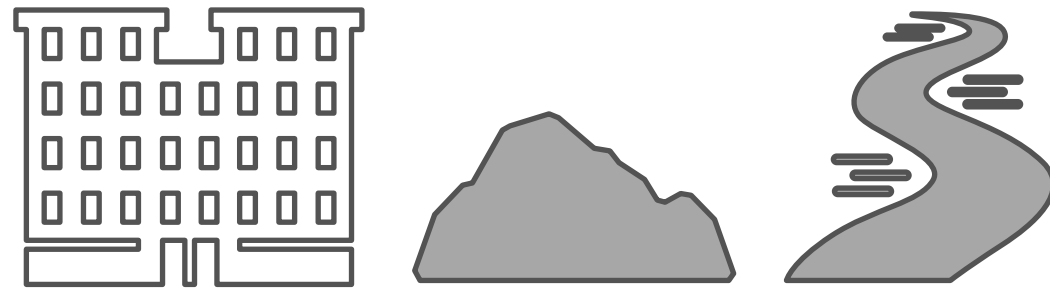
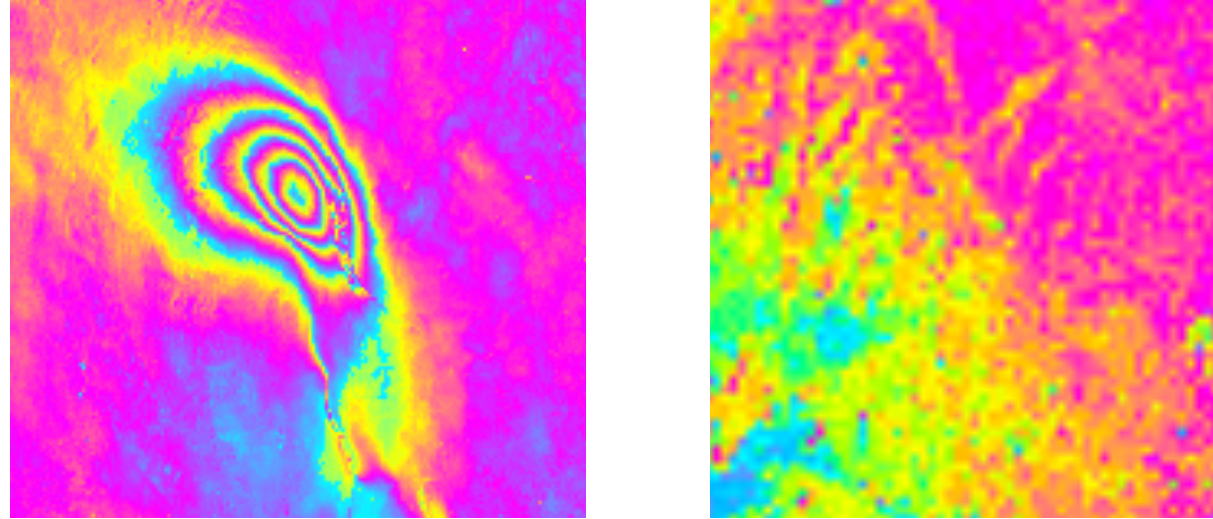
# Tracking subsidence in agricultural regions with InSAR: the issue of intermittent coherence and systematic closure phase.

**Lorette Drique (IPGP/CEA), Béatrice Pinel-Puysségur (CEA), Manon Dalaison, Nobuaki Fuji (IPGP), Sylvain Ferrant (CESBIO), Michael Fournelis (AUTH)**

**Contact : [drique@ipgp.fr](mailto:drique@ipgp.fr)**

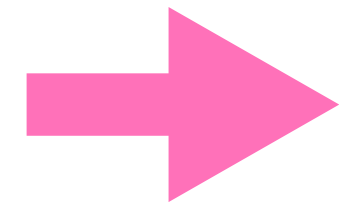
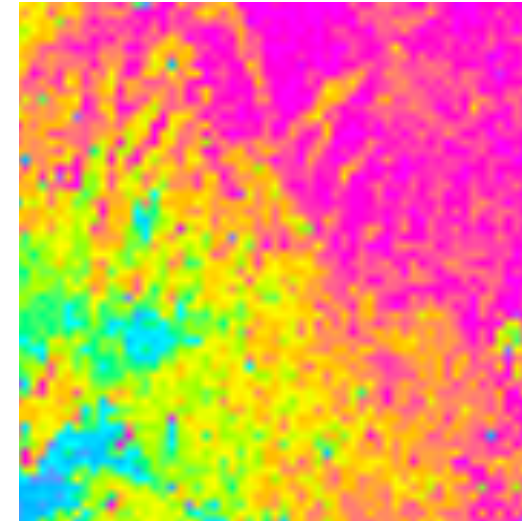
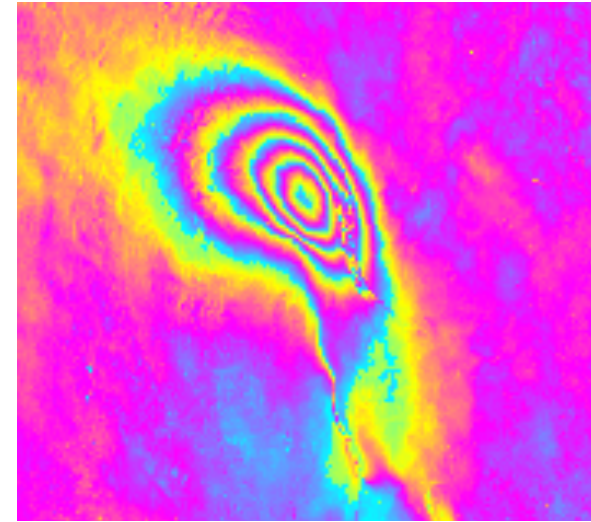
# InSAR-derived deformation

$$\Phi_{ij} = \angle z_j z_i^*$$



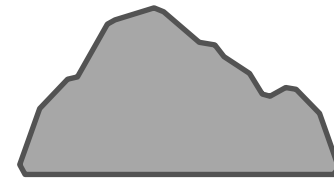
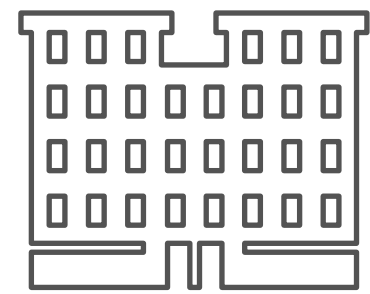
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High coherence

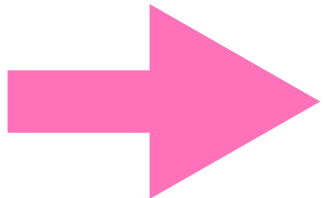
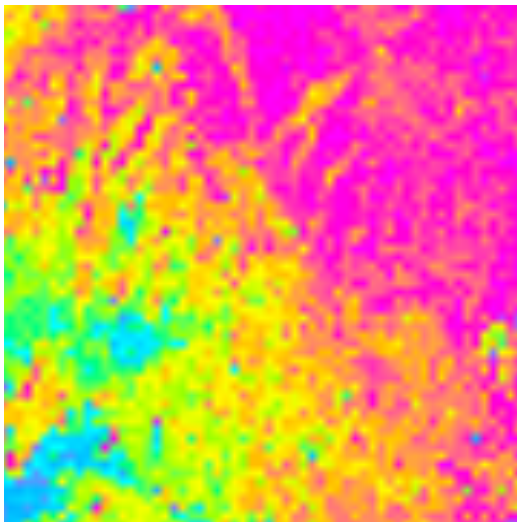
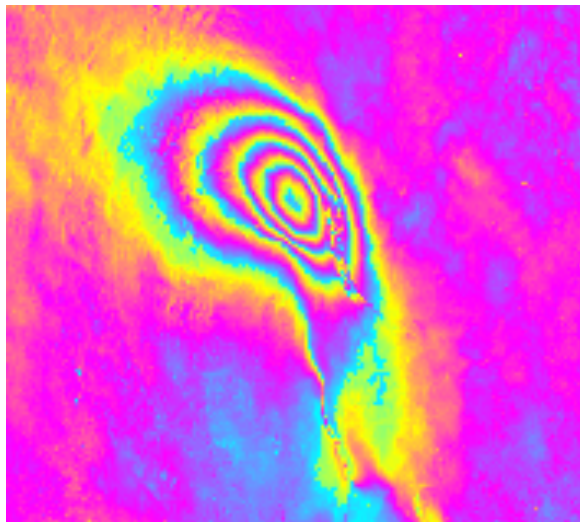
millimeter-precision  
deformation time  
series





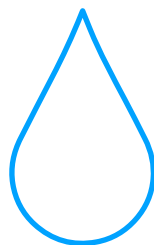
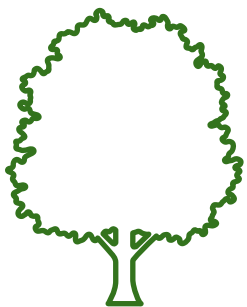
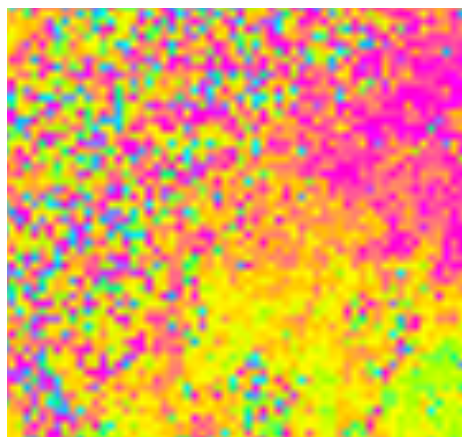
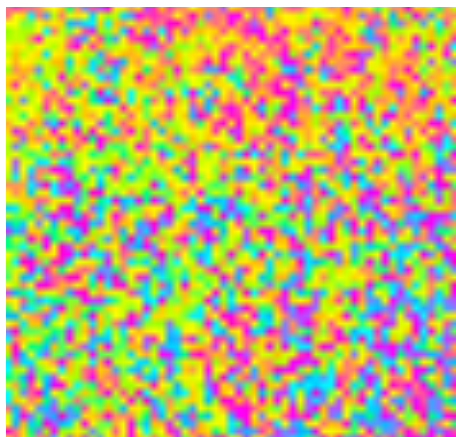
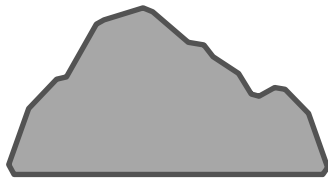
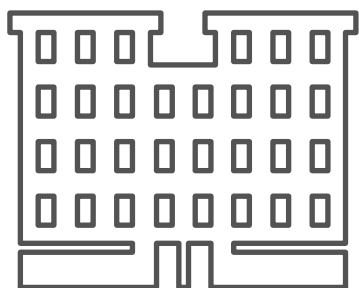
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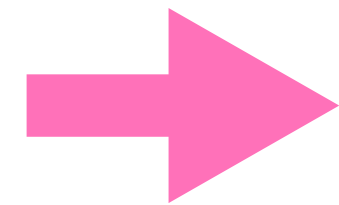
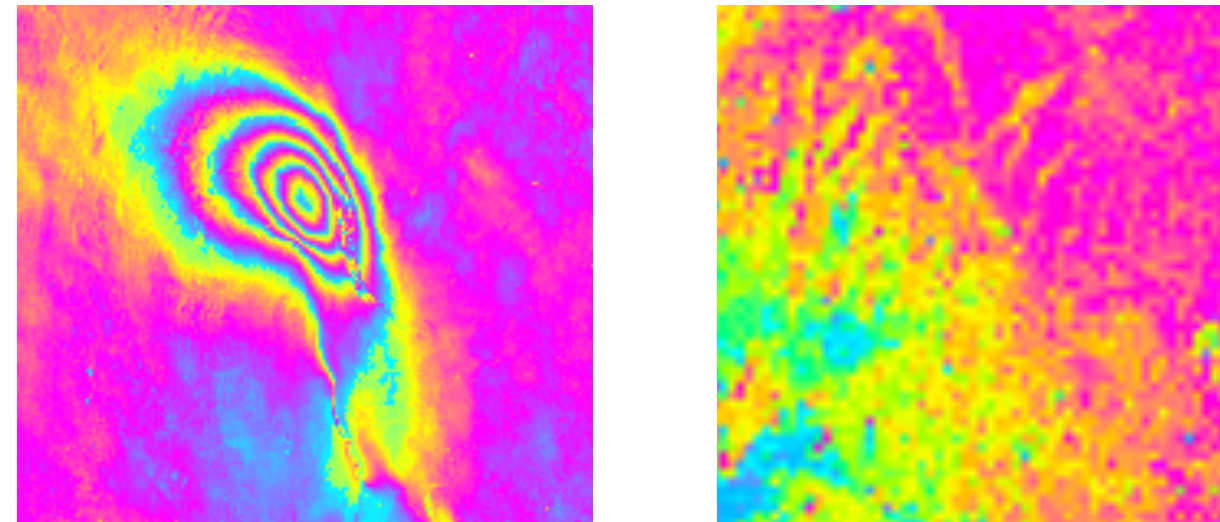
millimeter-precision  
deformation time  
series





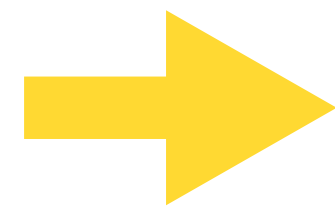
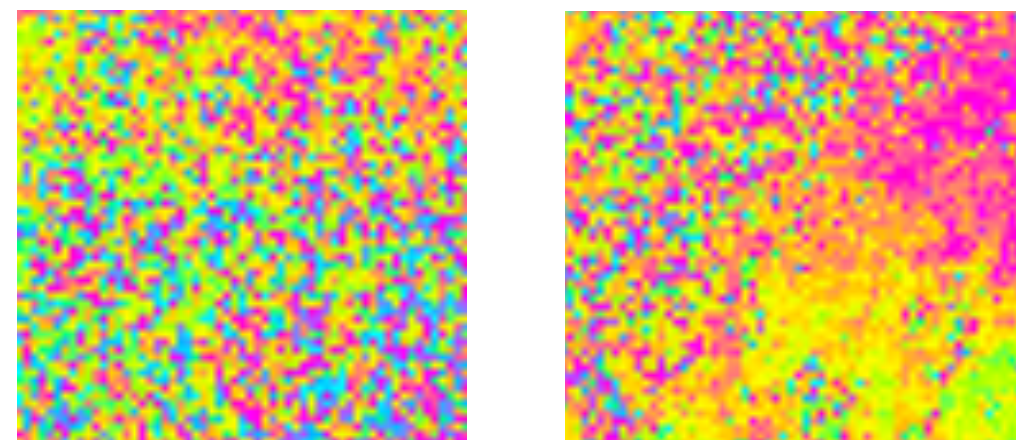
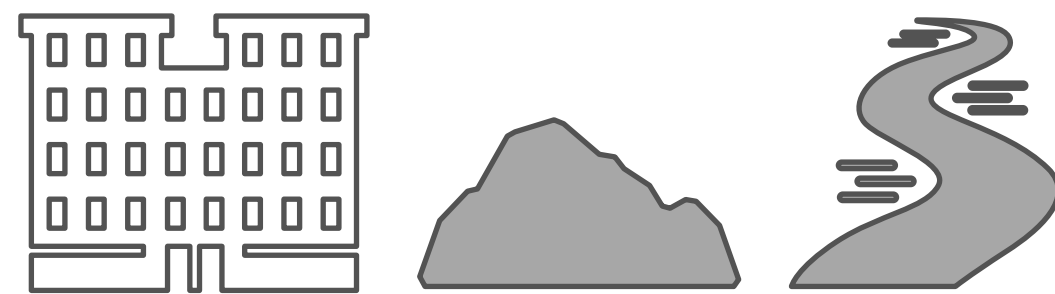
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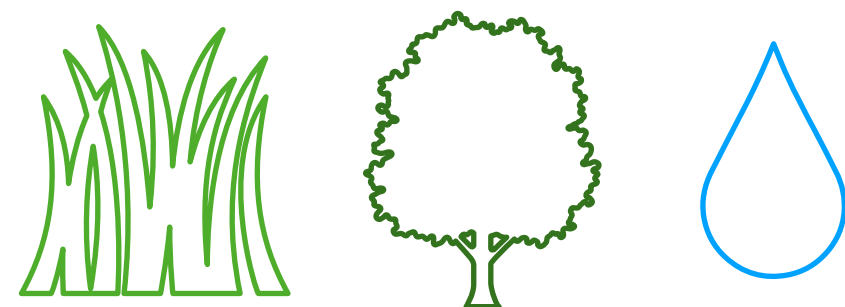
High coherence

millimeter-precision  
deformation time  
series



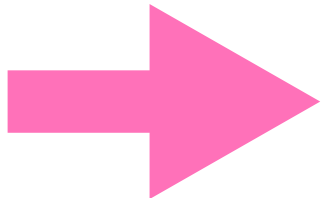
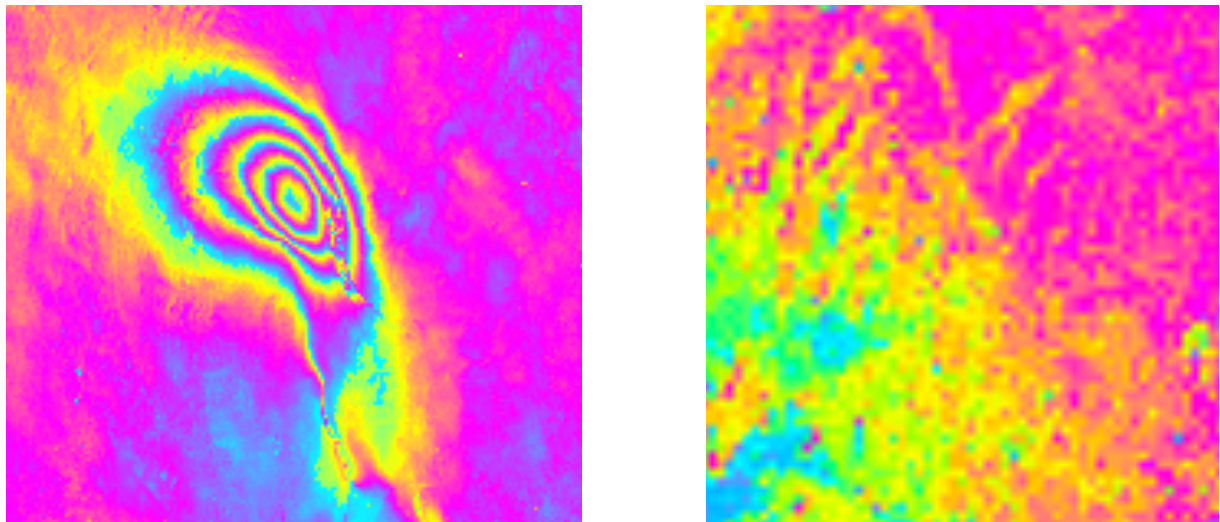
Low coherence

little-to-no  
interferometric  
information

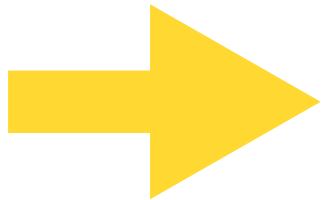
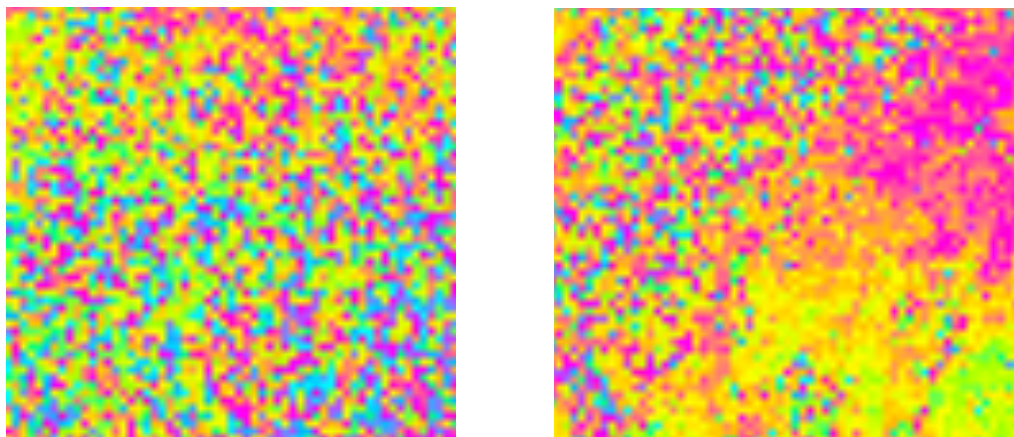
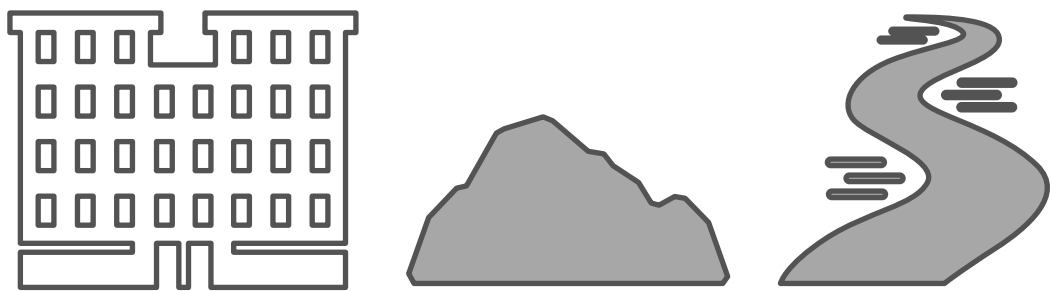


# InSAR-derived deformation

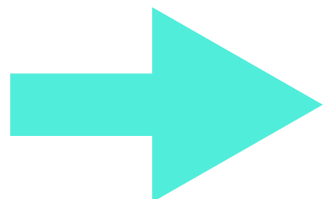
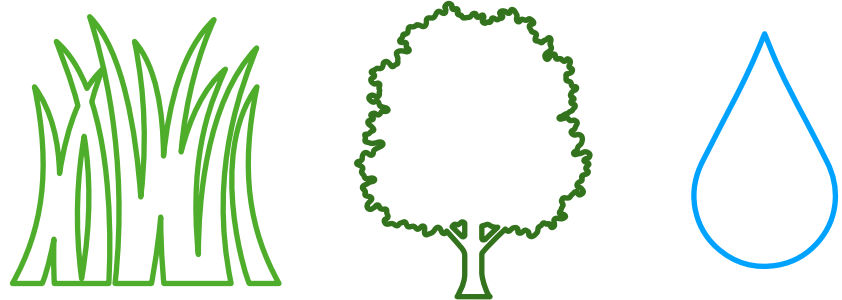
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High coherence  
millimeter-precision  
deformation time  
series

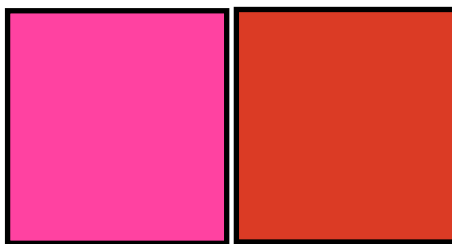
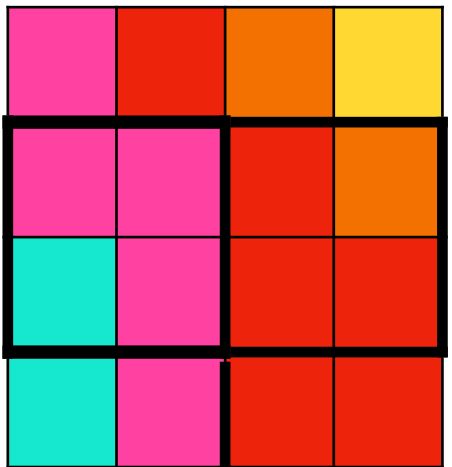


Low coherence  
little-to-no  
interferometric  
information



## Multilooking

Lee et al. 1994



Noise reduction  
& downgraded  
resolution

Inconsistencies between  
interferograms

# A systematic phase delay over crops

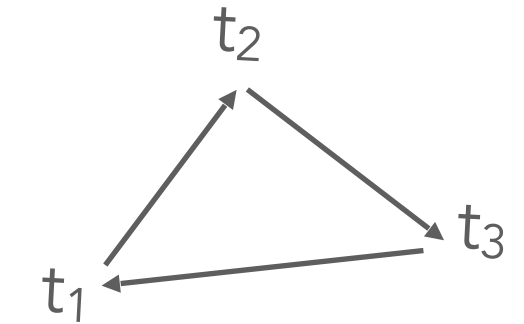




# A systematic phase delay over crops



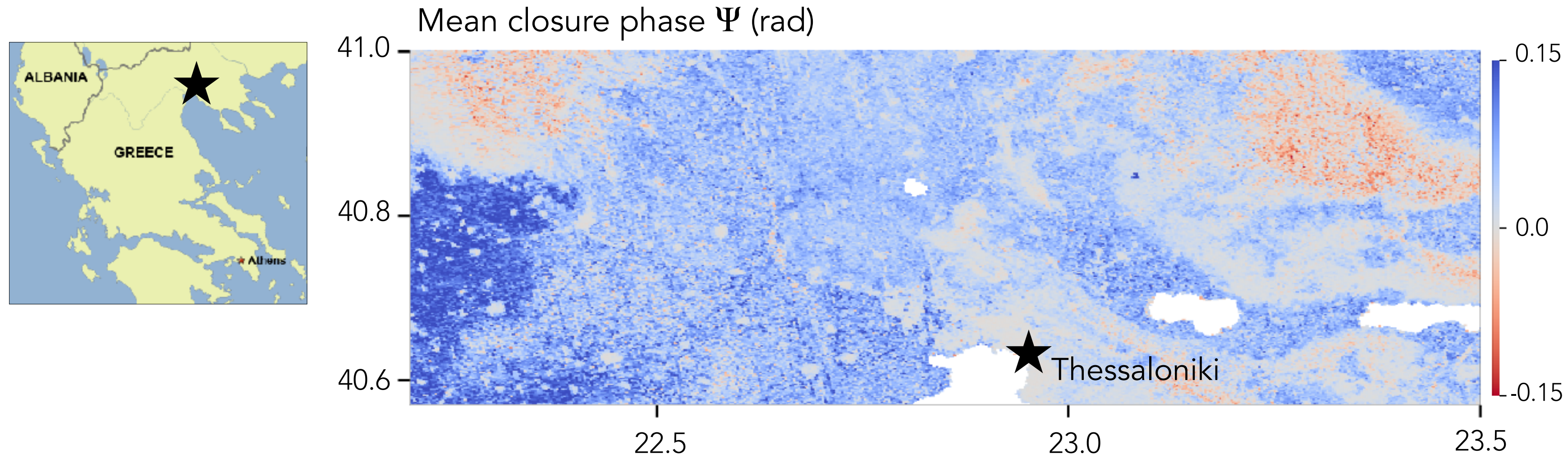
Triplet of interferograms



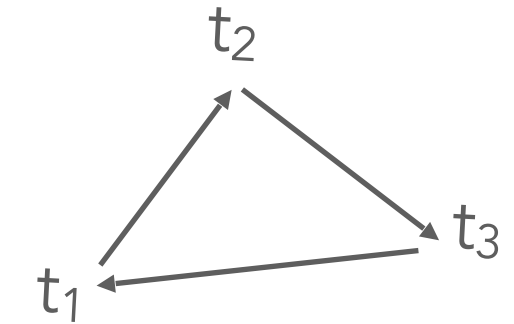
$$\overline{\phi}_{12} + \overline{\phi}_{23} - \overline{\phi}_{13} = \Psi_{123}$$

Closure phase with  
non-zero mean

# A systematic phase delay over crops



Triplet of interferograms

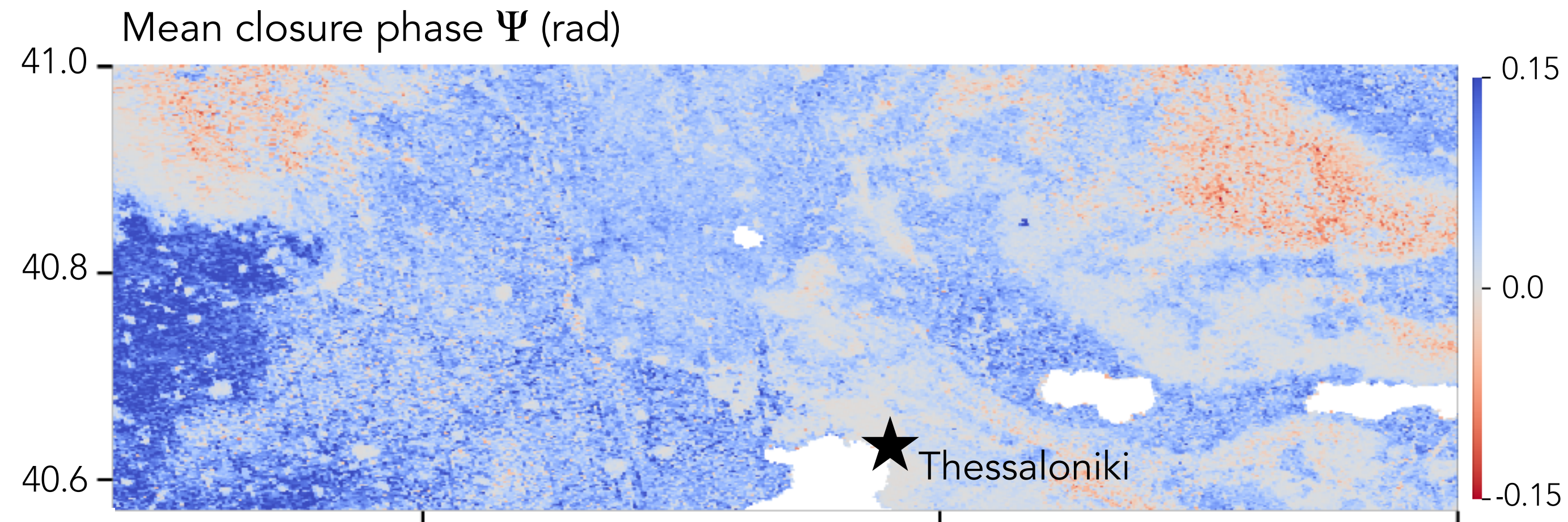


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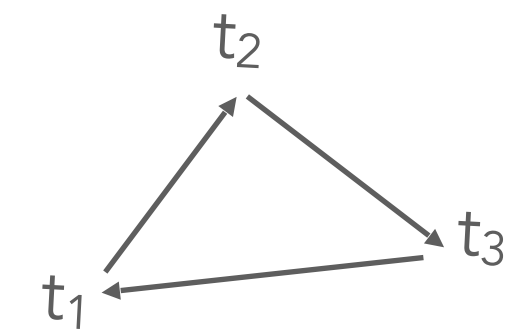
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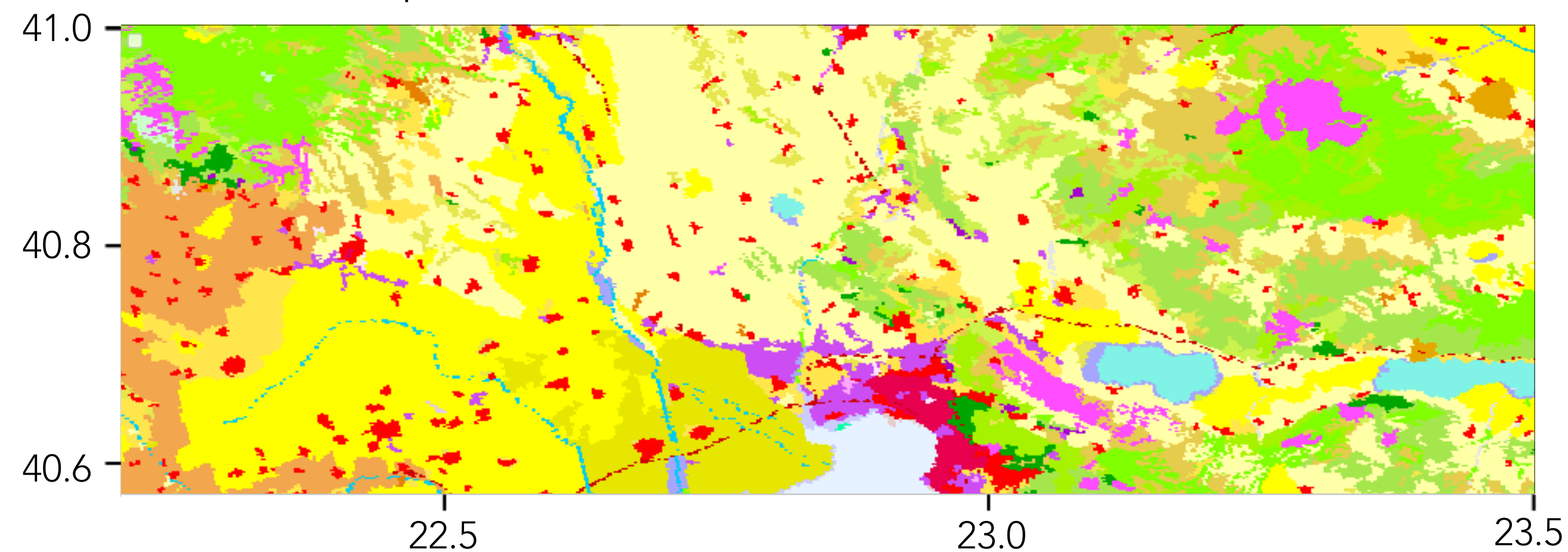
Triplet of interferograms



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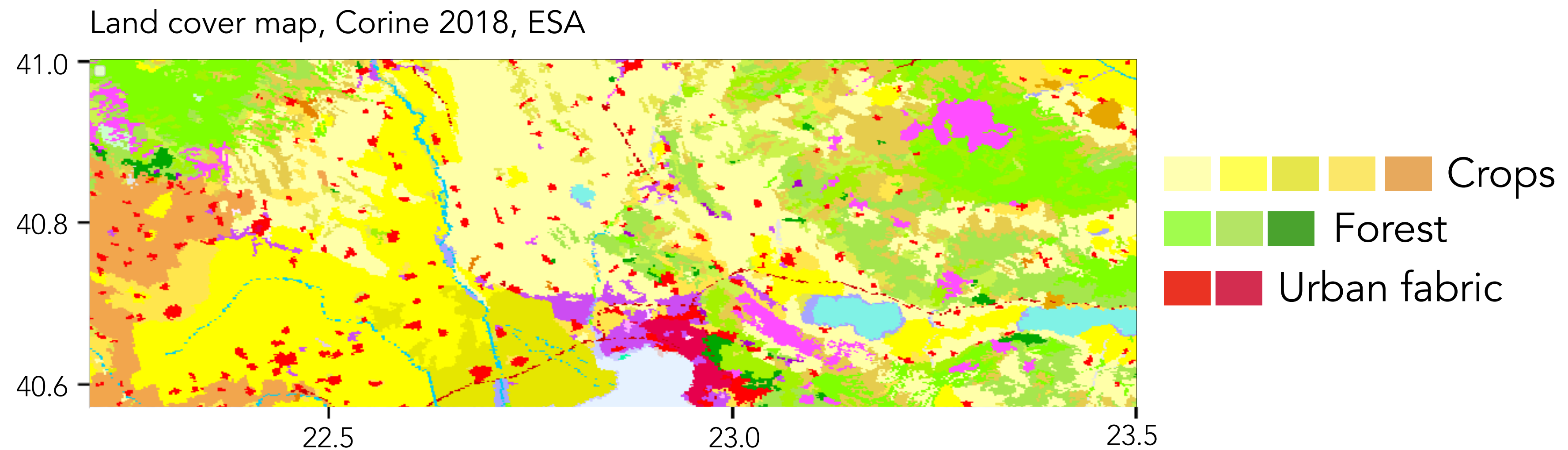
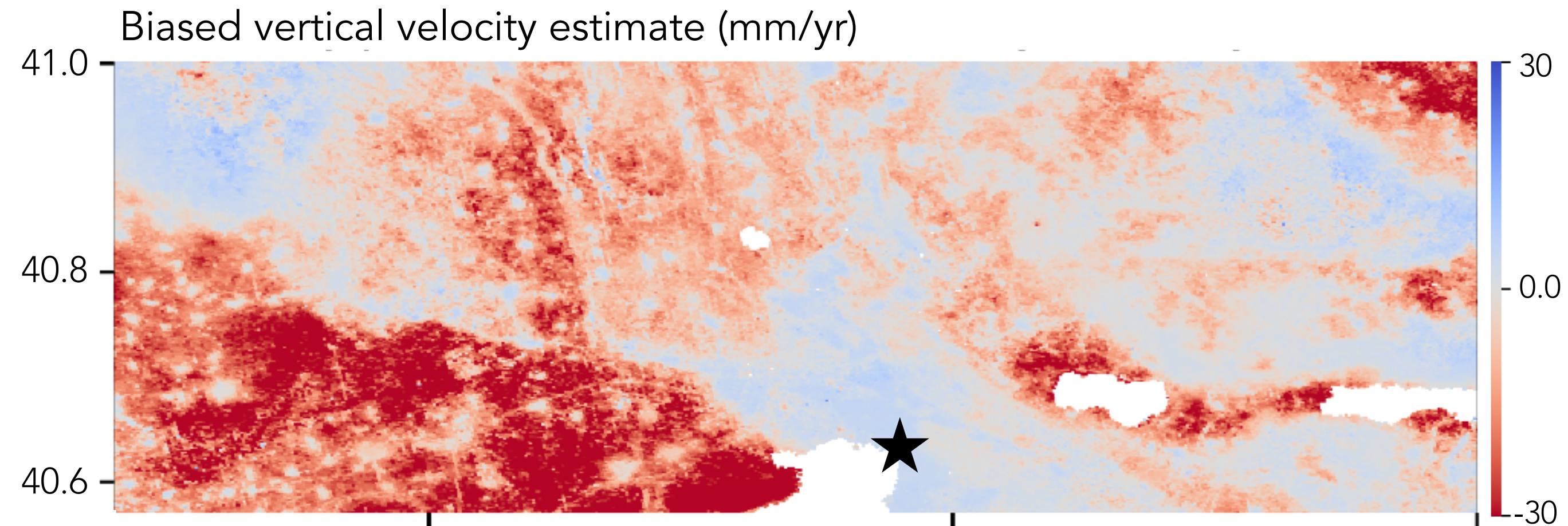
Closure phase with non-zero mean

Land cover map, Corine 2018, ESA





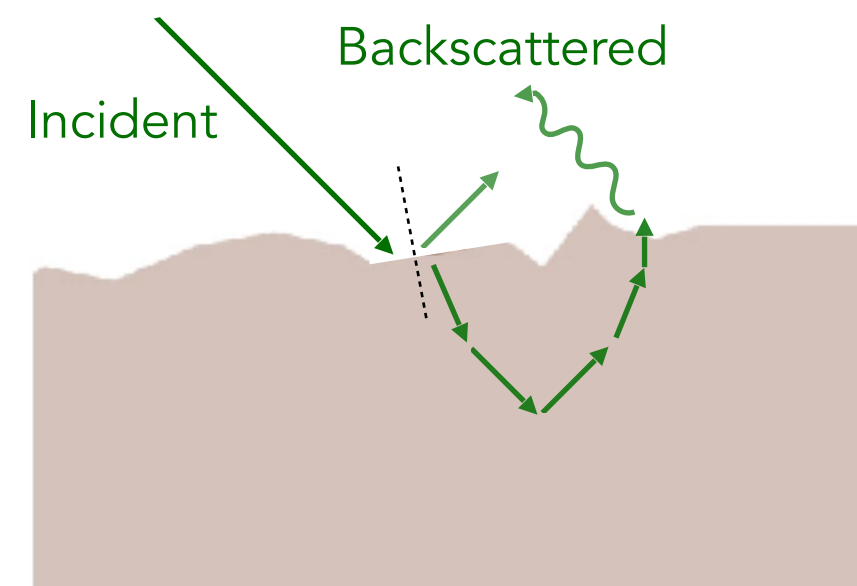
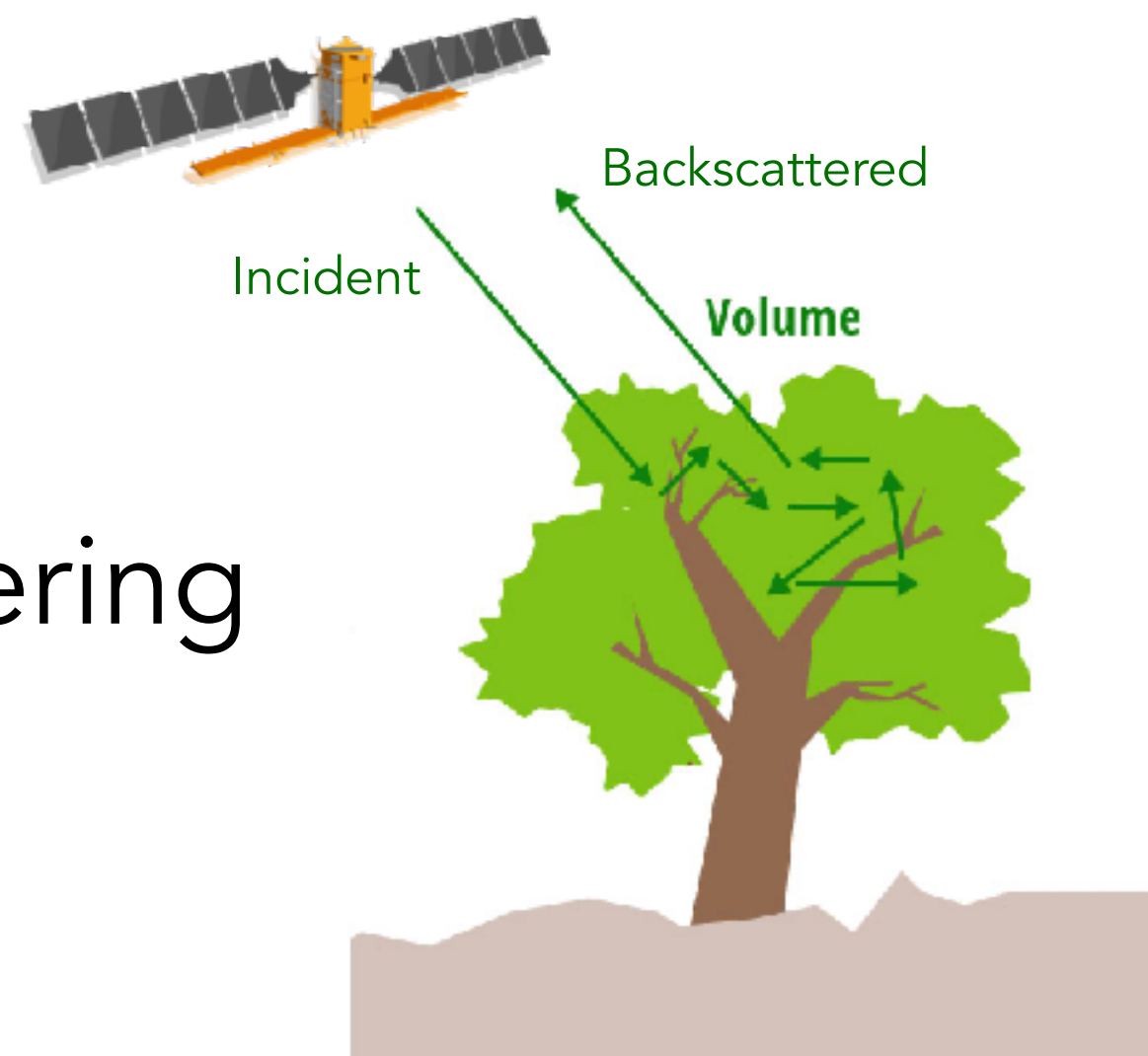
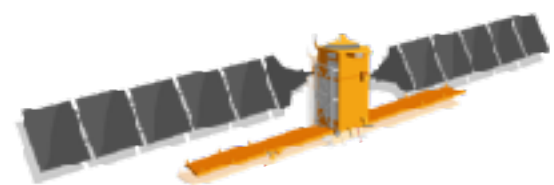
# A systematic bias in deformation estimates



# The closure phase problem

Variable dielectric      Volume scattering

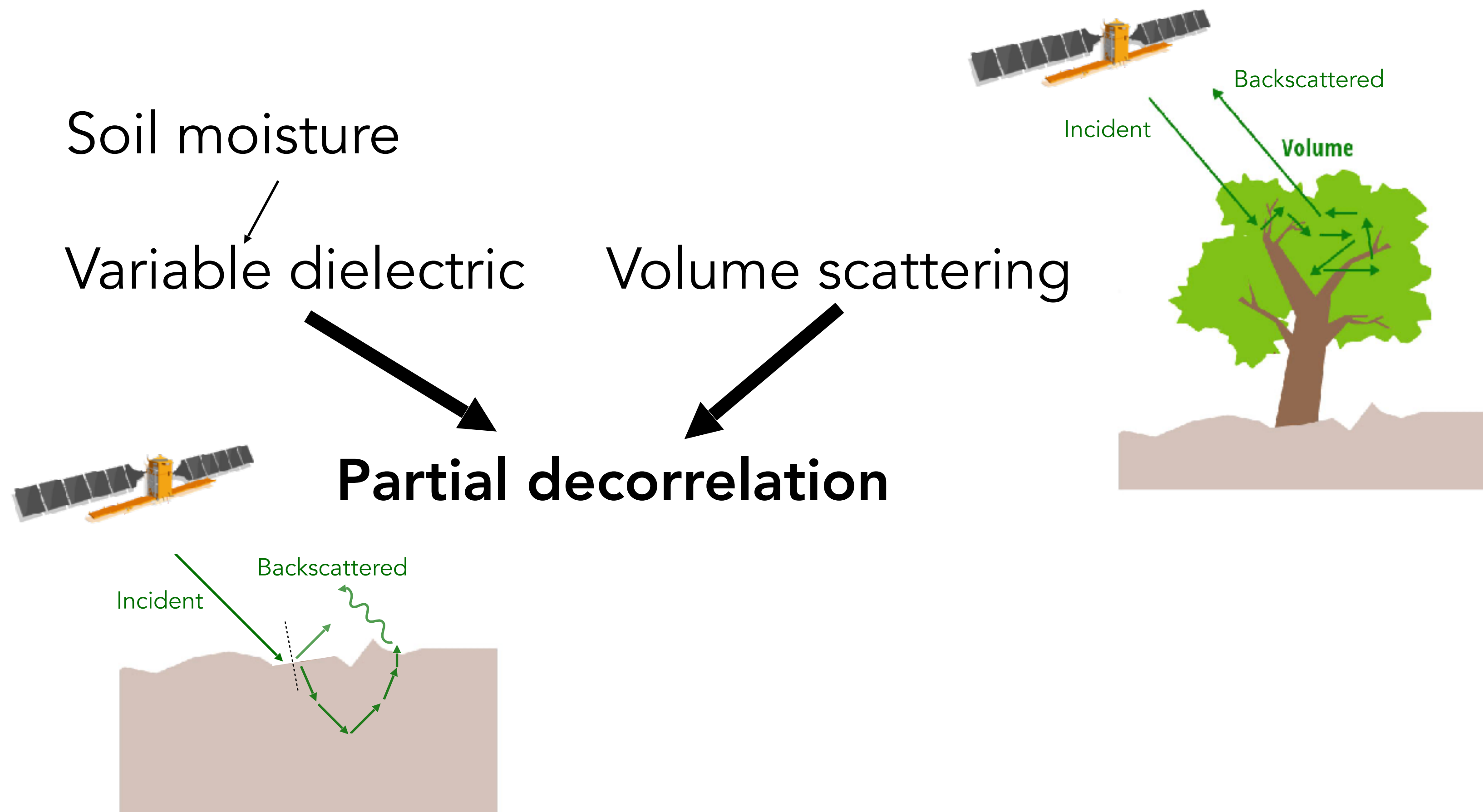
**Partial decorrelation**



De Zan et al. (2015)

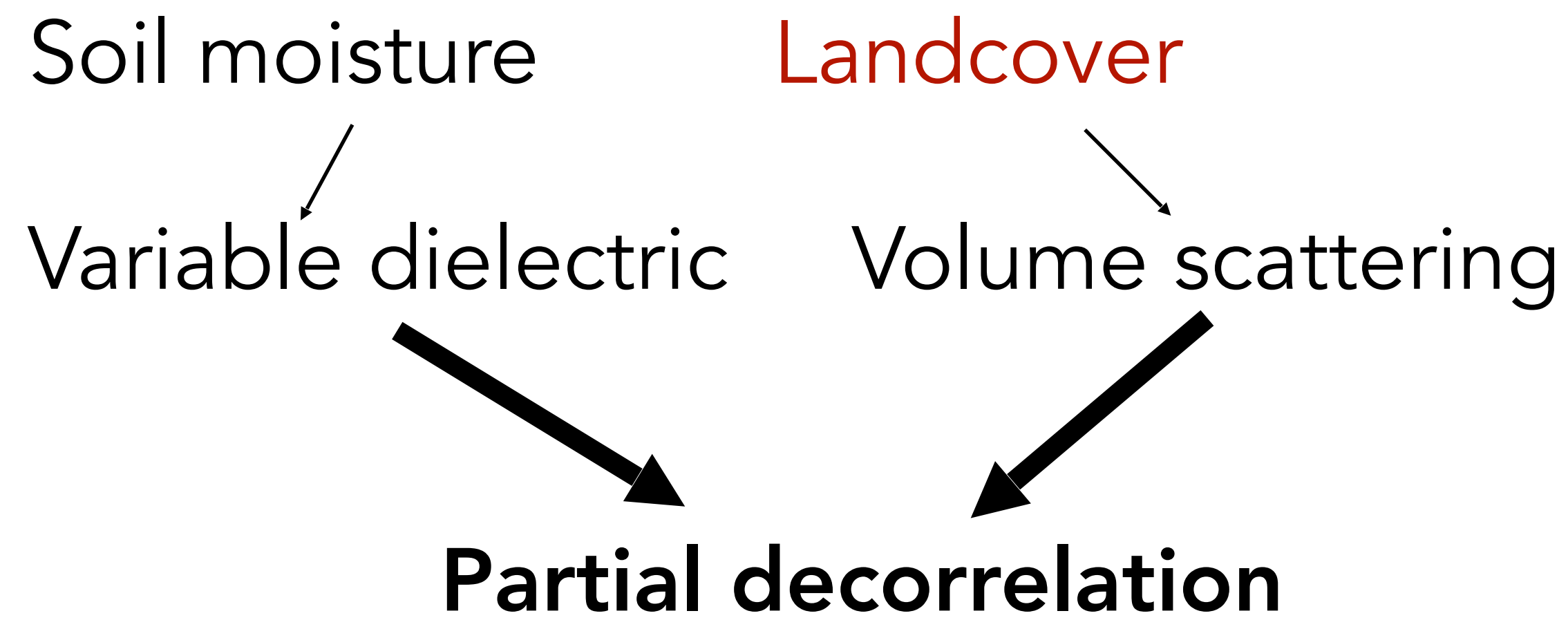


# The closure phase problem

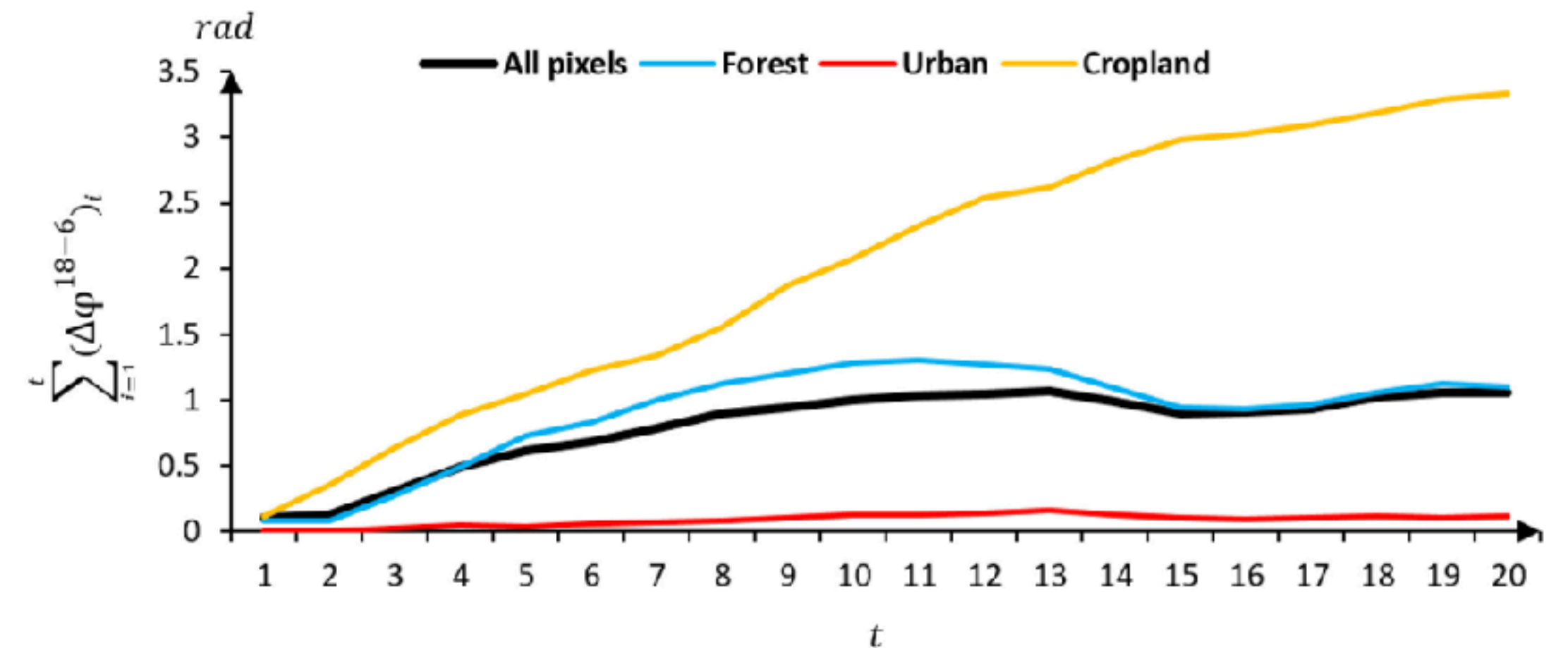


De Zan et al. (2015)

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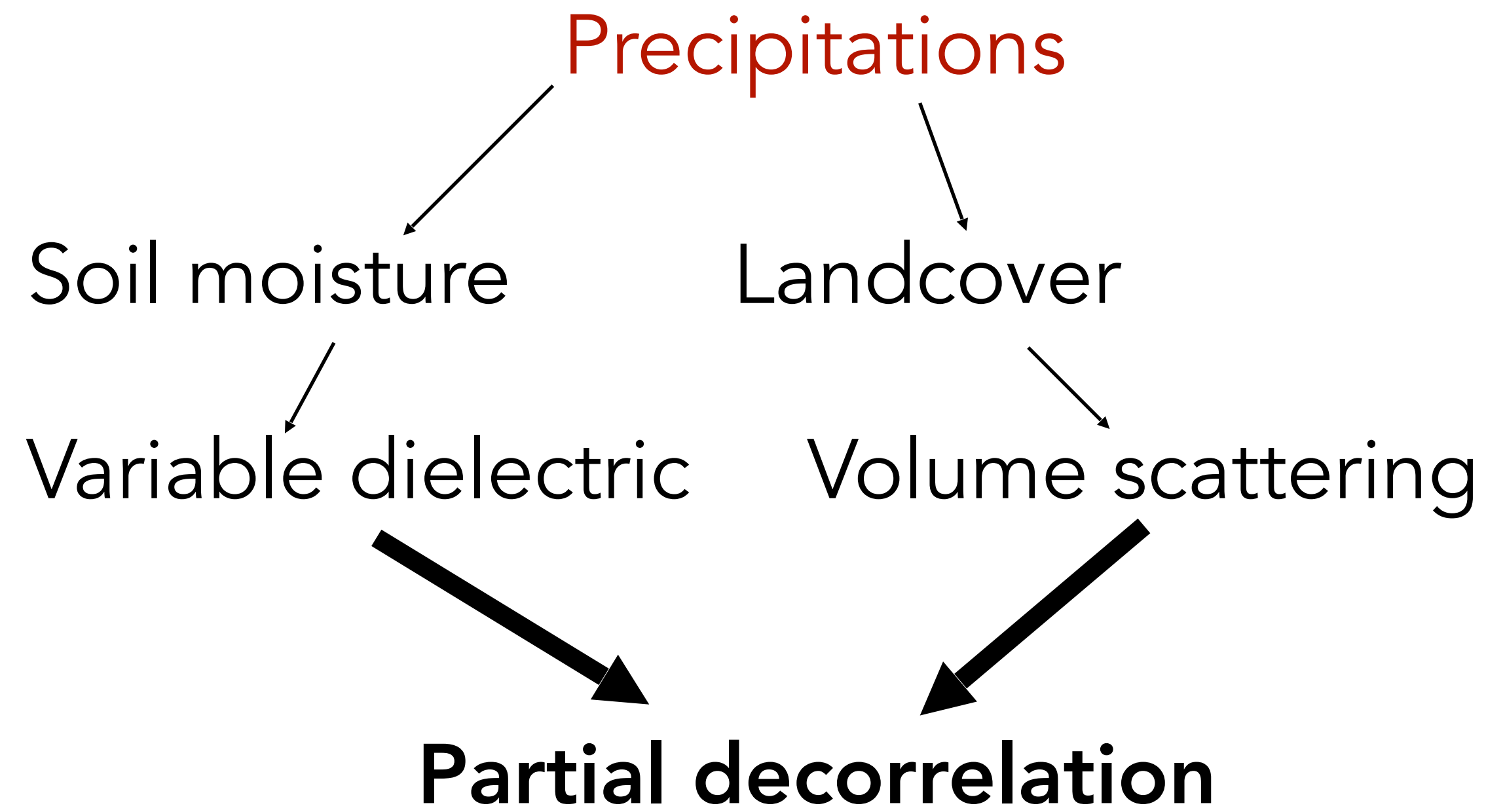


From Maghsoudi et al. (2022)

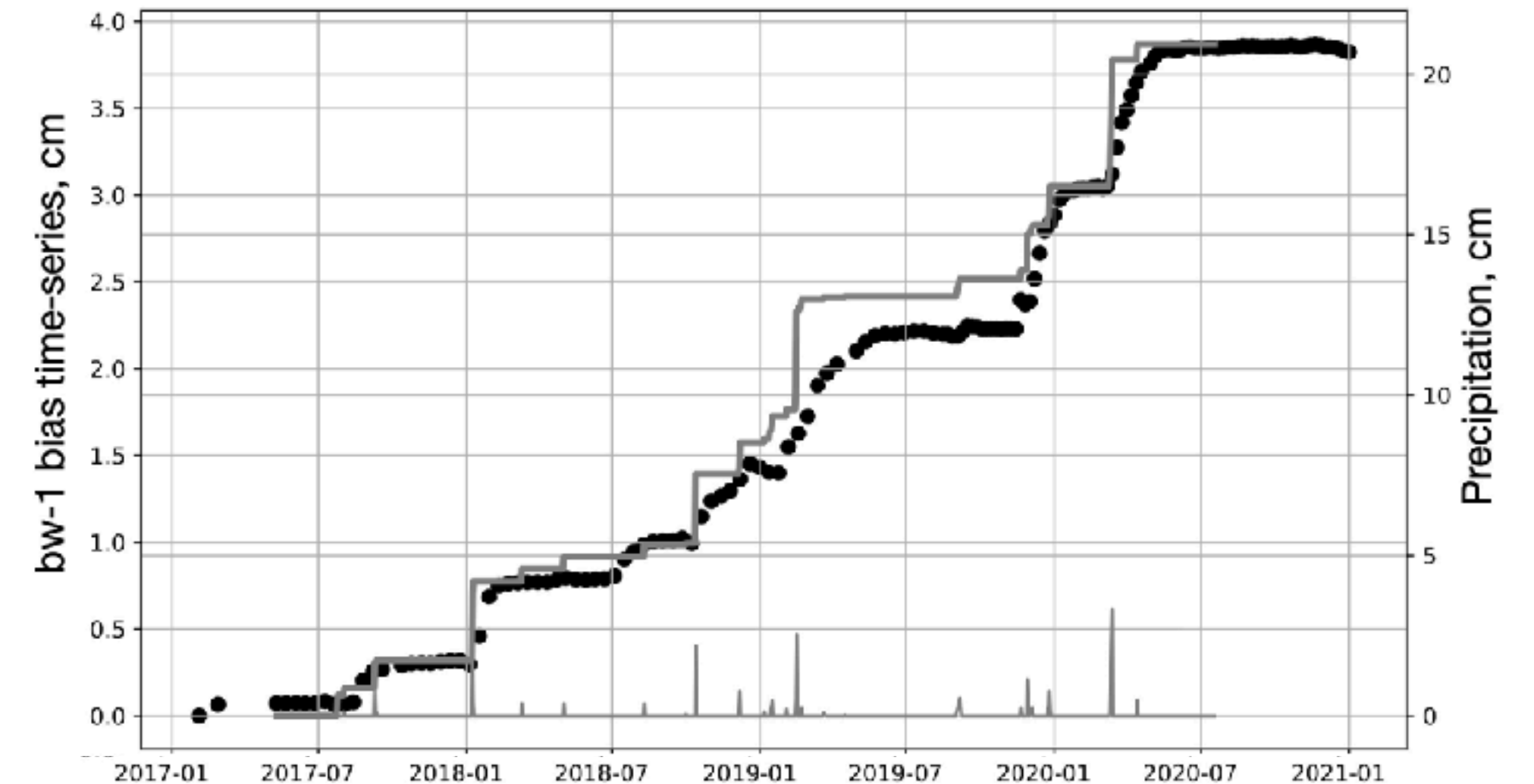




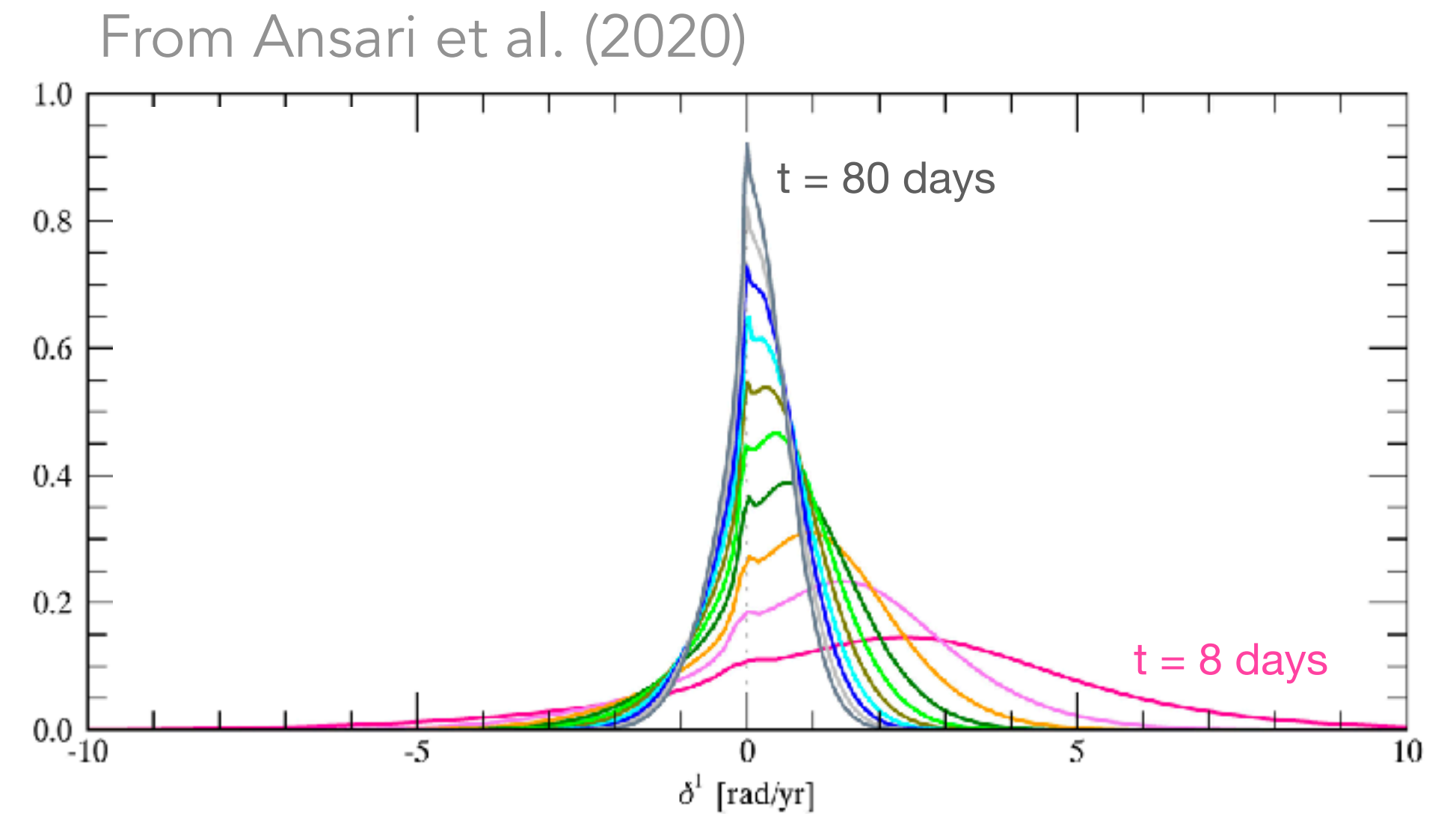
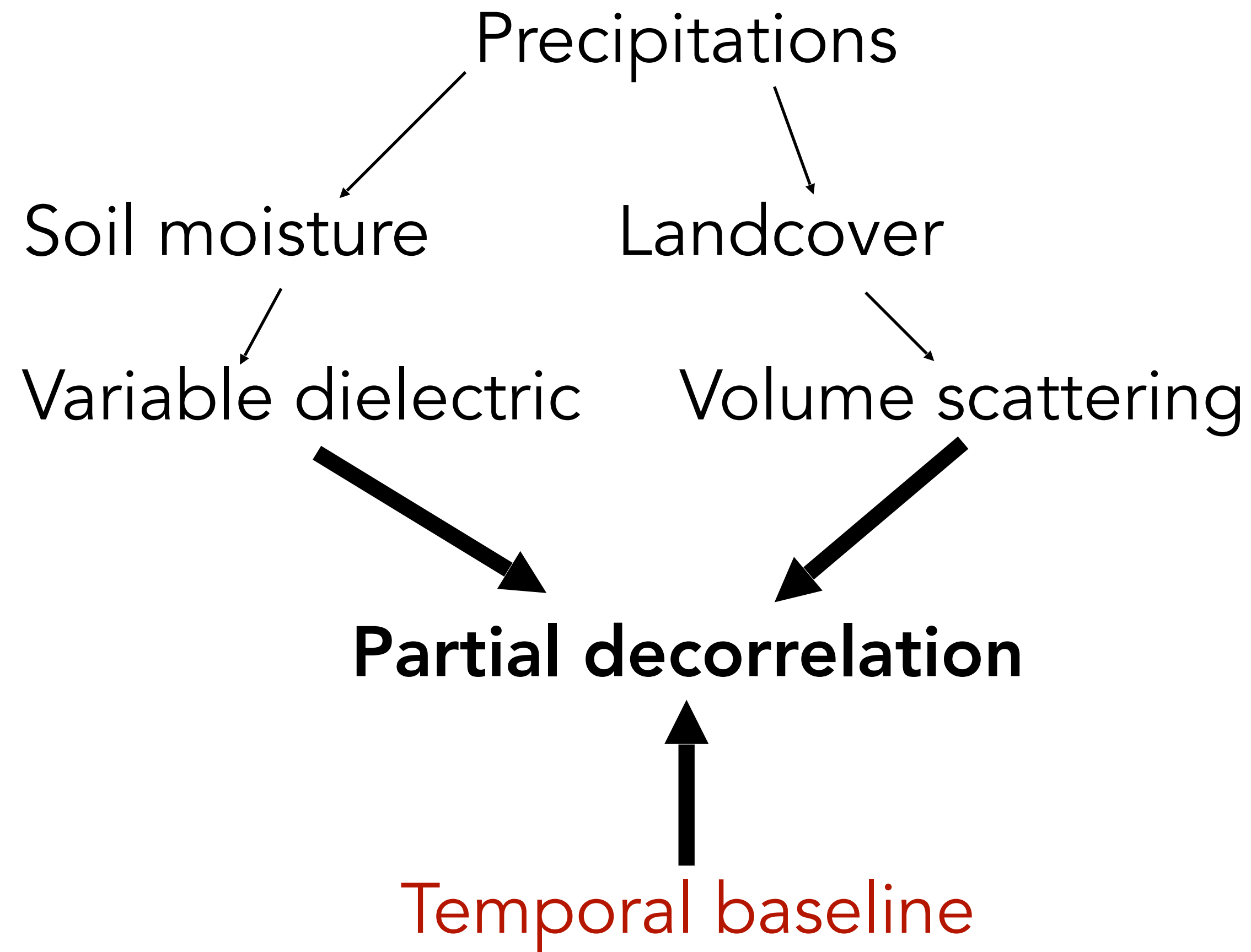
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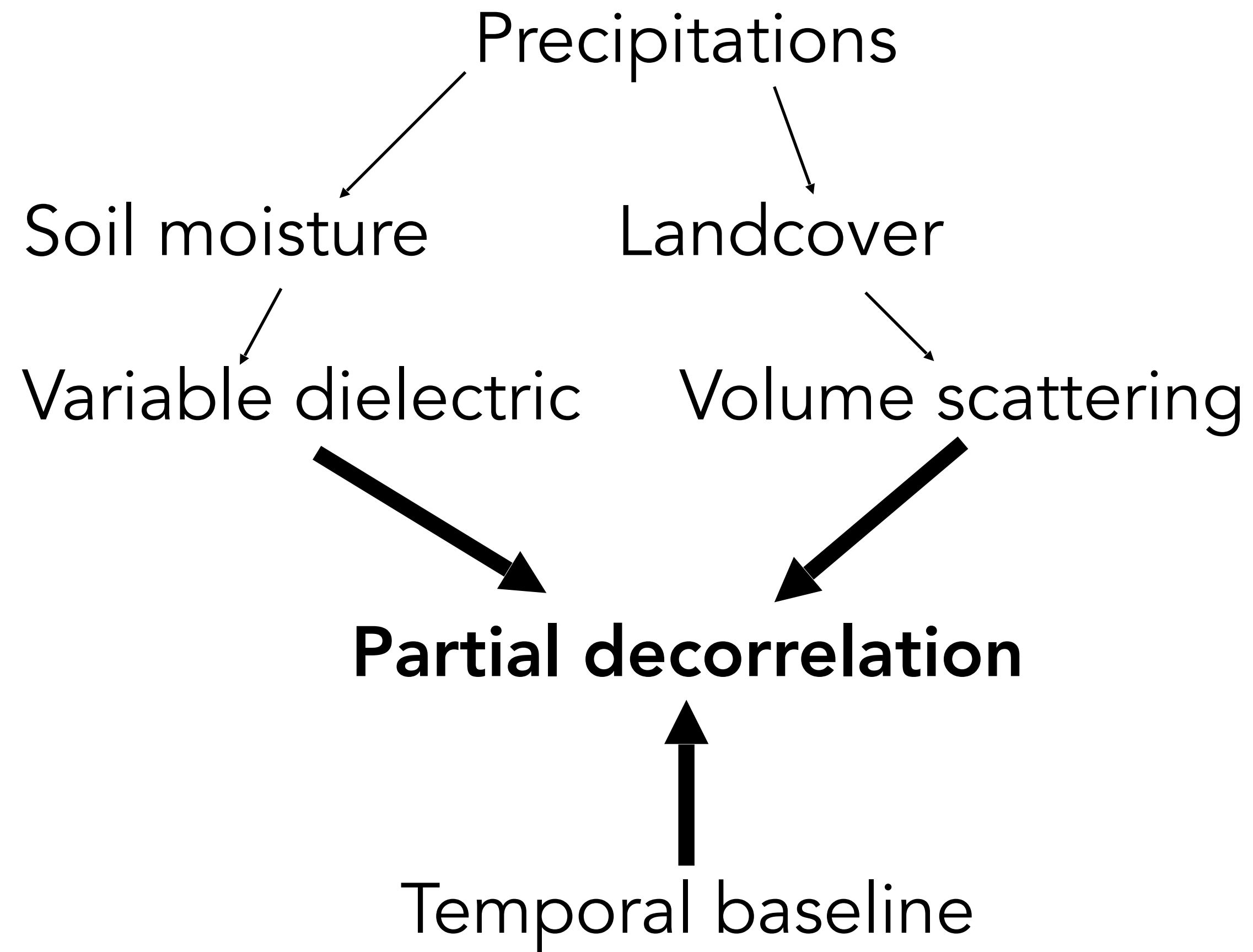
From Zheng et al. (2022)



# The closure phase problem

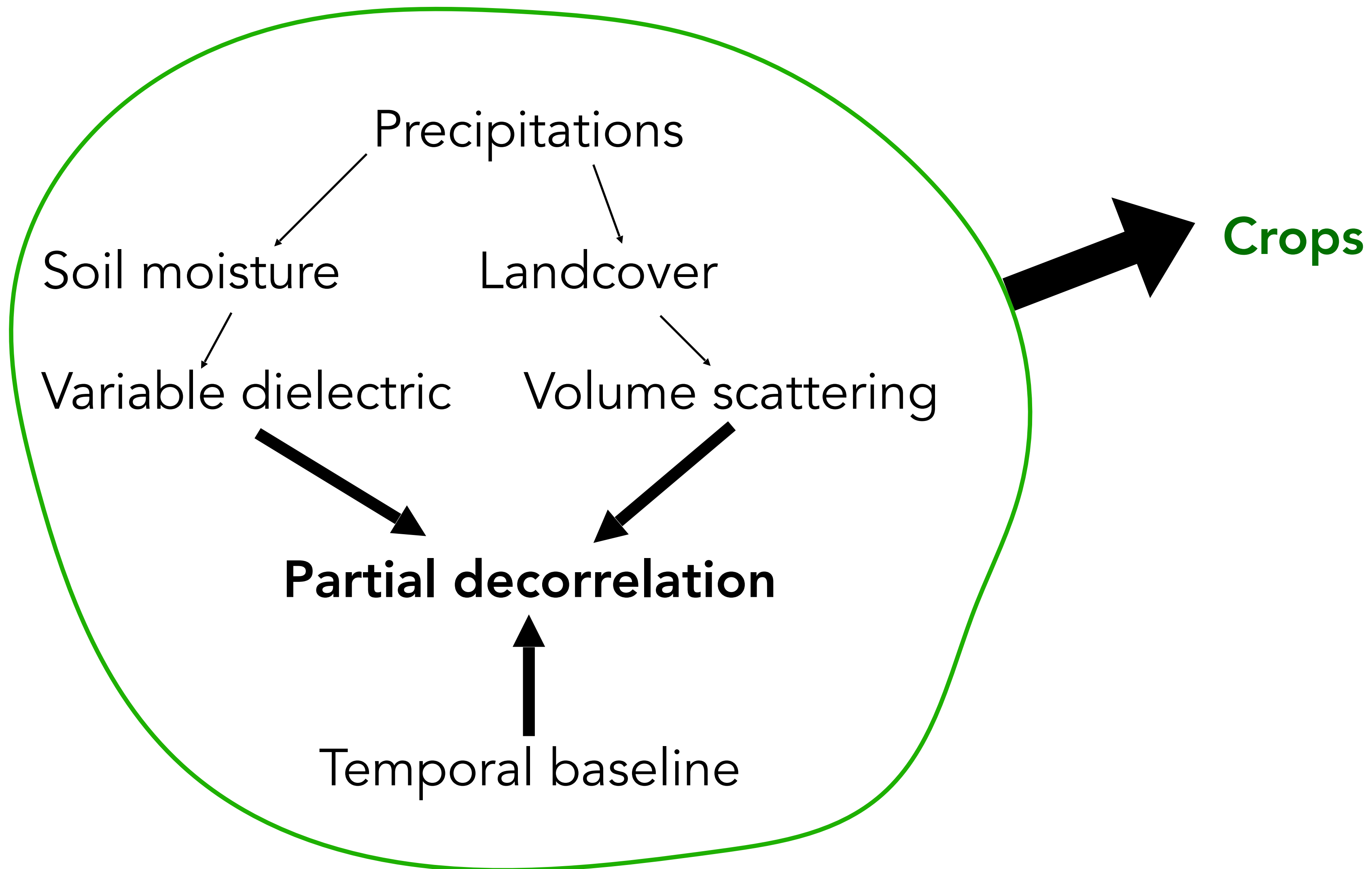


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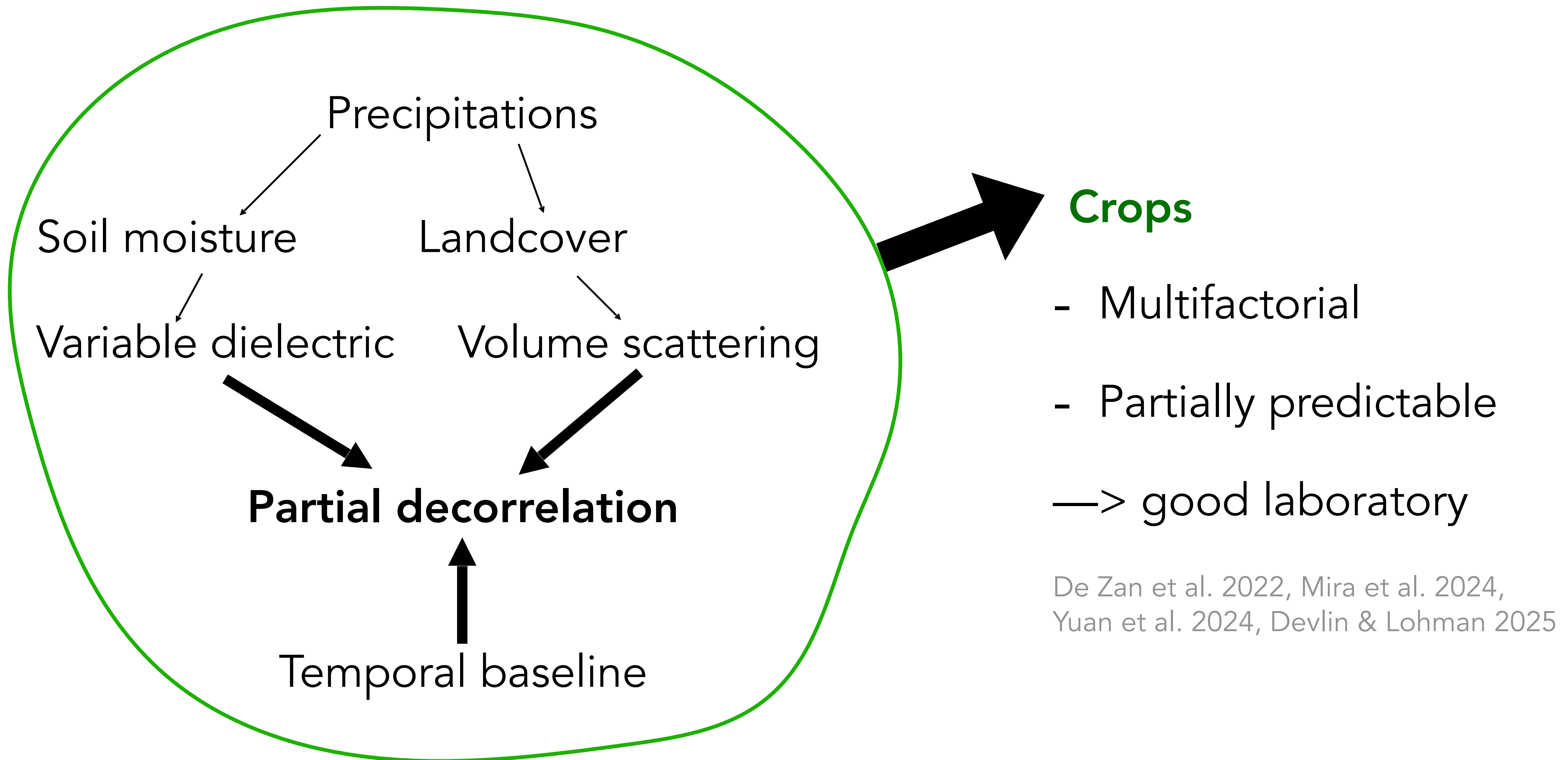




# The closure phase problem



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# The Thessaloniki region

## Crop signatures and subsidence

- ▶ Diverse agriculture - Mediterranean climate (dry hot summers and mild wet winters)



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Rice



Fruit trees

➡ Water-intensive crops



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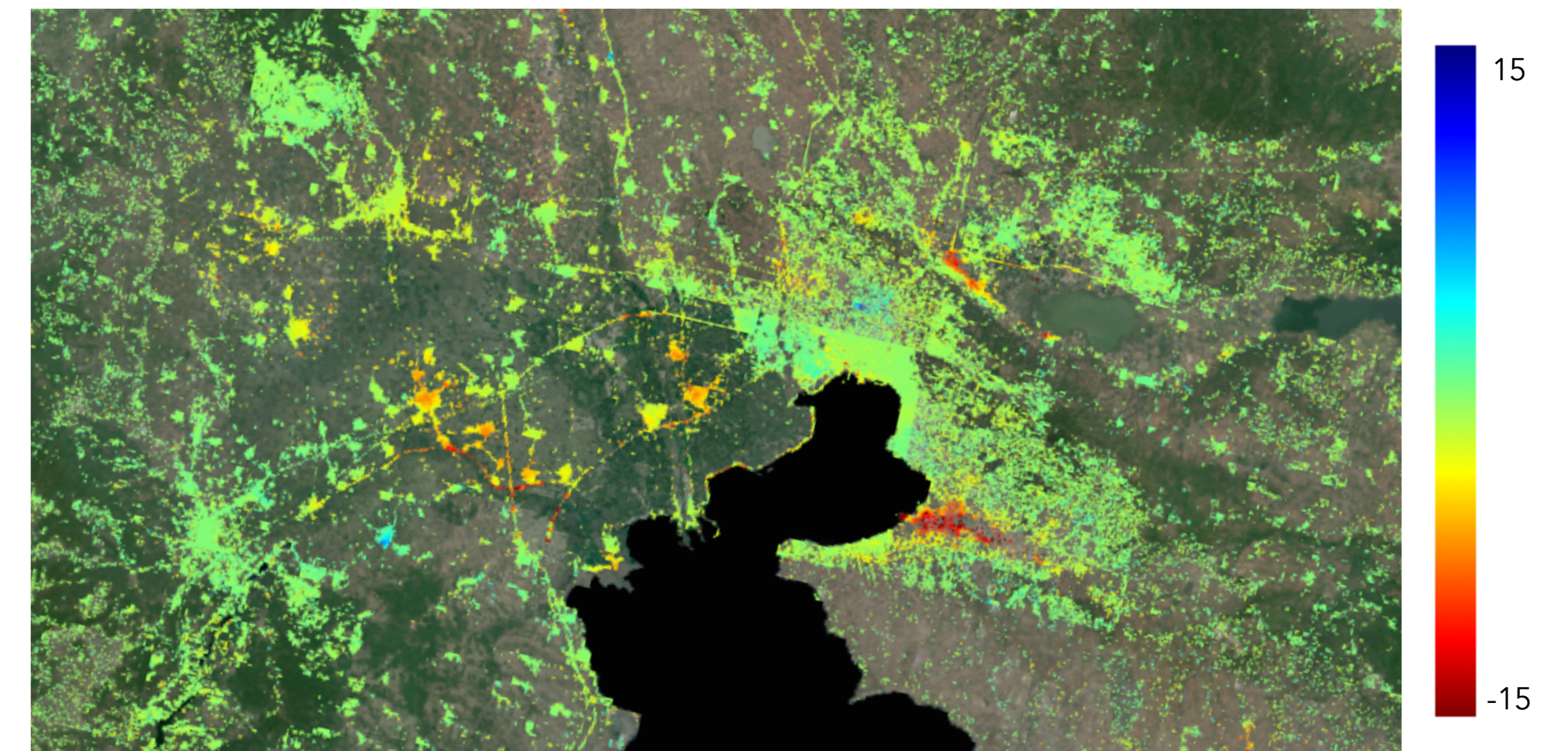


Fruit trees

➡ Water-intensive crops

- Identified subsidence linked to :
  - groundwater withdrawal
  - sediment compaction

Psimoulis et al. 2007, Loupasakis et al. 2020



Deformation velocity estimate (mm/yr), computed with PS-DS method (EGMS, Copernicus)



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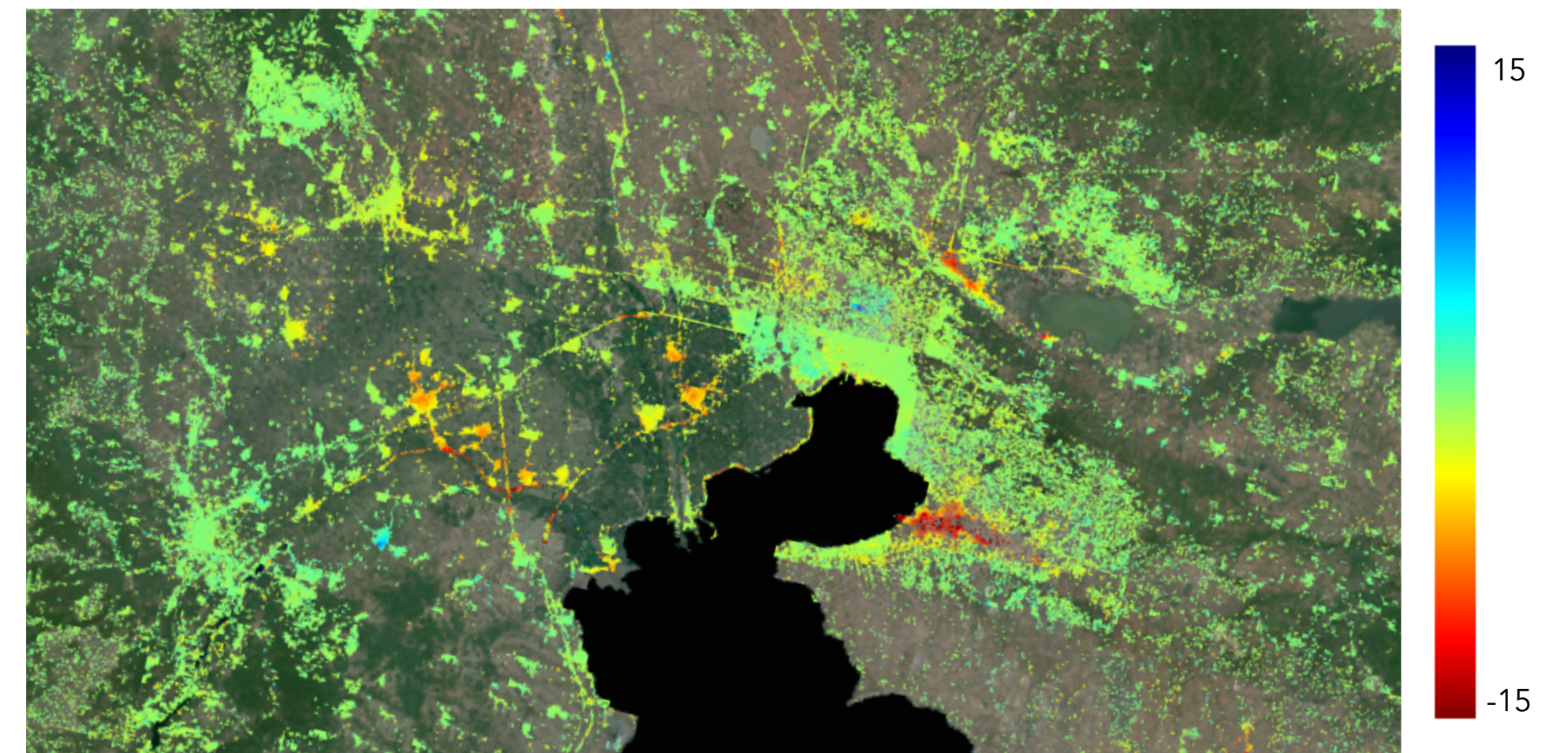


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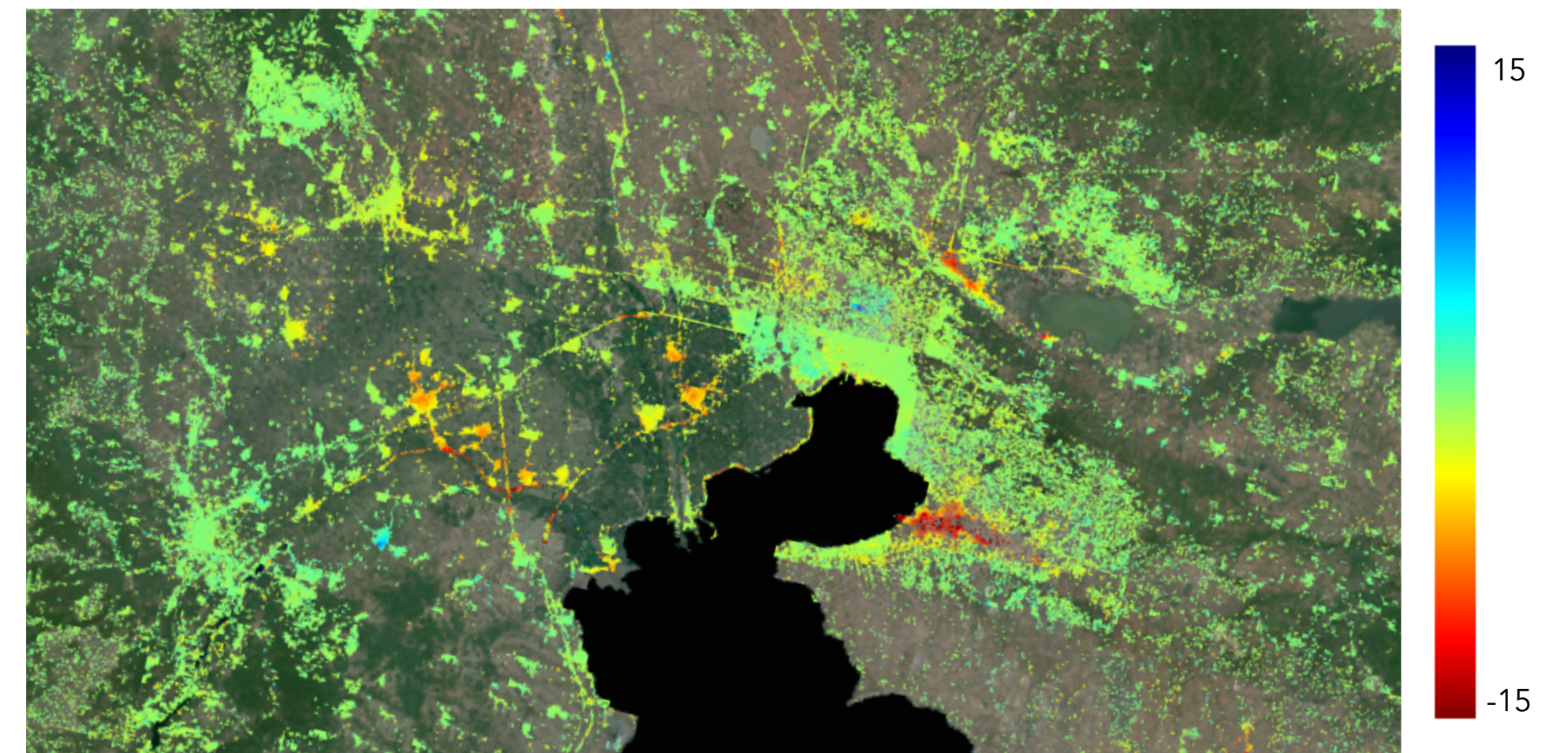


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- But limited spatial coverage of existing studies

- How can we characterize the phase delay over these crops ?
- How can we extend the deformation estimates for subsidence monitoring ?



1. Spatio-temporal characterization of the closure phase on crops over multiple years
2. From phase error to velocity bias : perspectives



# Our processing set up



**5 years** of Sentinel-1 A/B (2017 to 2022)

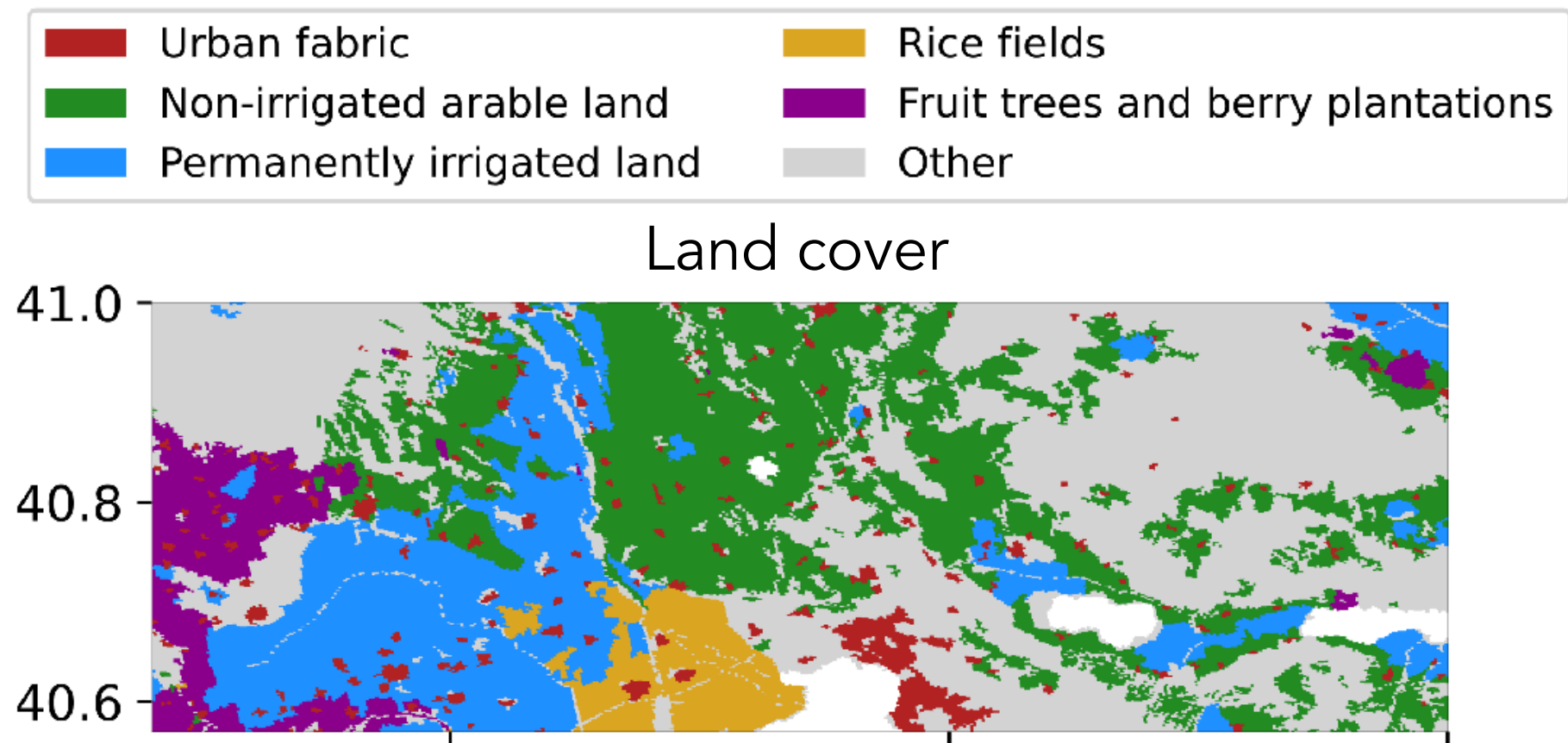
Short baseline interferograms : 6 and 12 days

Large multilooking window : 14x70

Triplets are 6-6-12

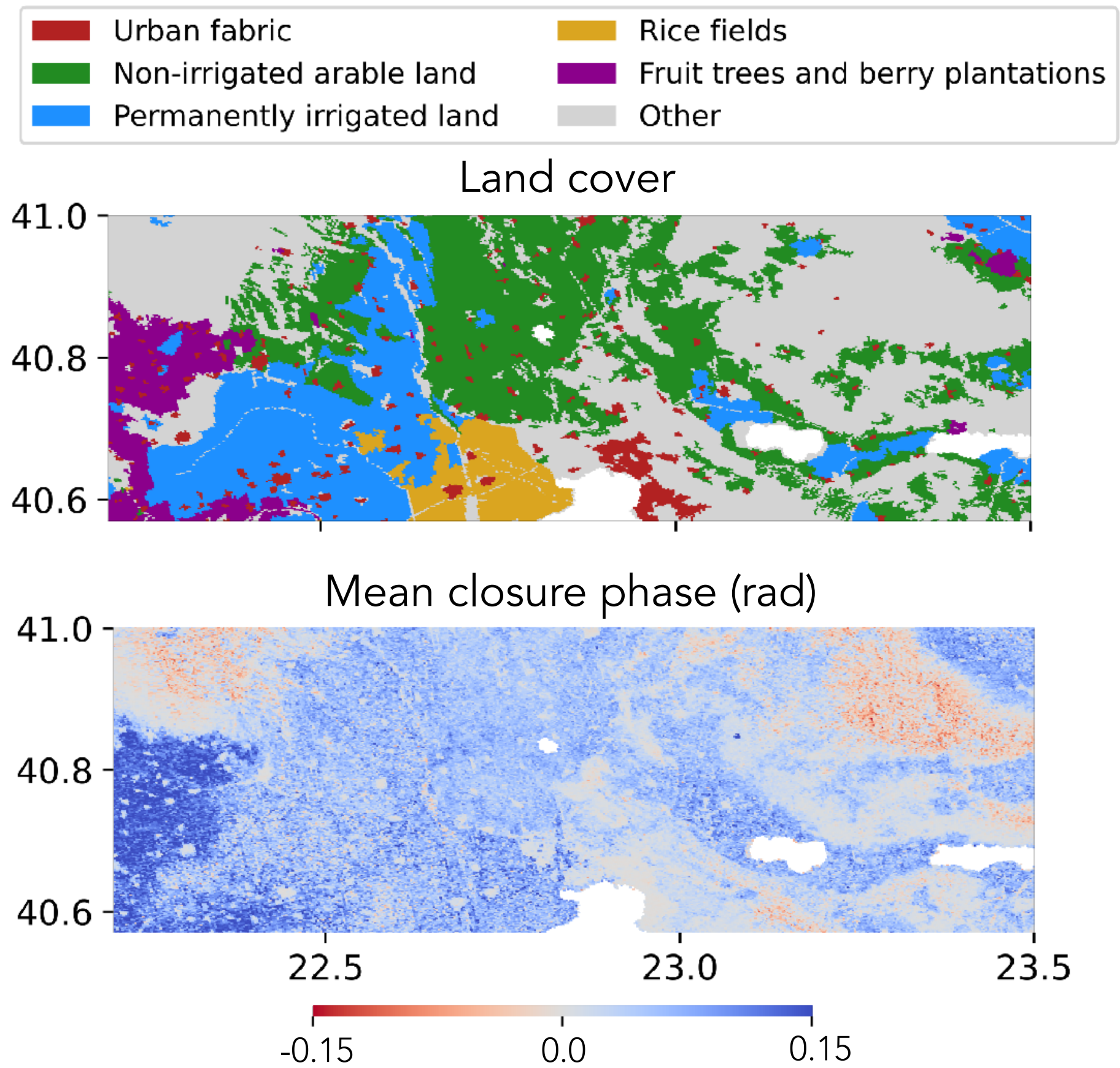
$$\text{Coherence } \gamma_{ij} = \frac{|\sum^L z_i z_j^*|}{\sqrt{\left(\sum^L z_i z_i^*\right) \left(\sum^L z_j z_j^*\right)}} .$$

# Strong spatial correlation



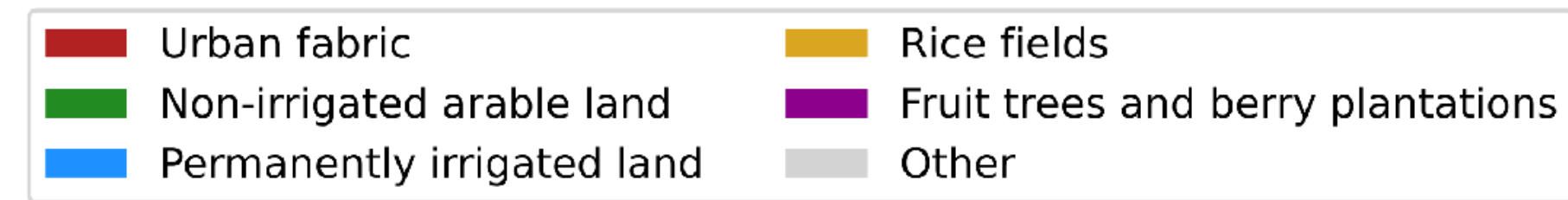


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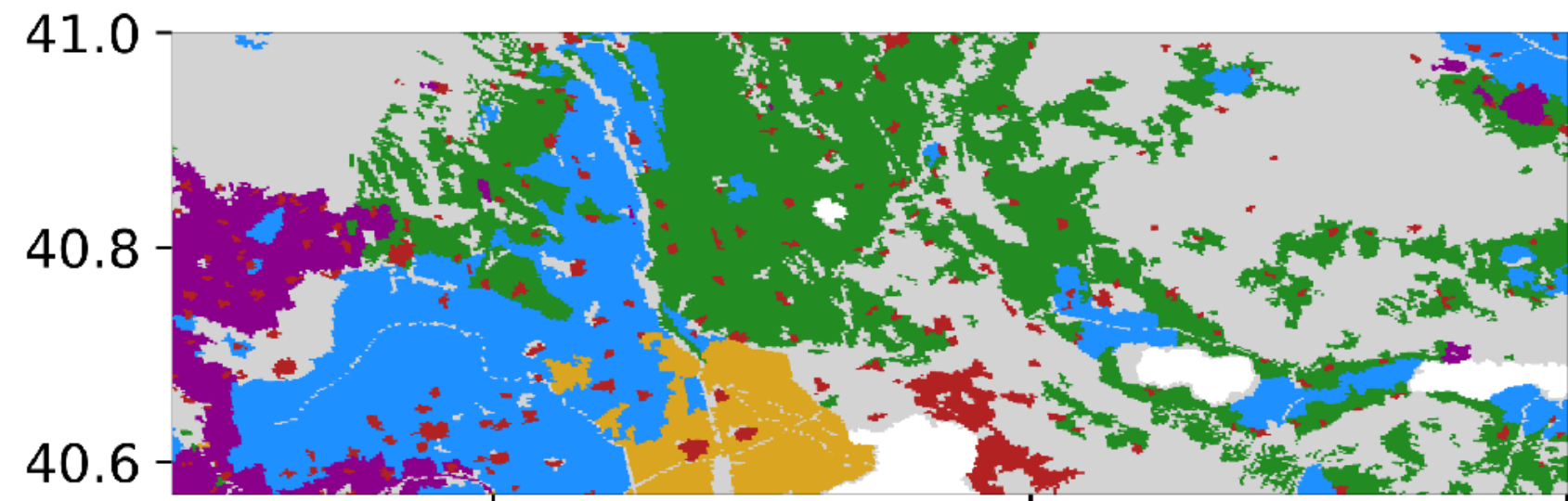




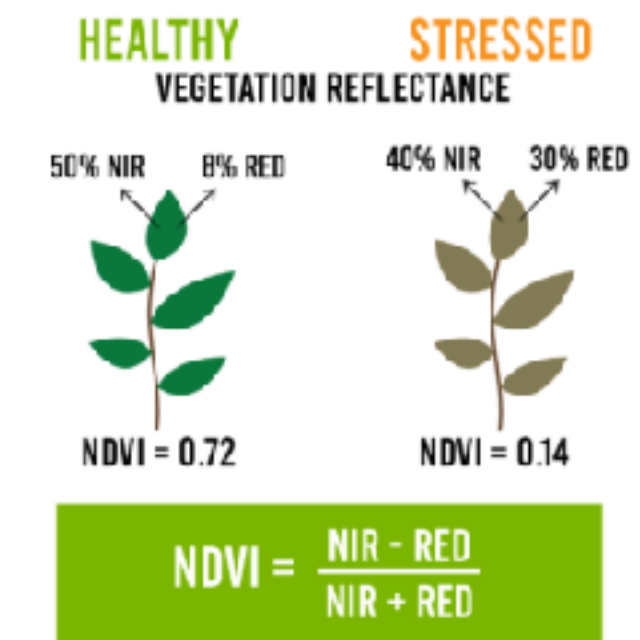
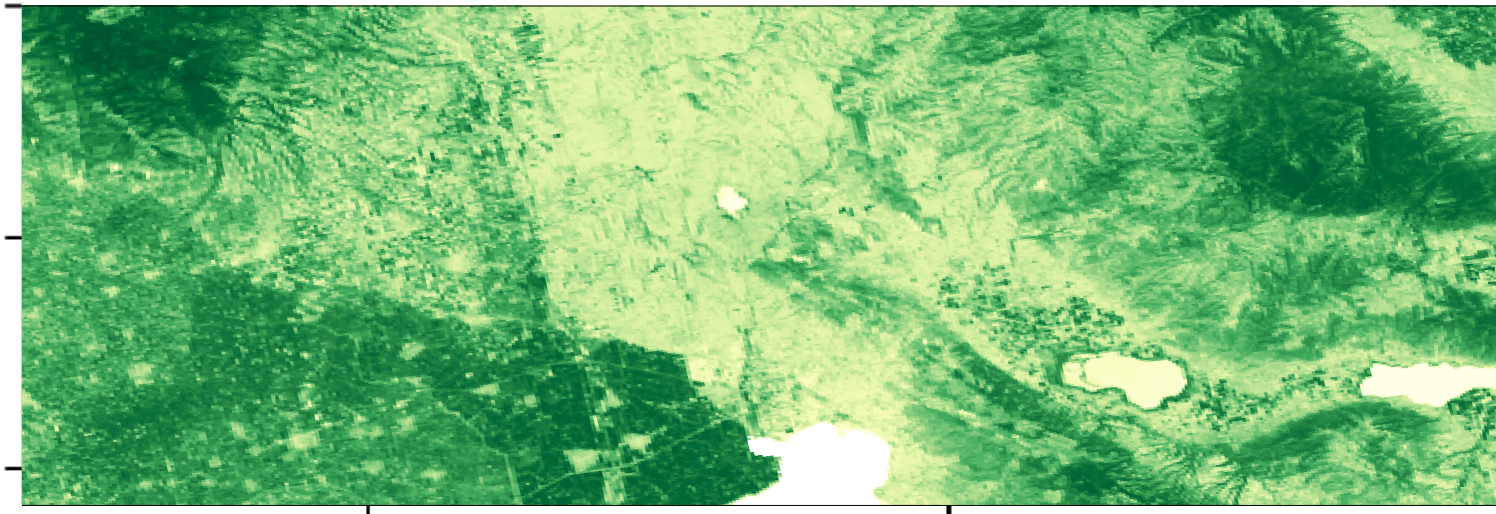
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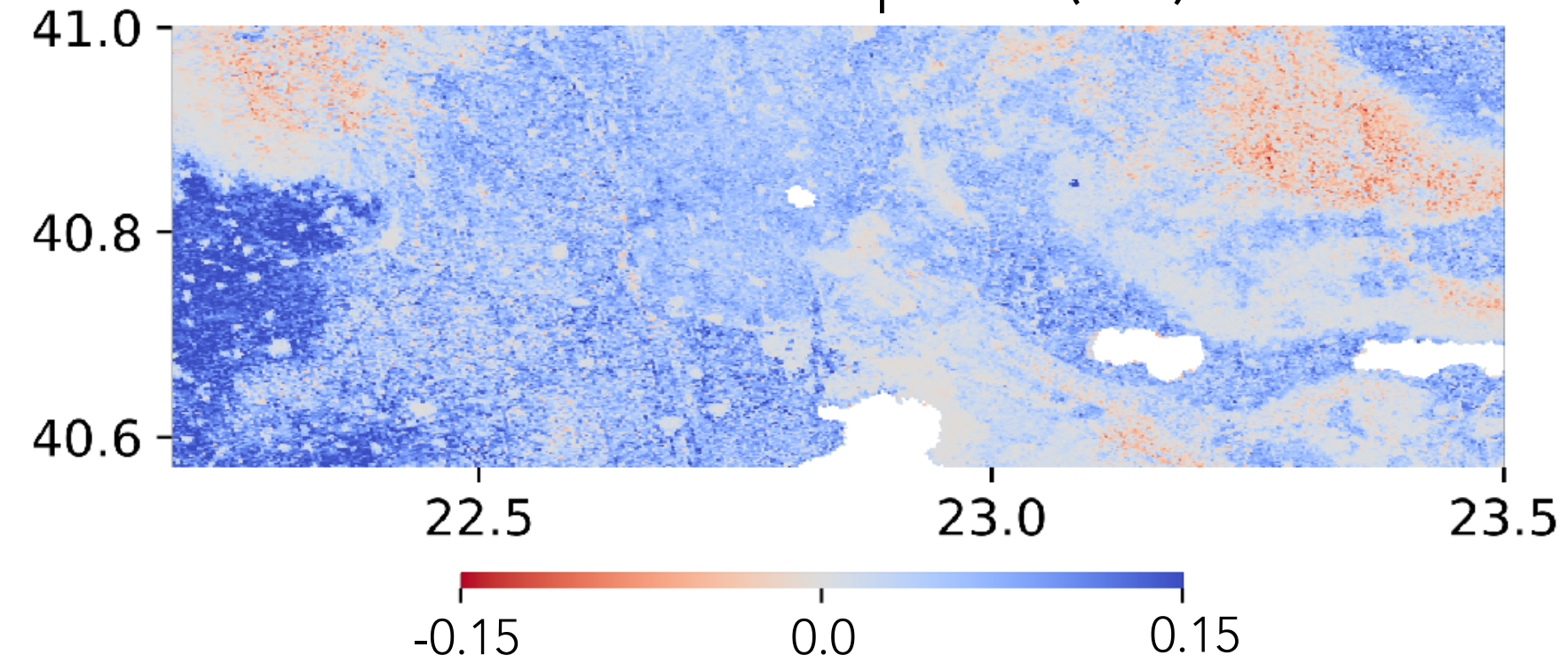
Land cover



July NDVI



Mean closure phase (rad)

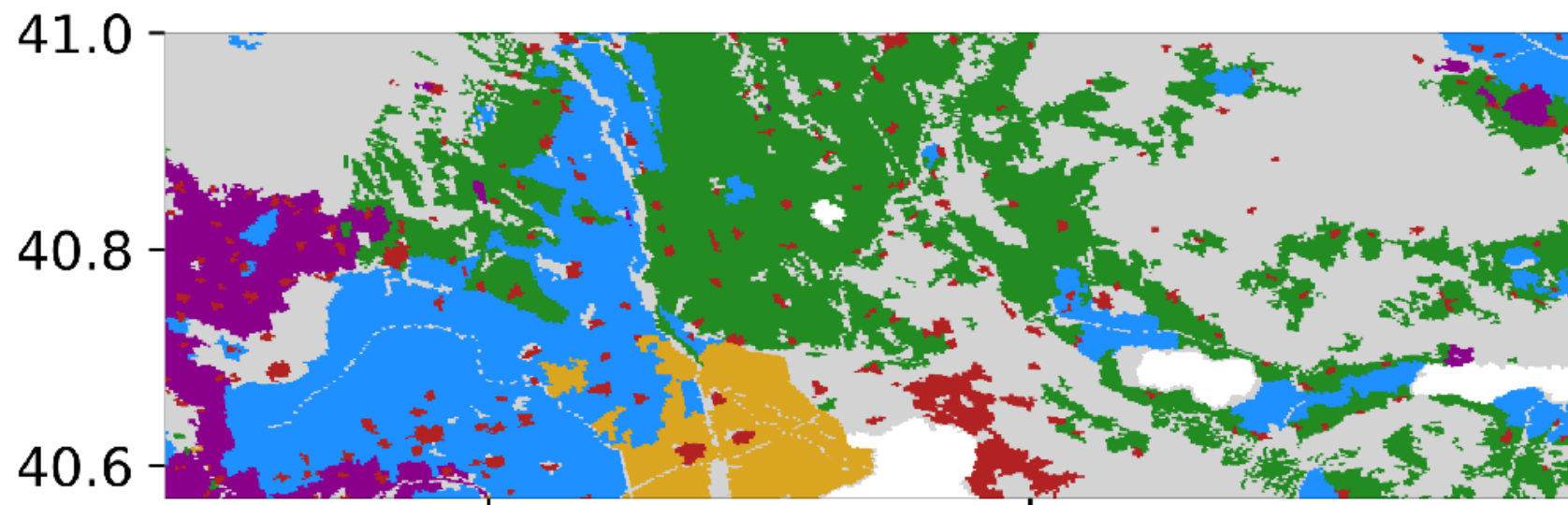




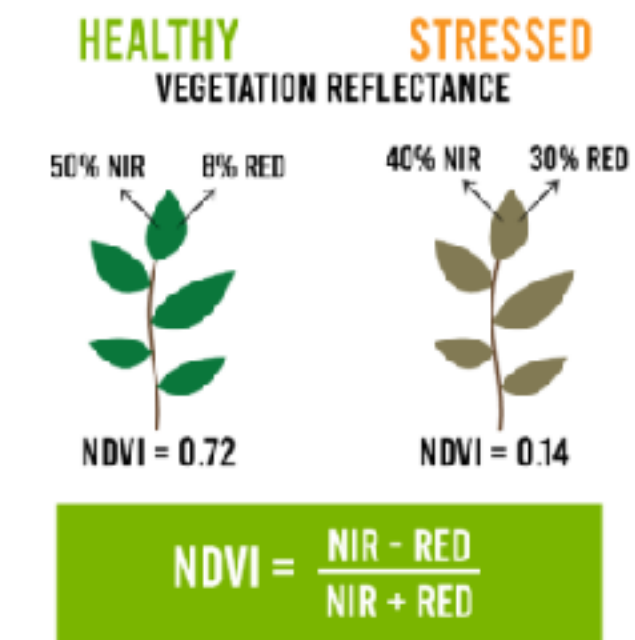
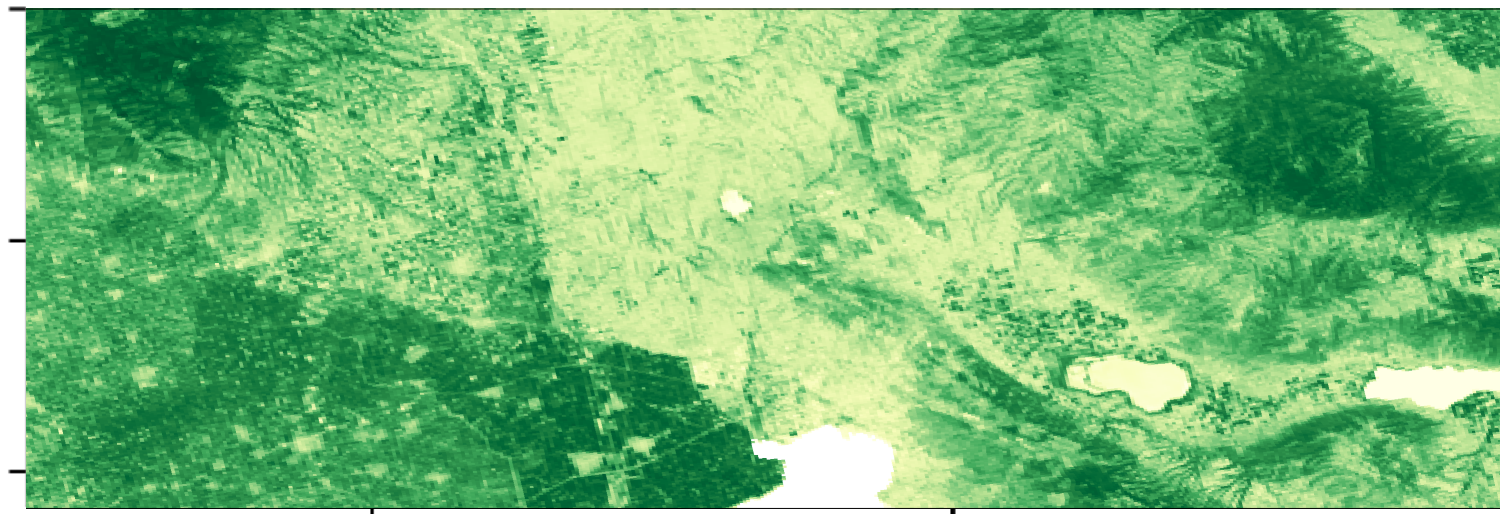
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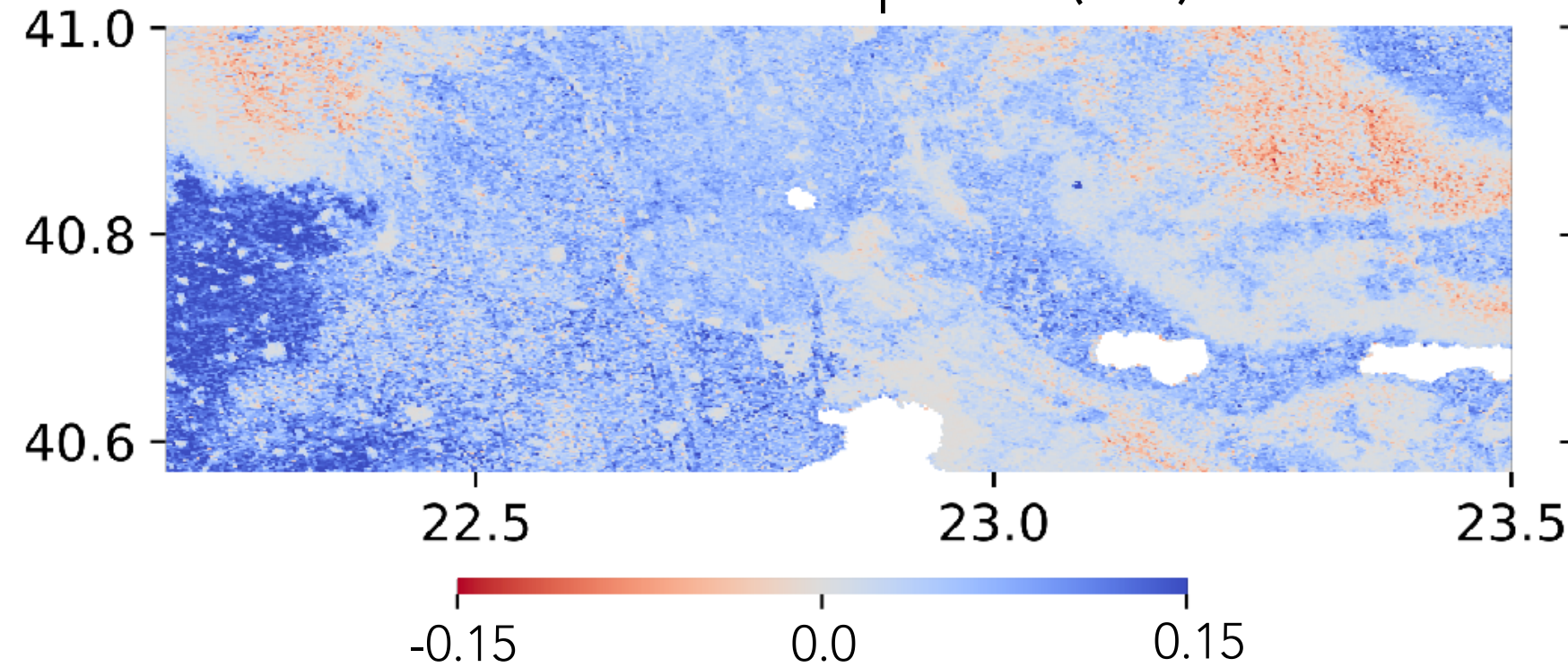
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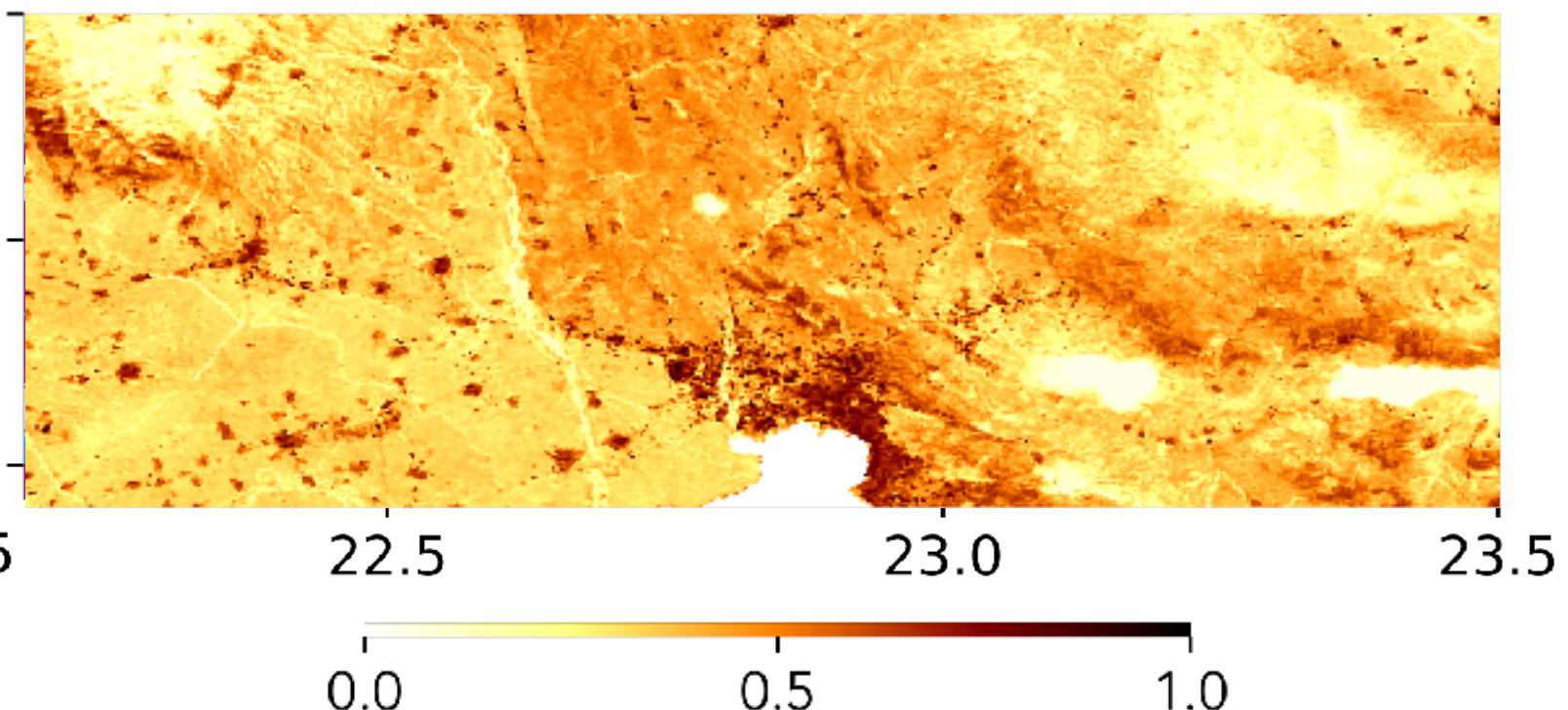
July NDVI



Mean closure phase (rad)



Mean coherence

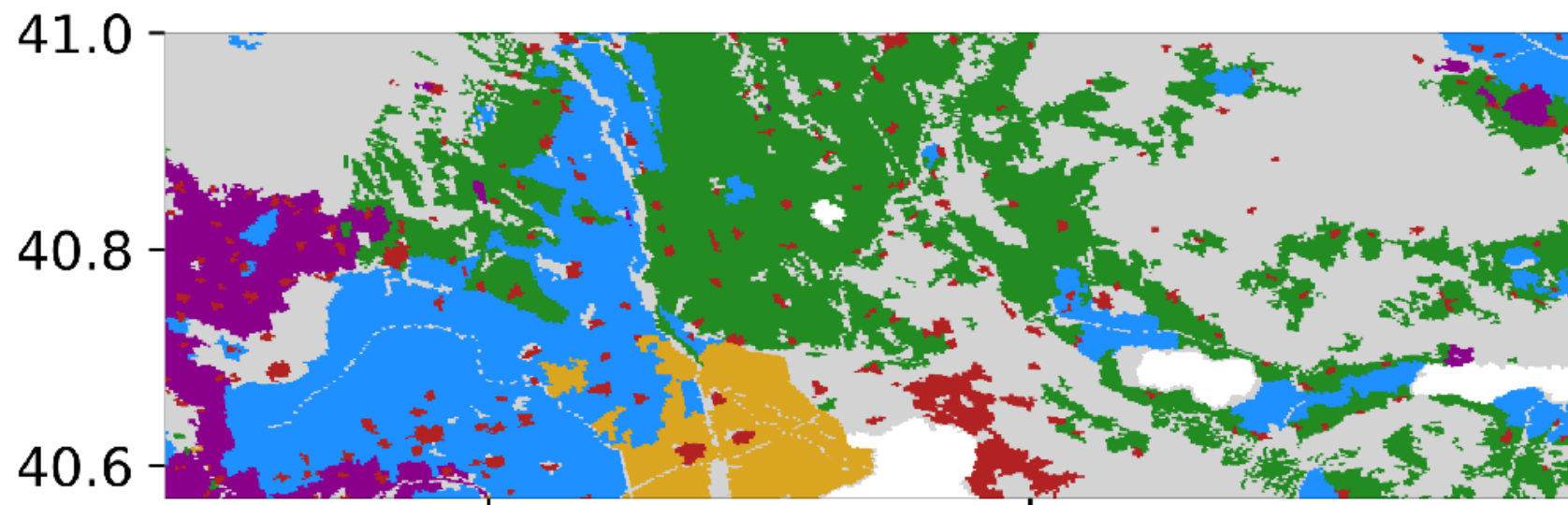




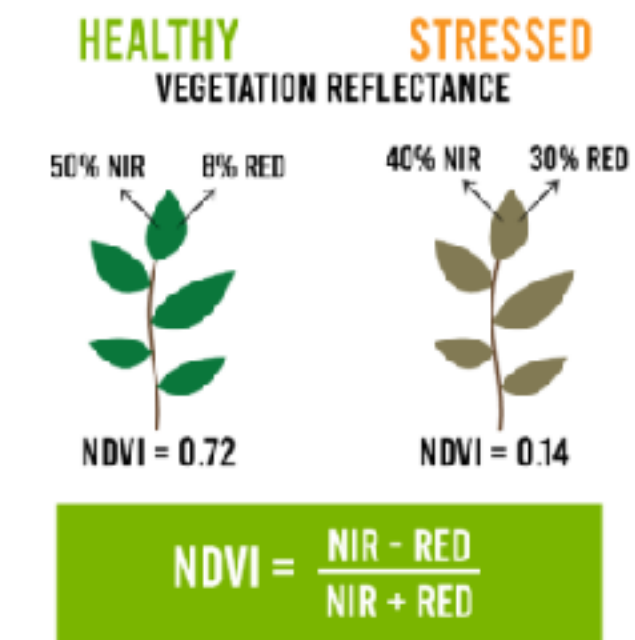
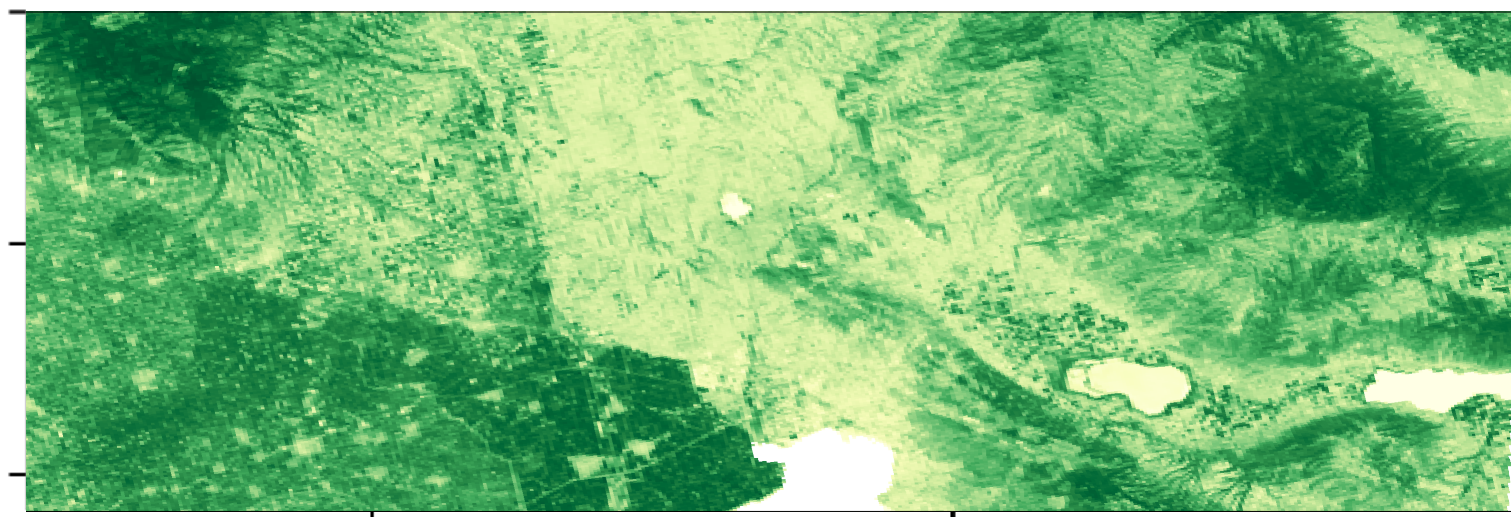
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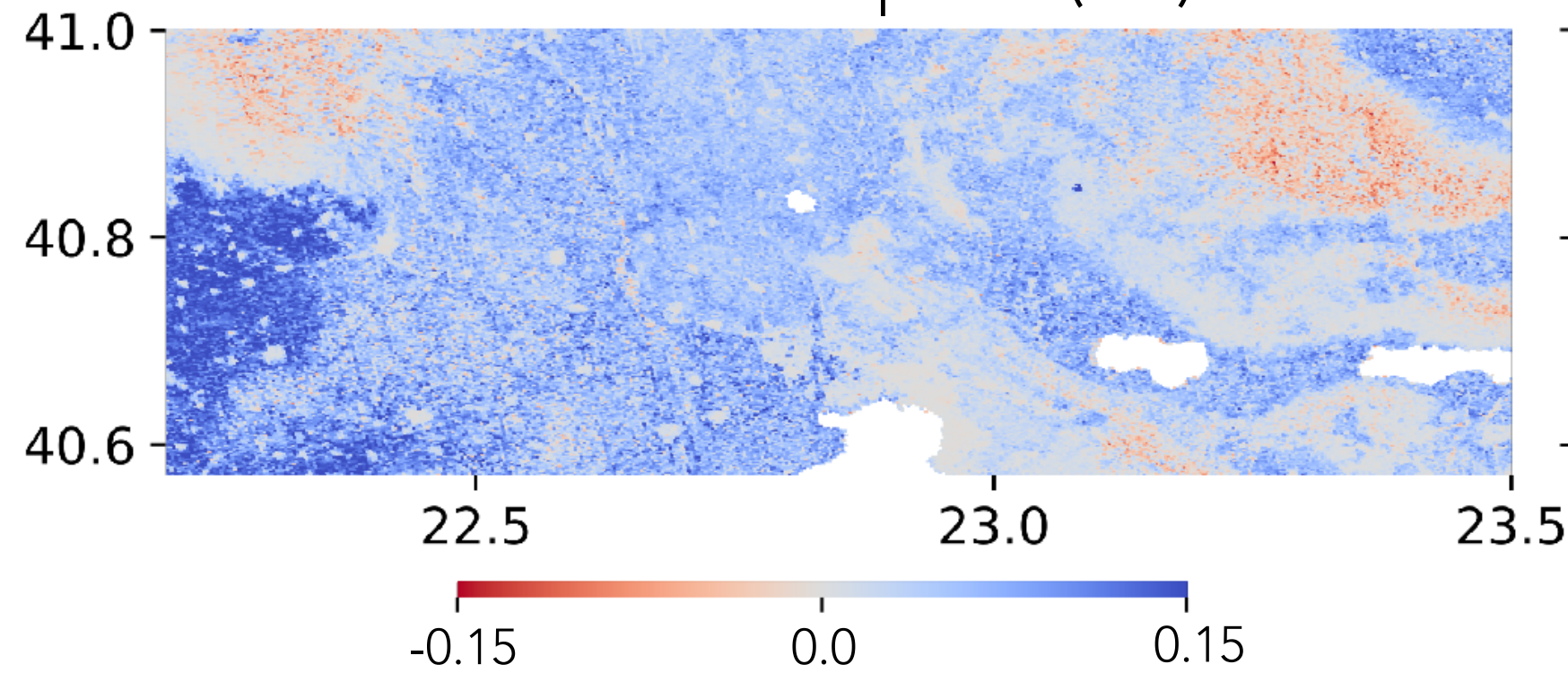
Land cover



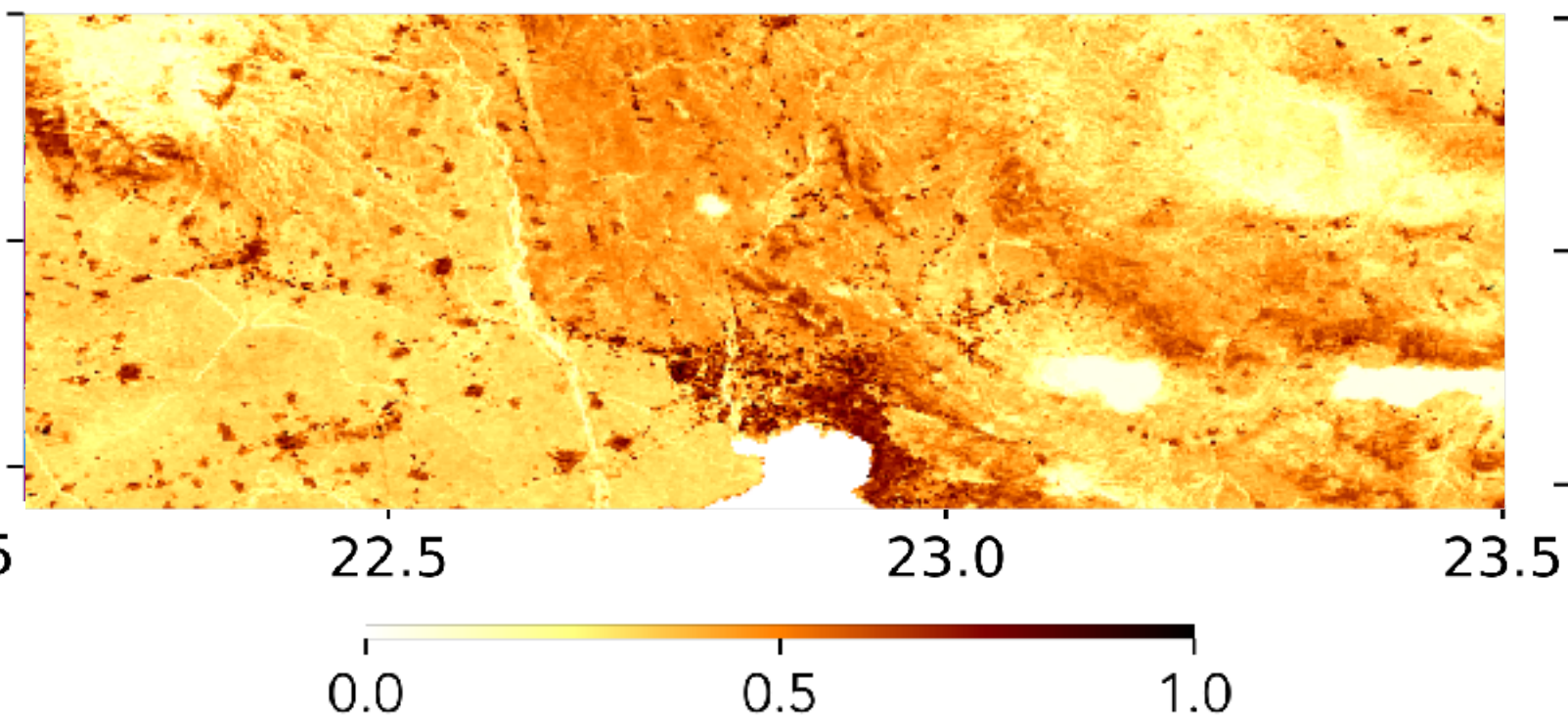
July NDVI



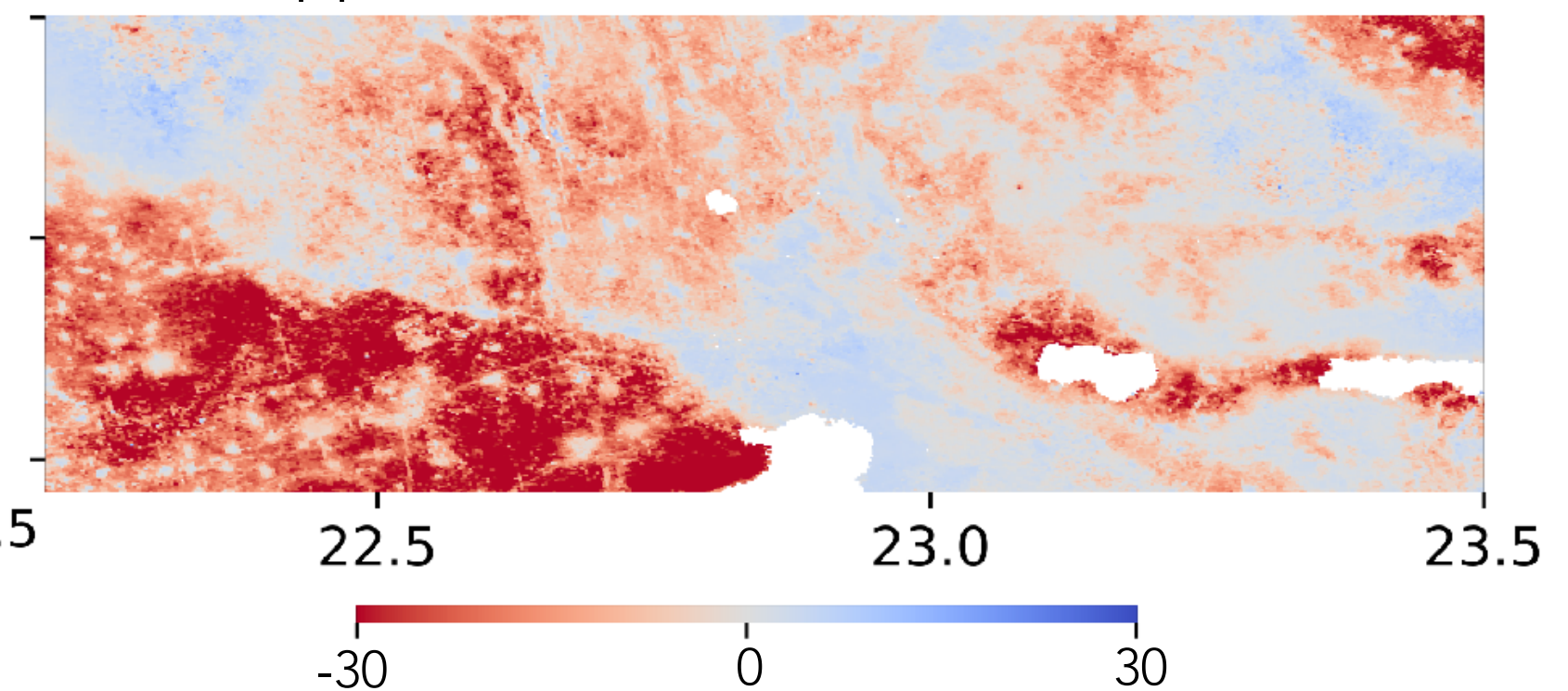
Mean closure phase (rad)



Mean coherence

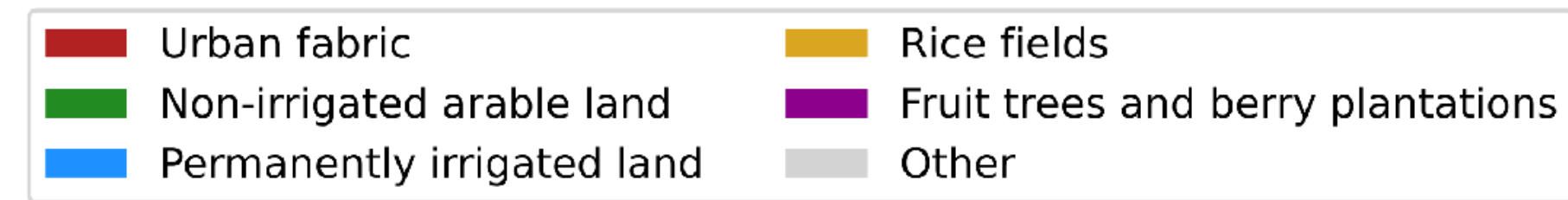


Apparent vertical velocity (mm/yr)

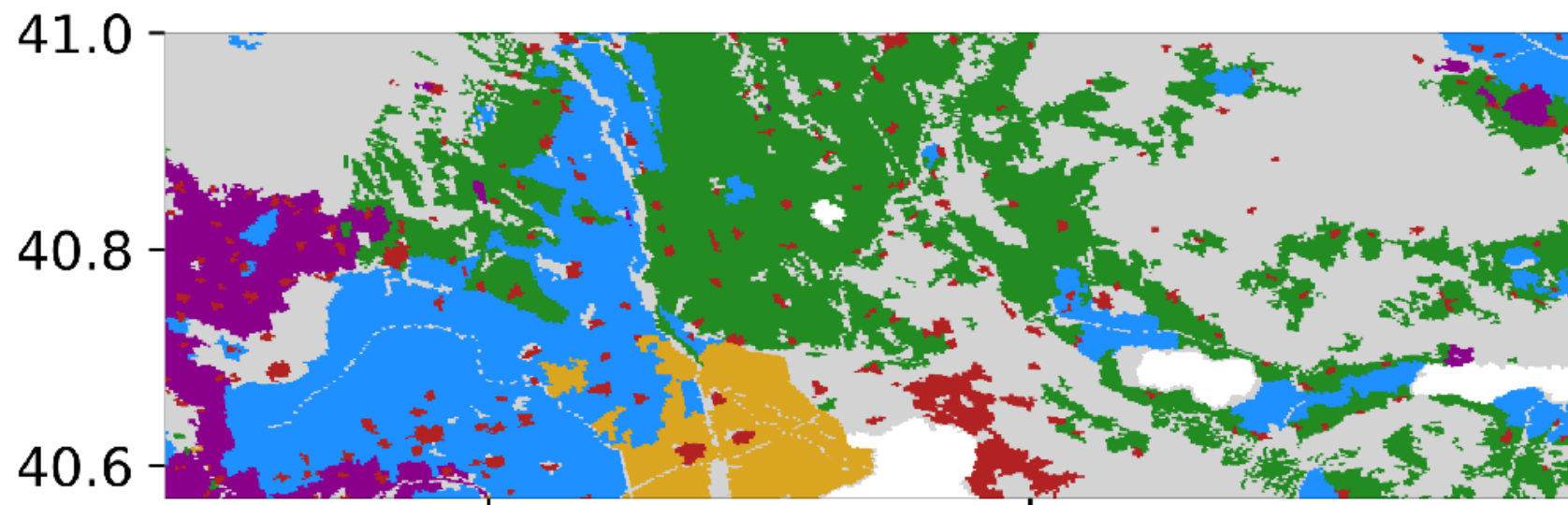




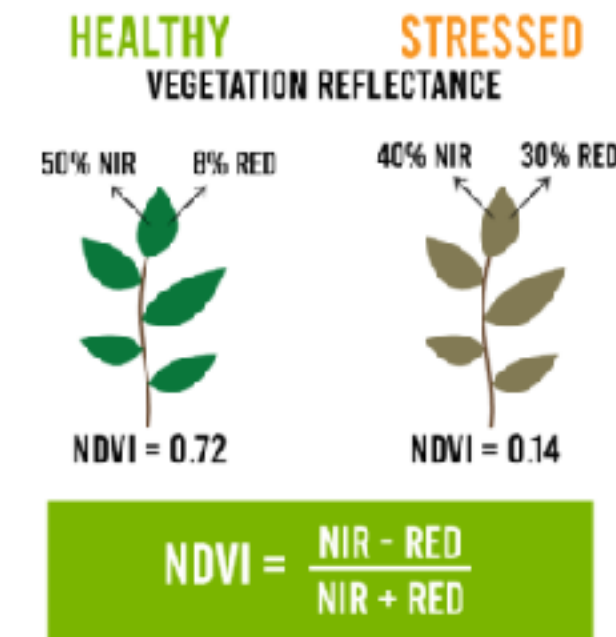
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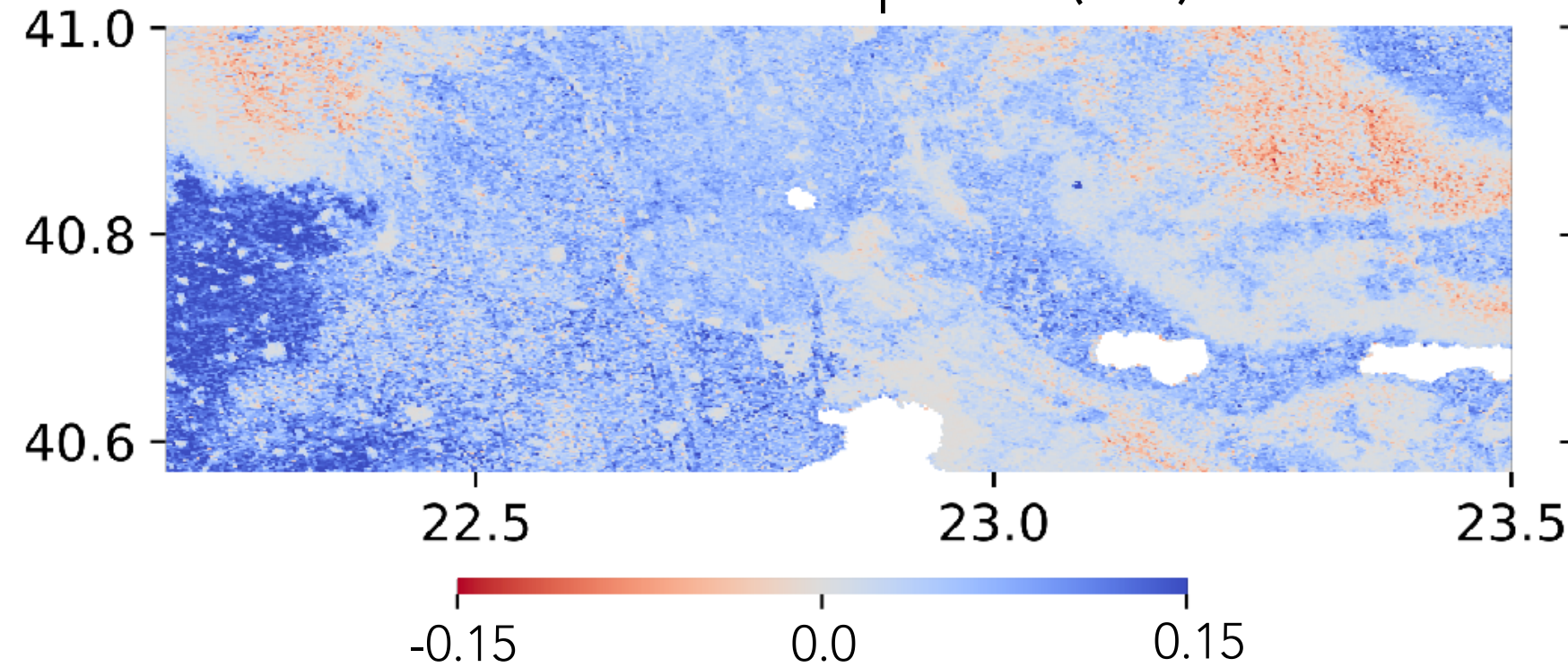
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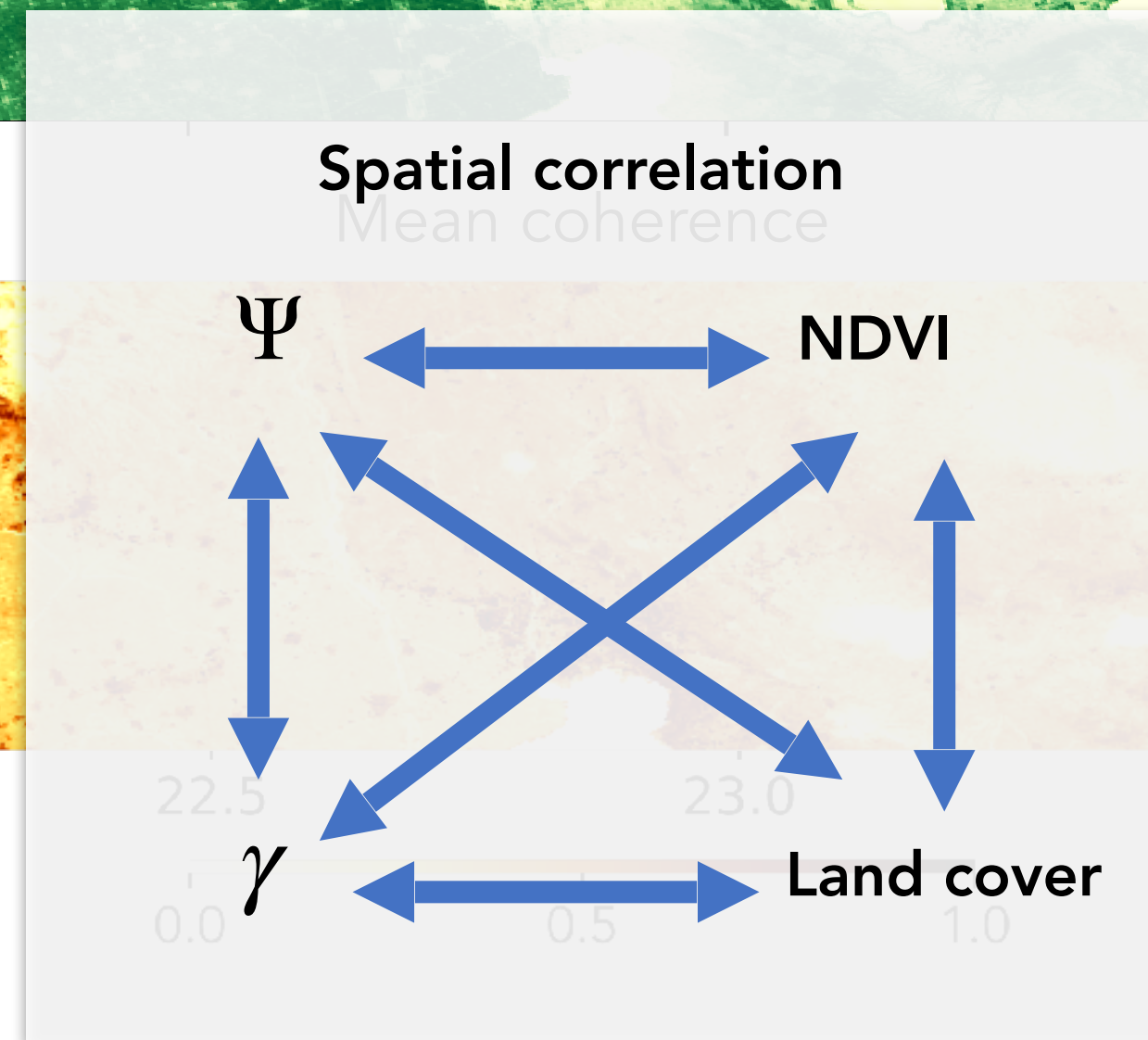
July NDVI



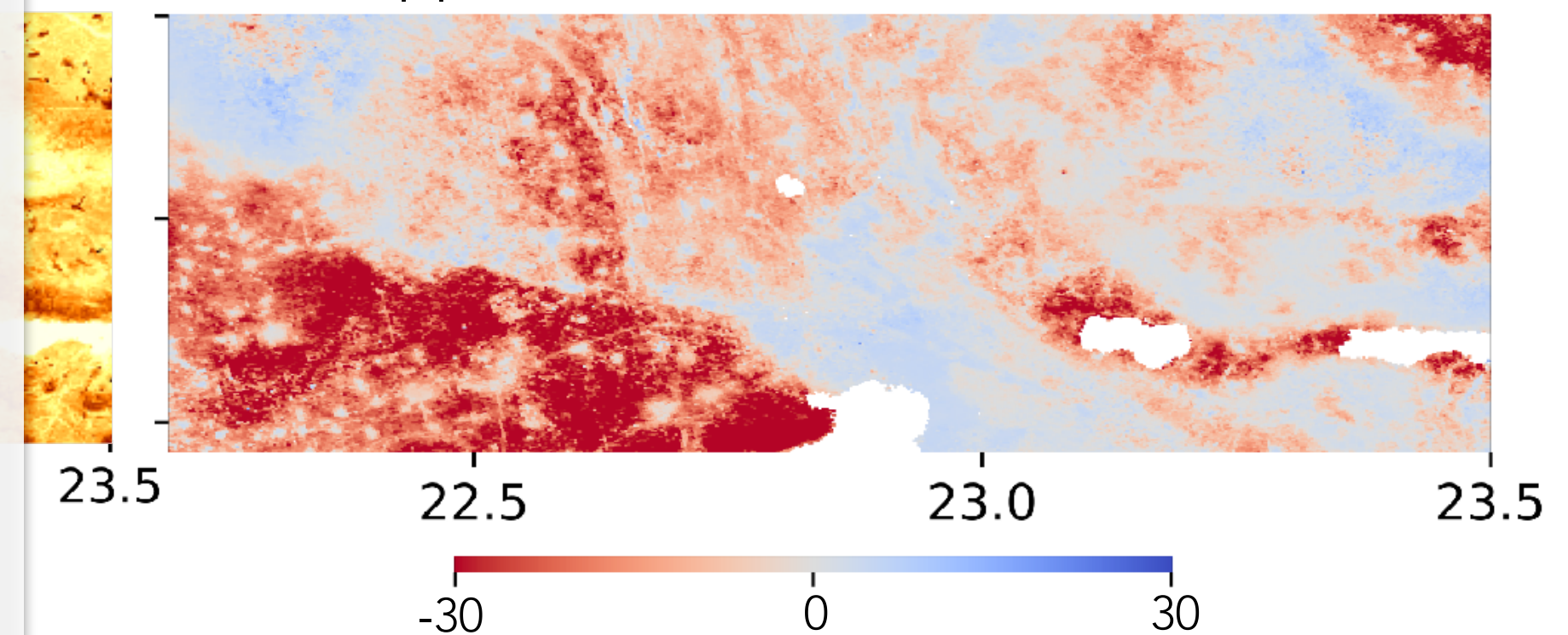
Mean closure phase (rad)



Spatial correlation



Apparent vertical velocity (mm/yr)

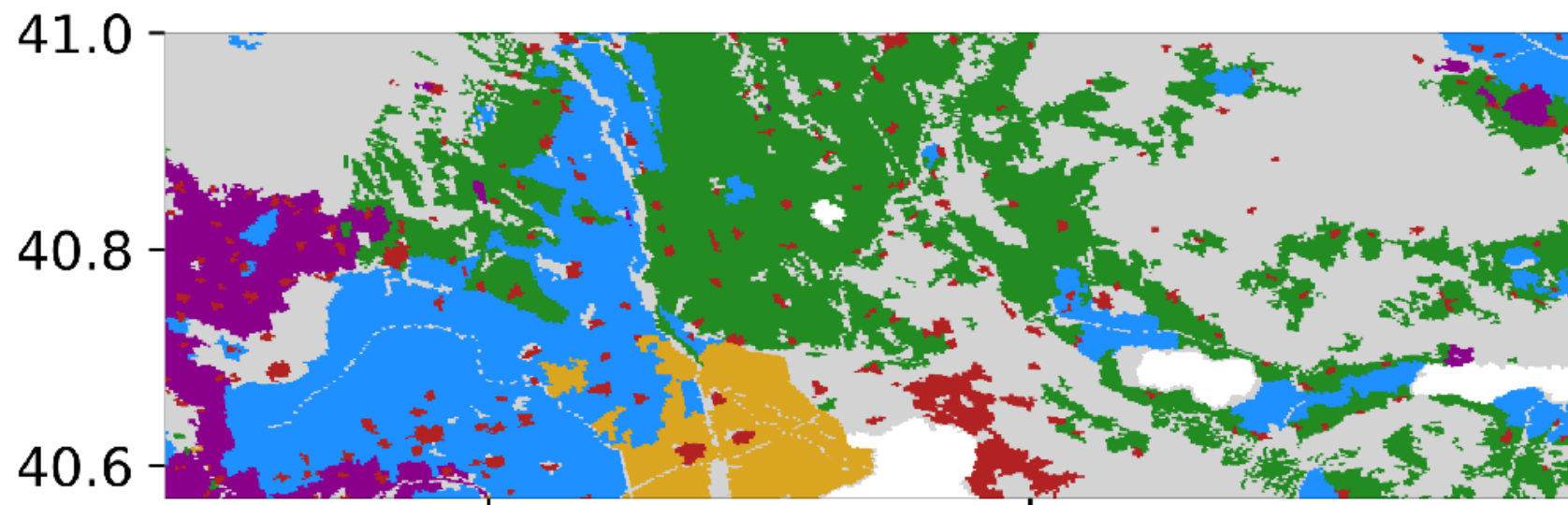




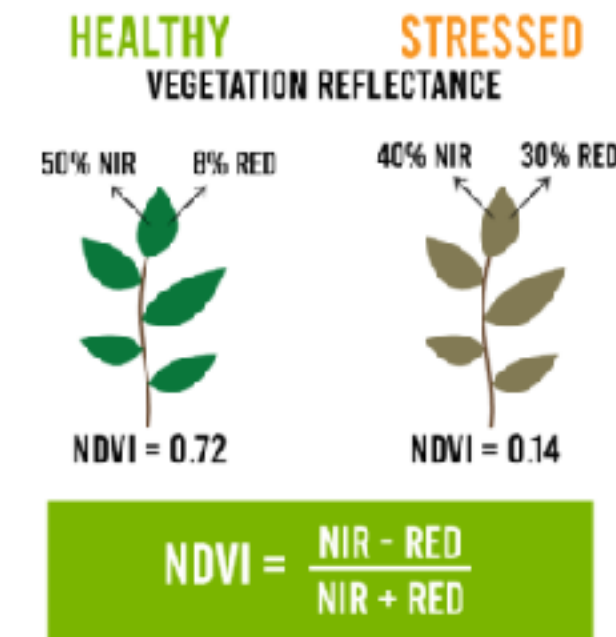
# Strong spatial correlation



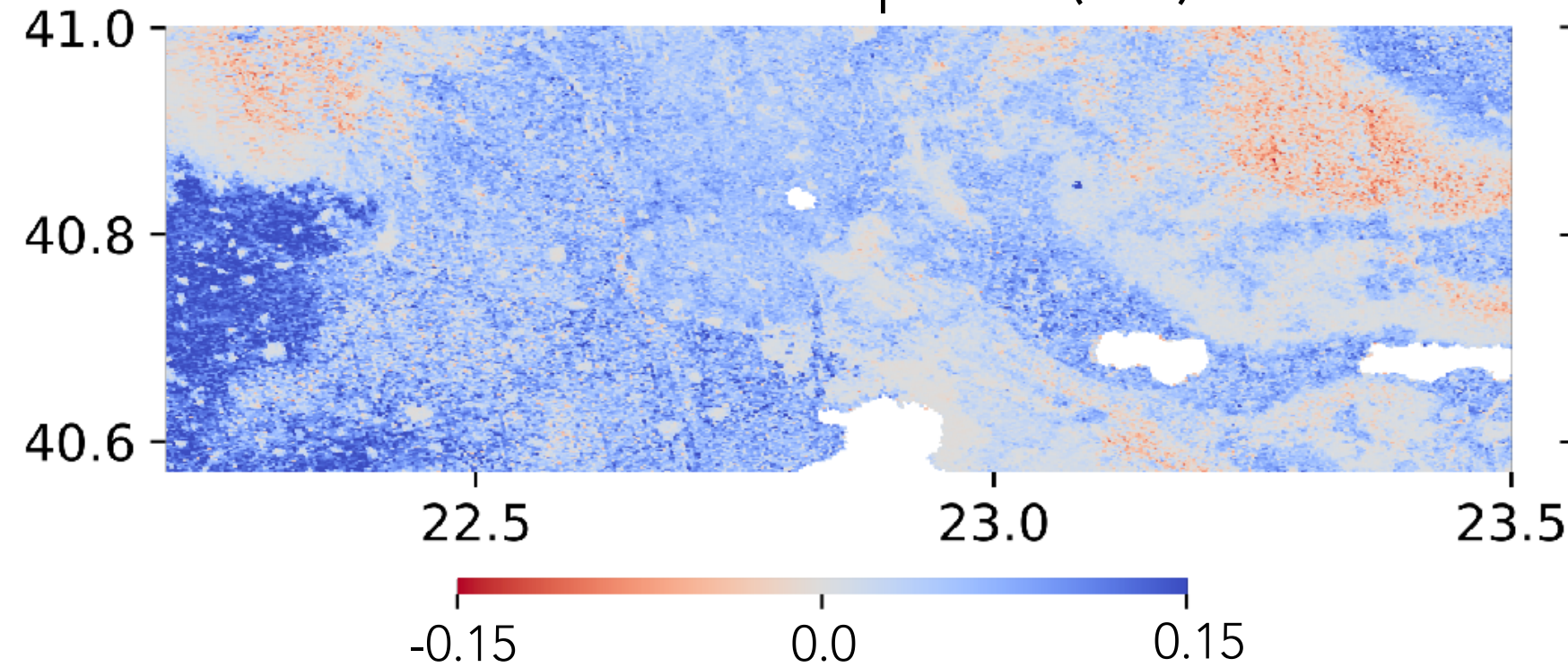
Land cover



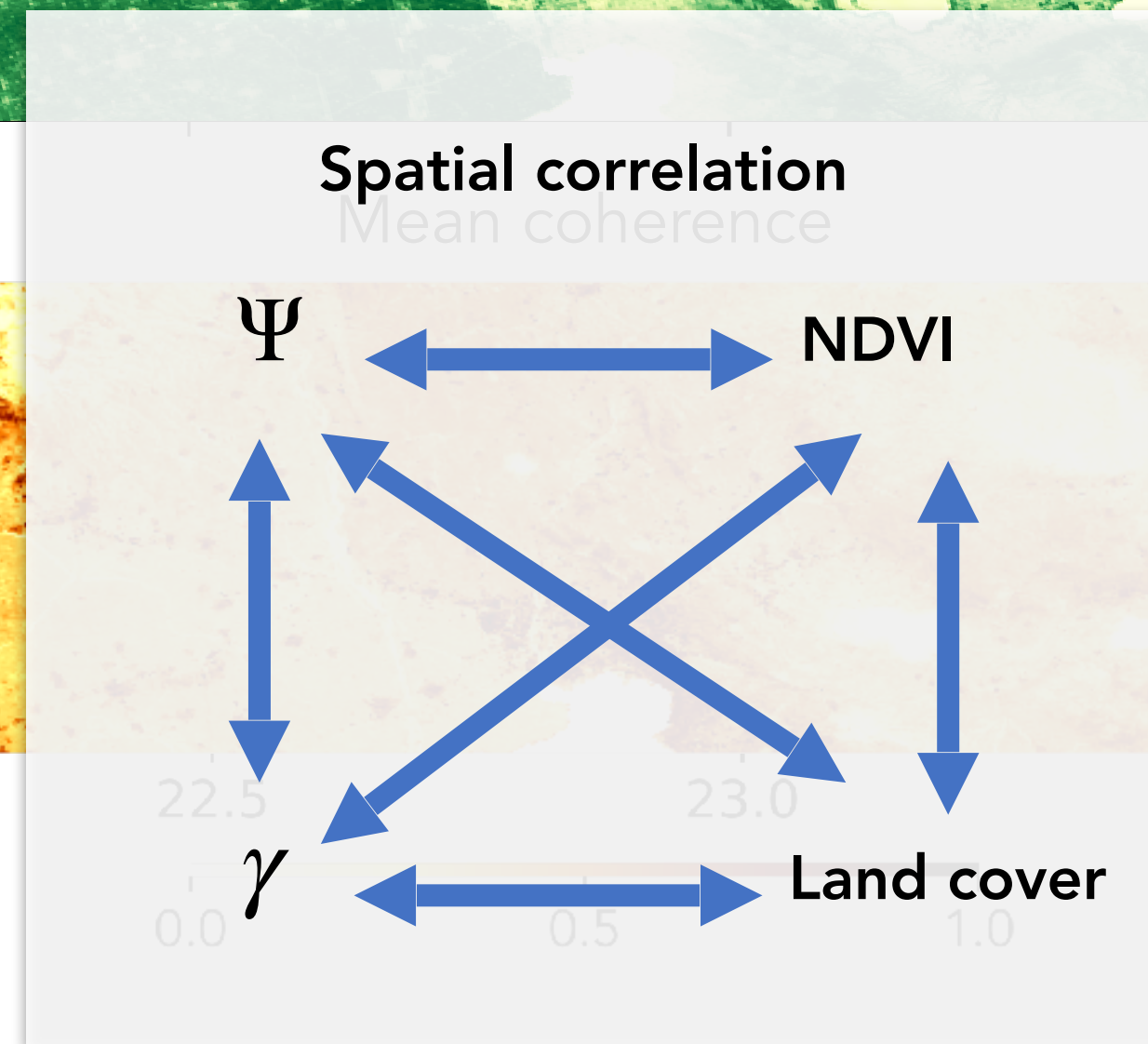
July NDVI



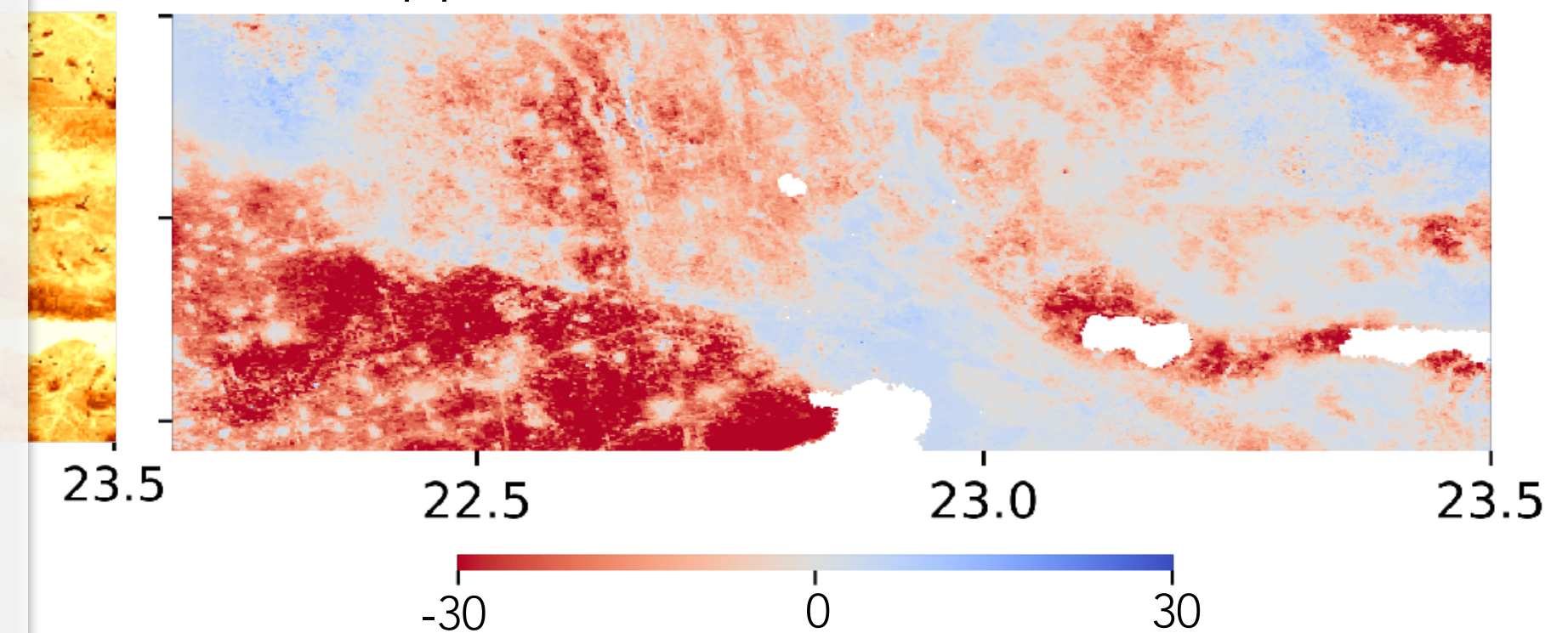
Mean closure phase (rad)



Spatial correlation

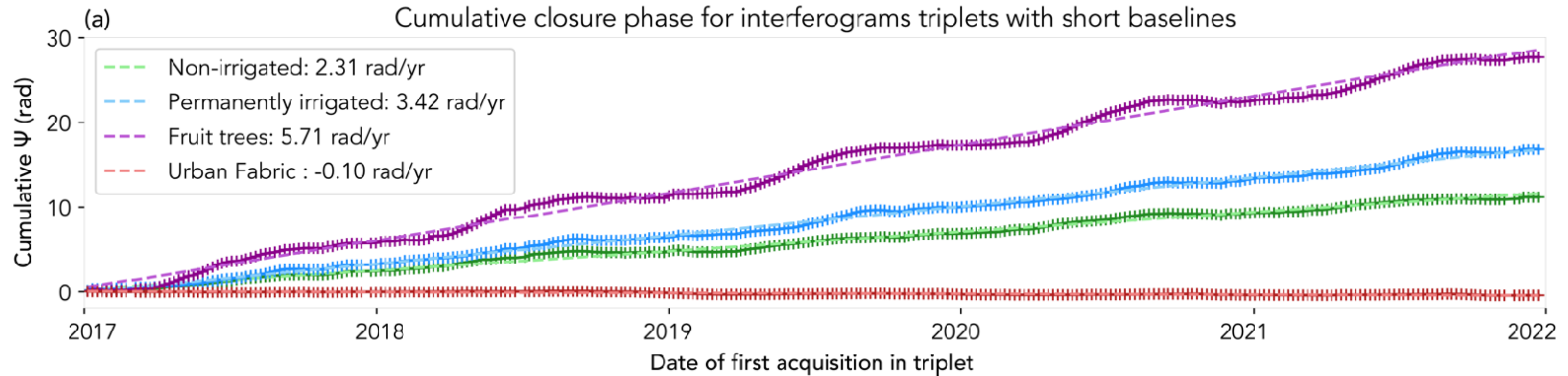


Apparent vertical velocity (mm/yr)



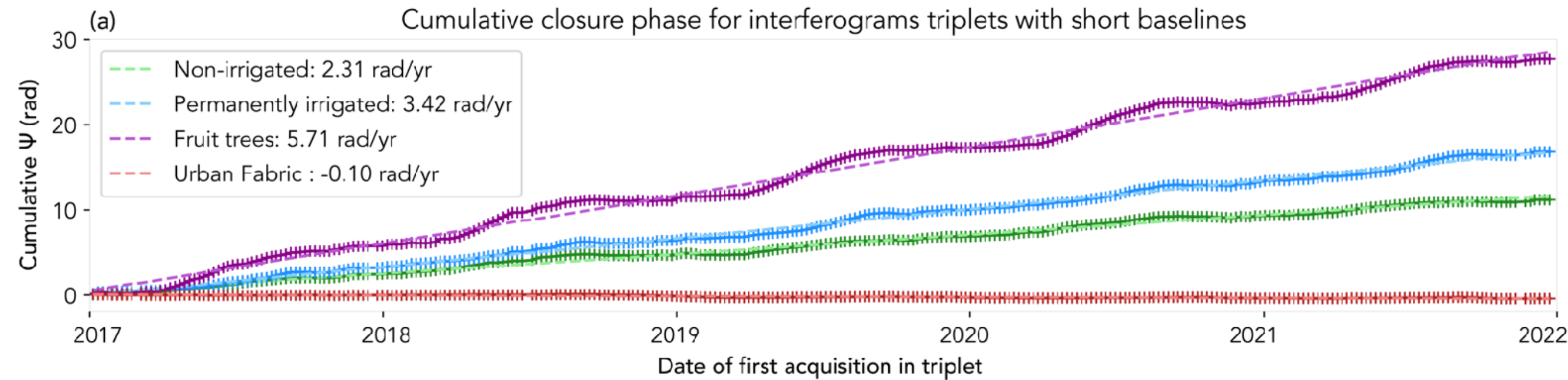


# Coherence and Closure phase on different types of crops



- More error cumulated on irrigated crops than non-irrigated.
- Error accumulation over fruit trees is almost only seasonal.

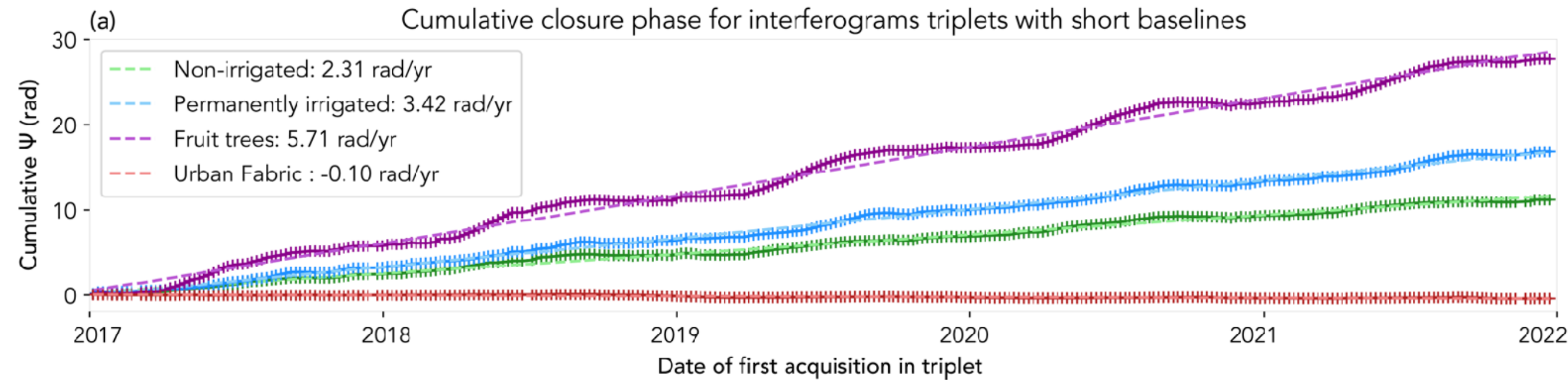
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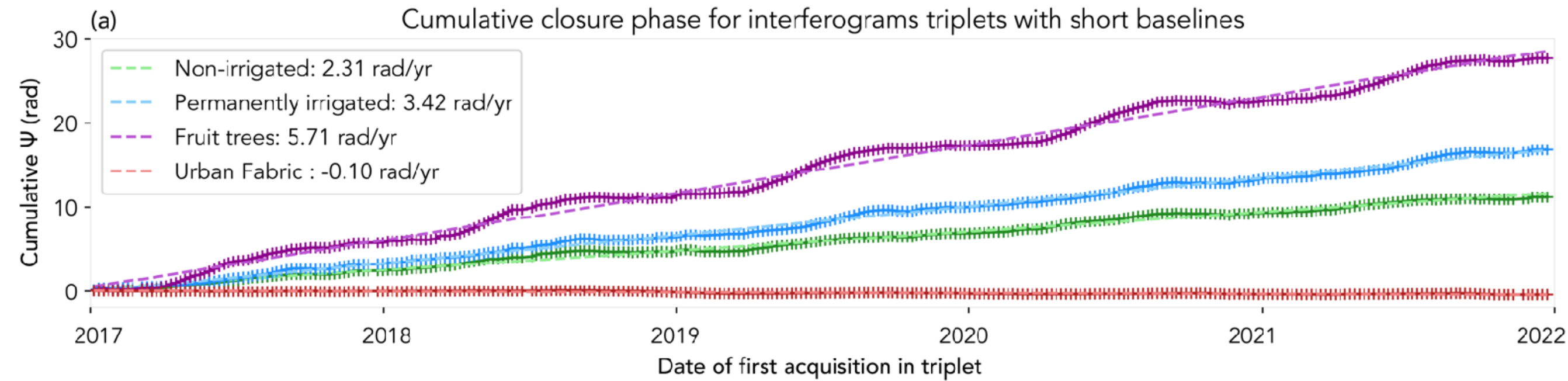


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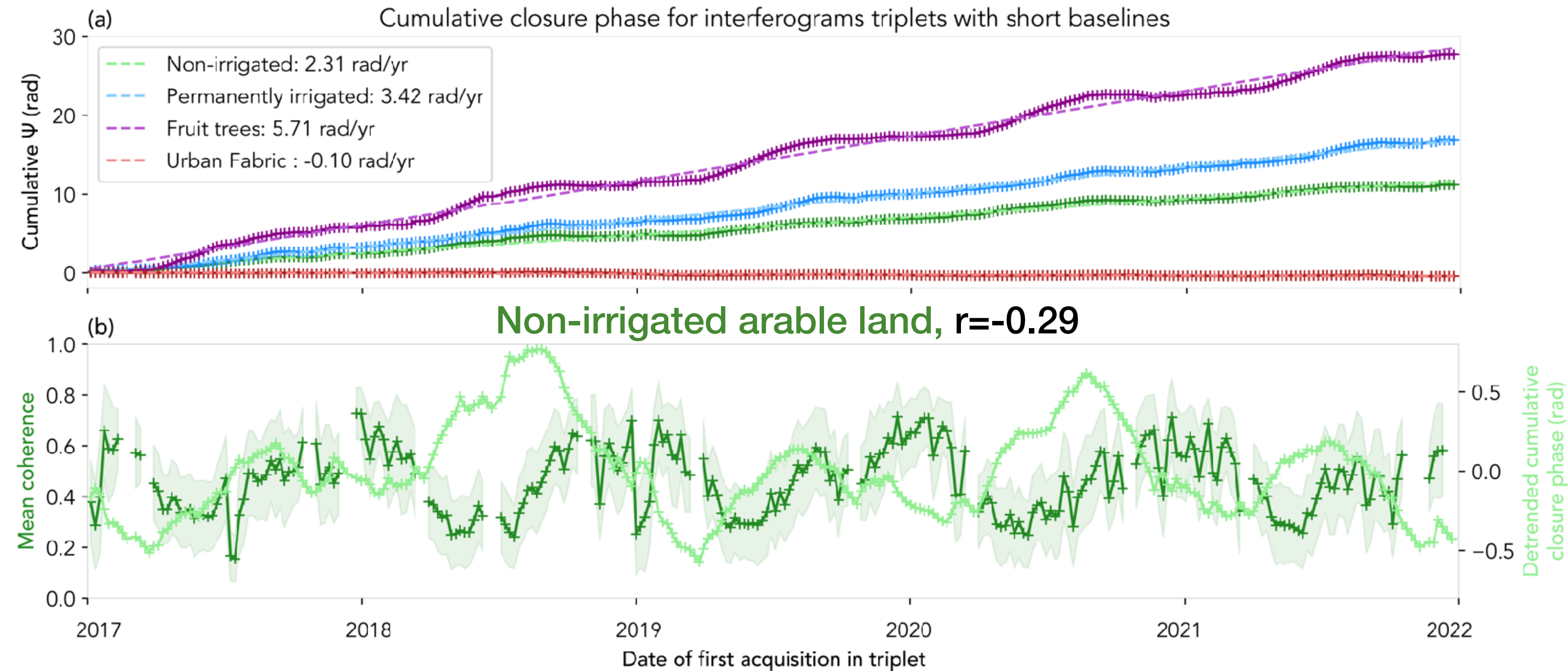
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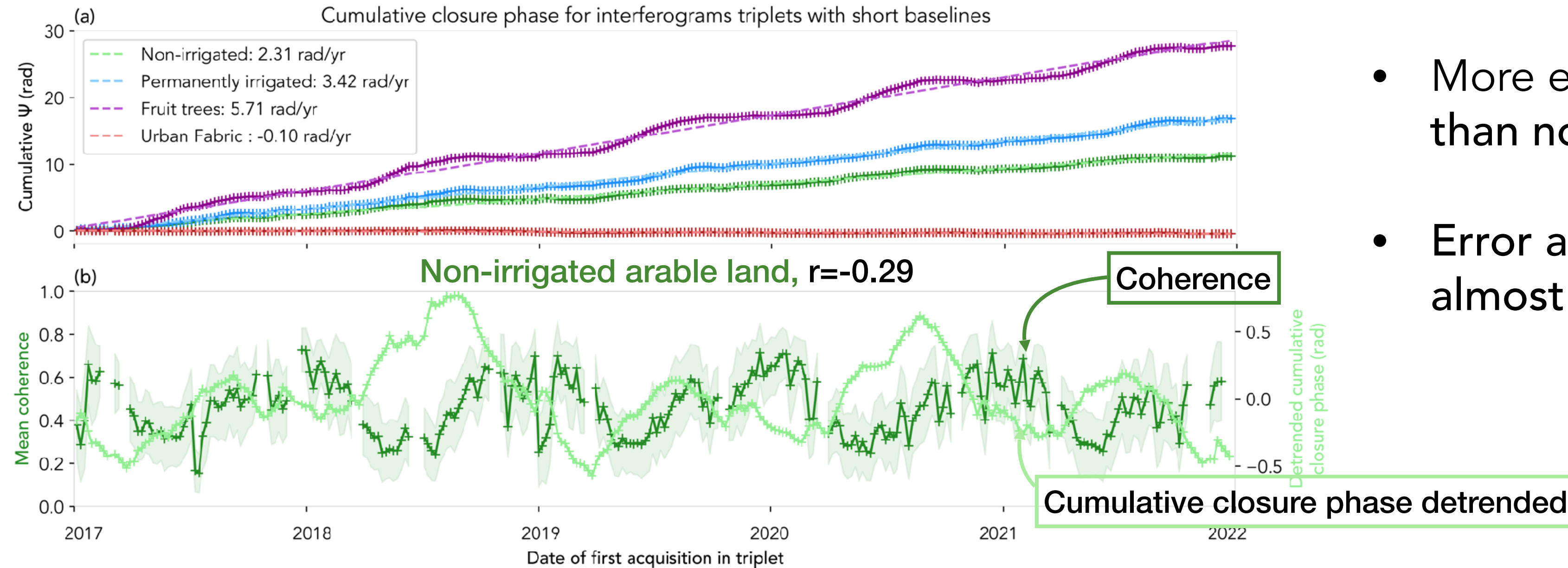


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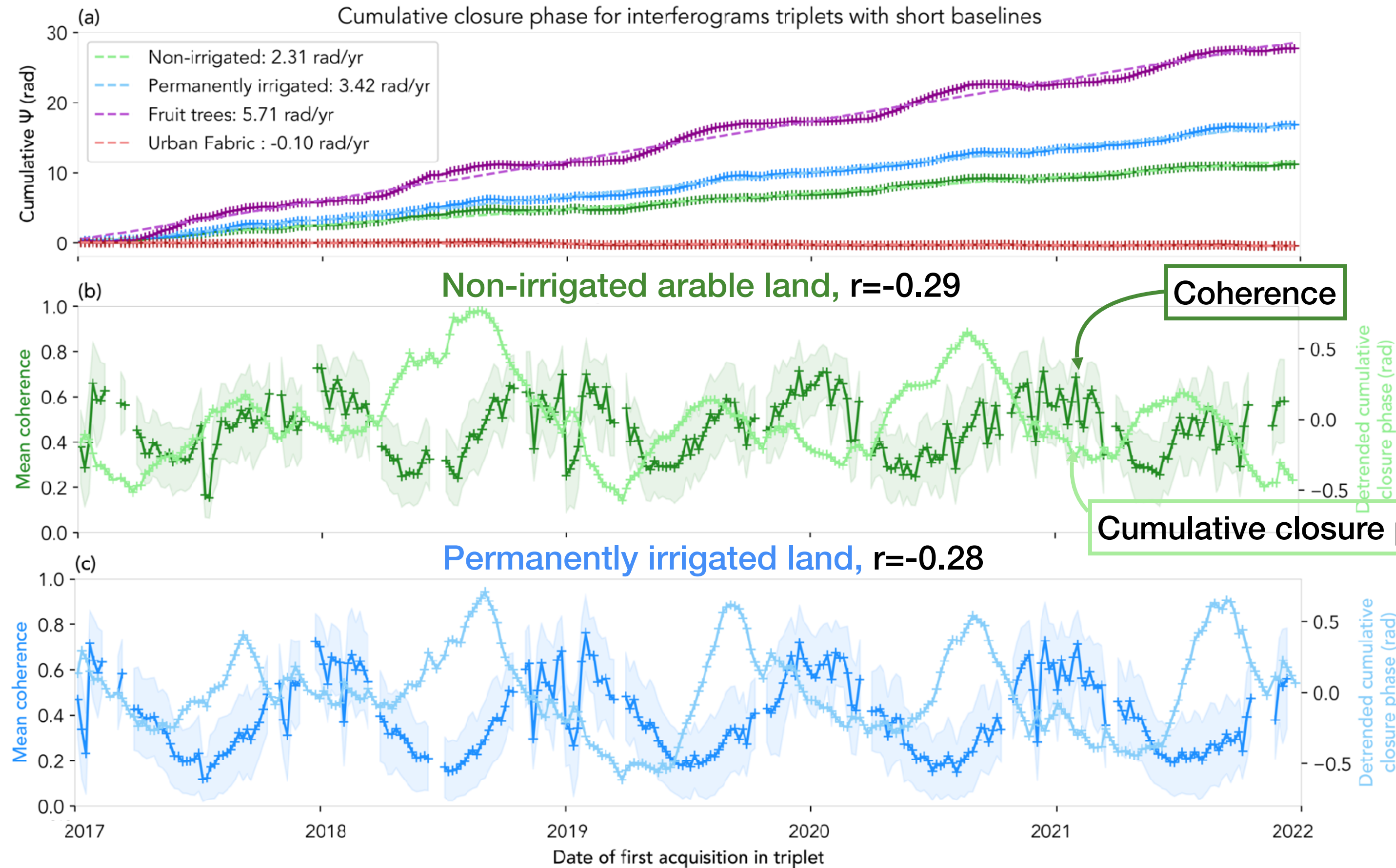
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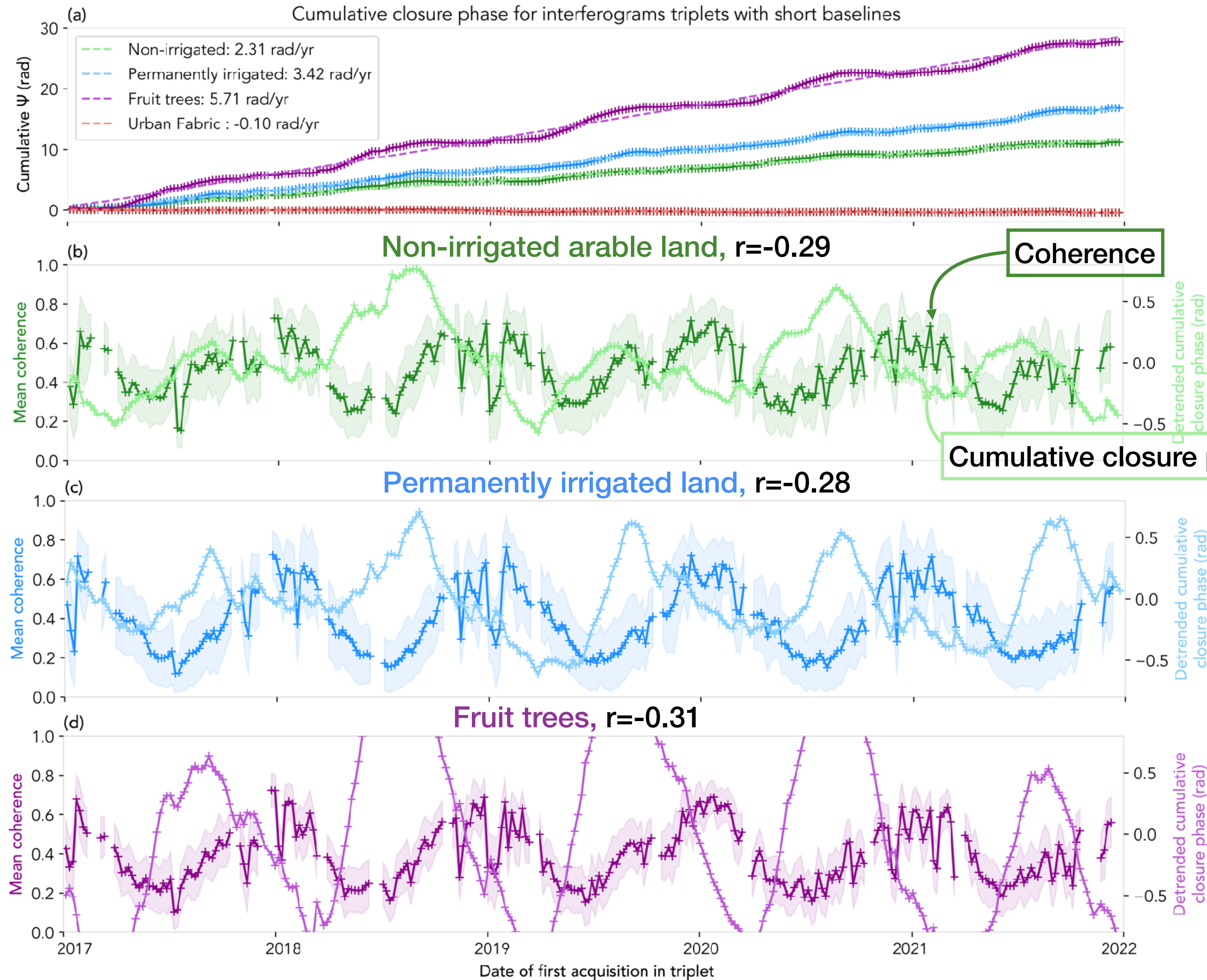
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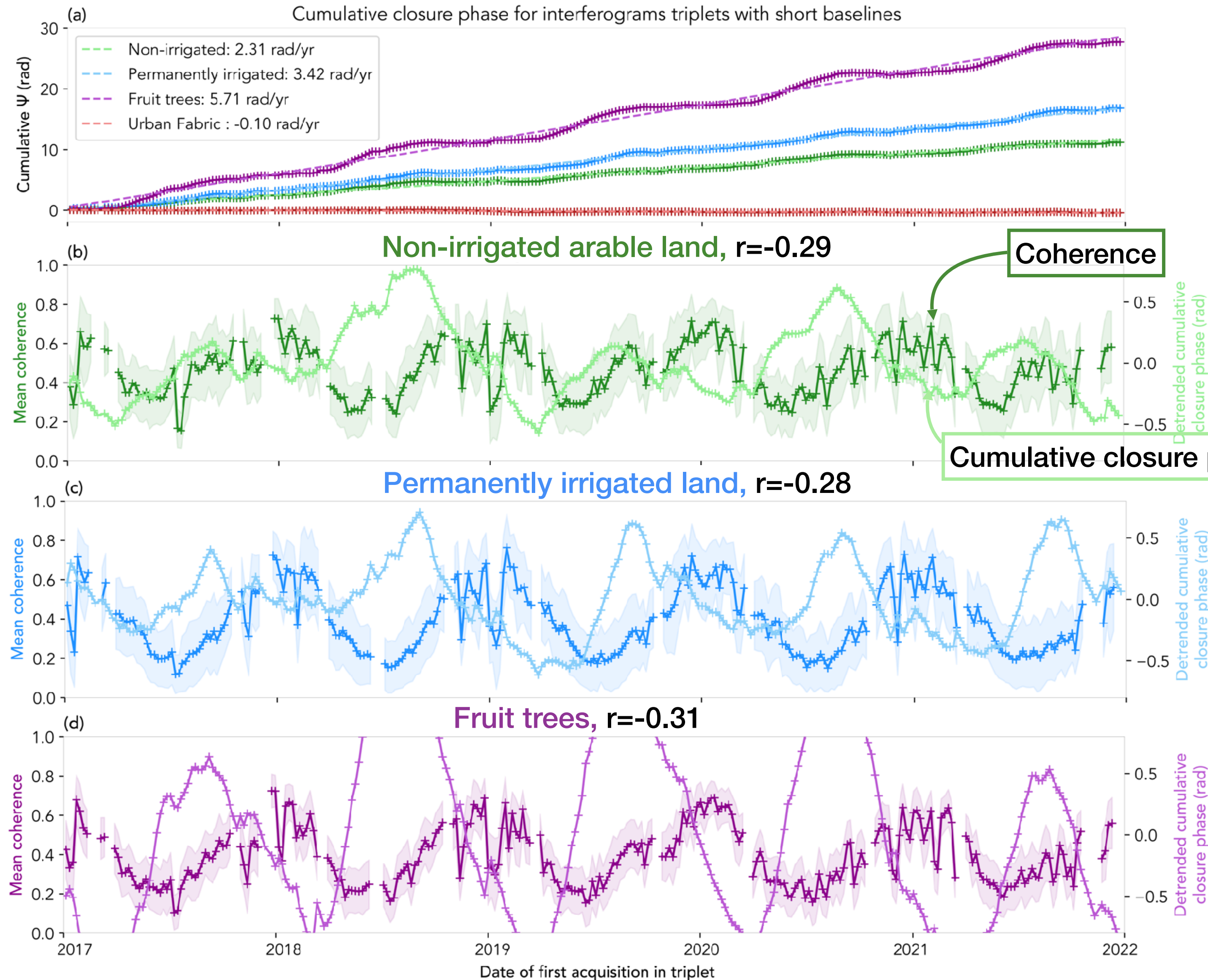
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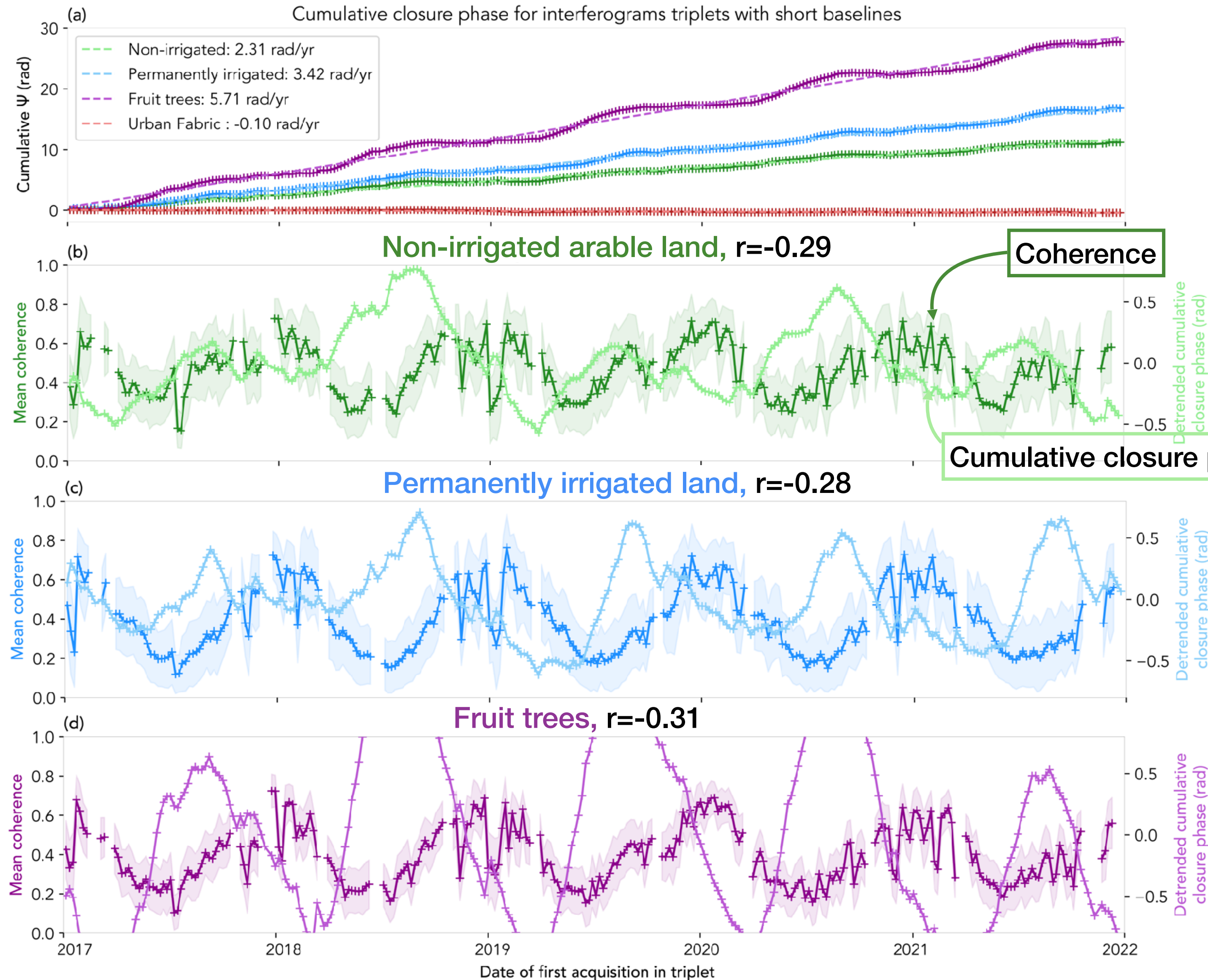
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- Anticorrelation between closure phase seasonal accumulation and coherence.



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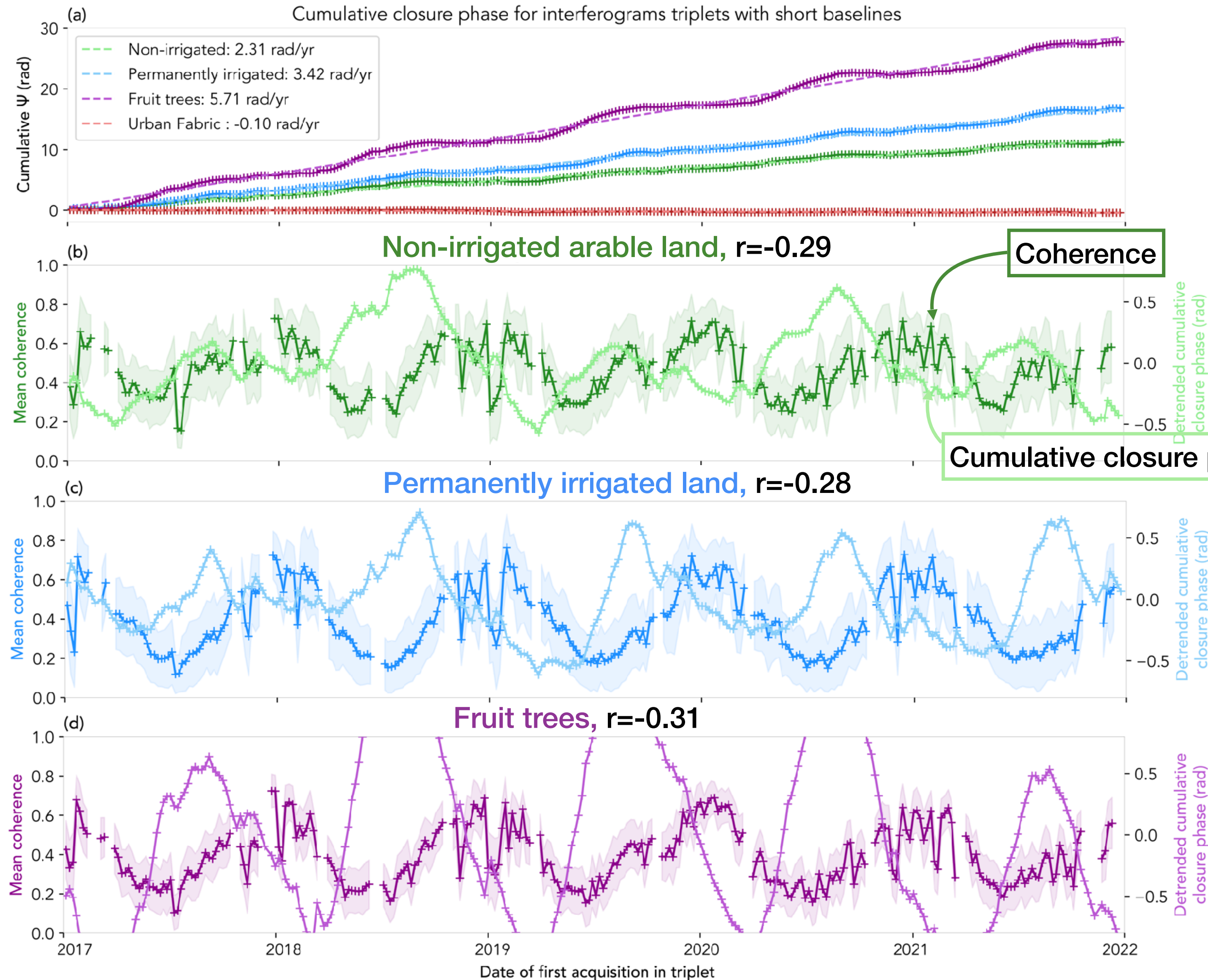


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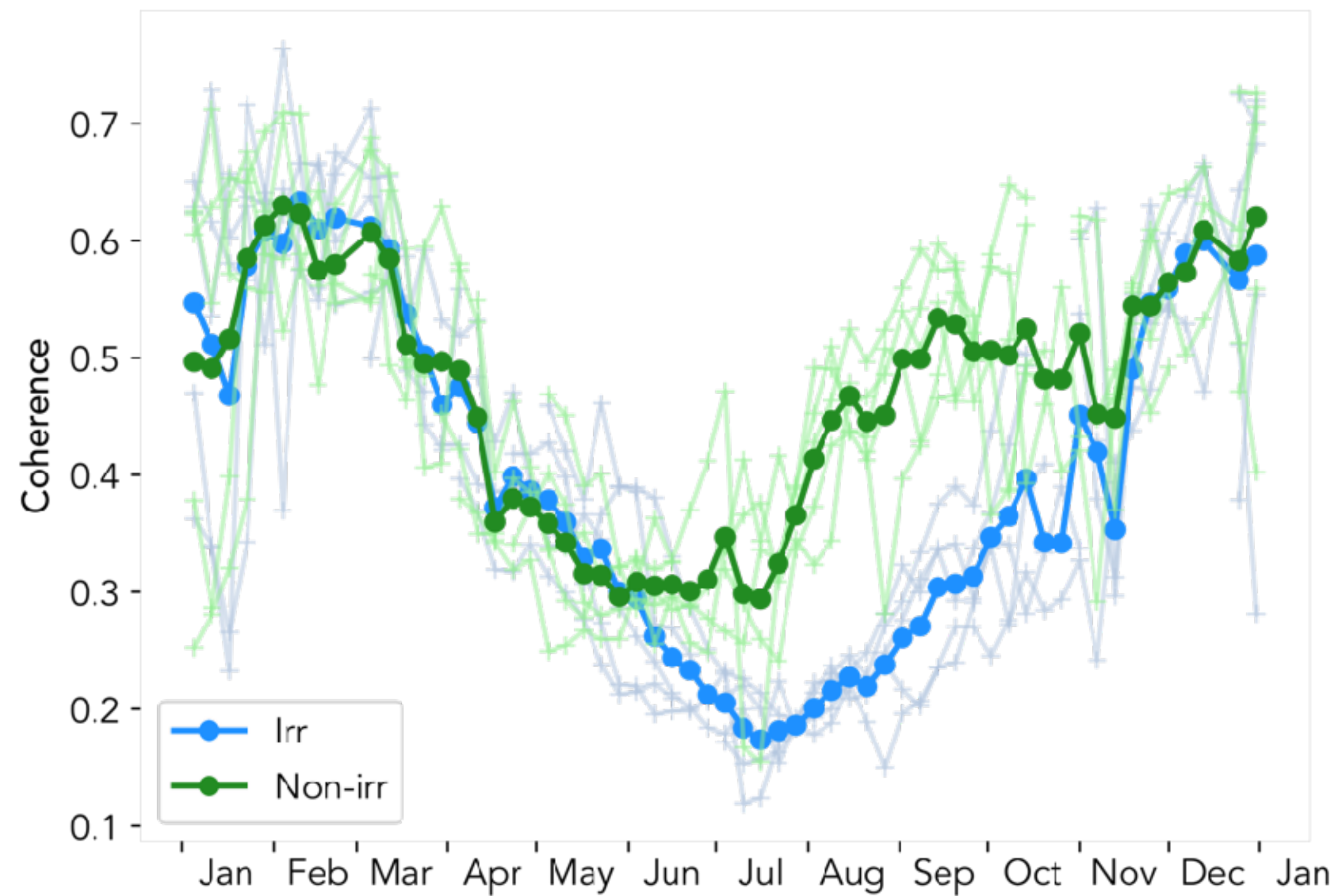


- More error cumulated on irrigated crops than non-irrigated.
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- But delayed peaks.
- Year-to-year variations not captured in coherence

# The annual coherence

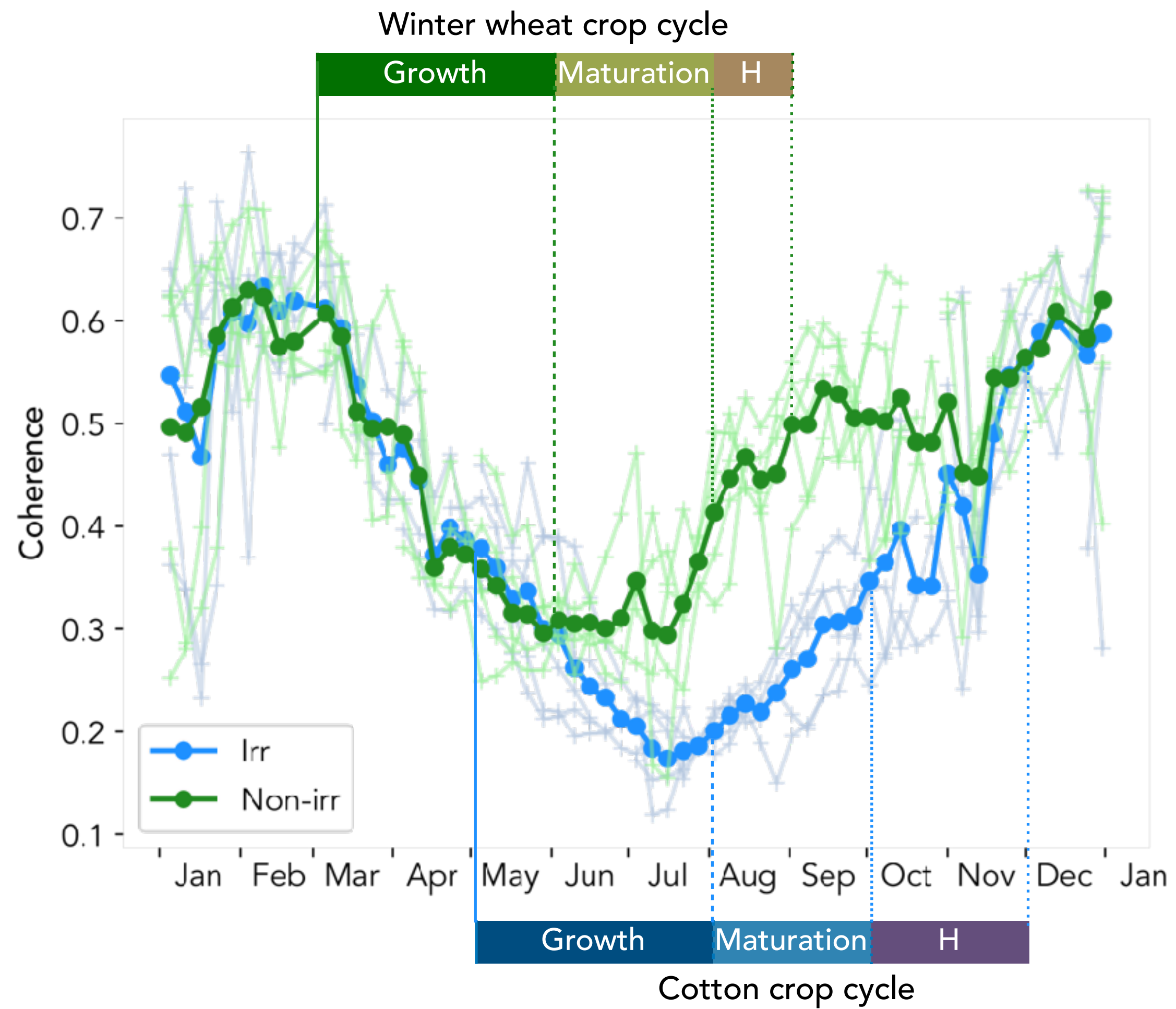
Relation to the crop cycle





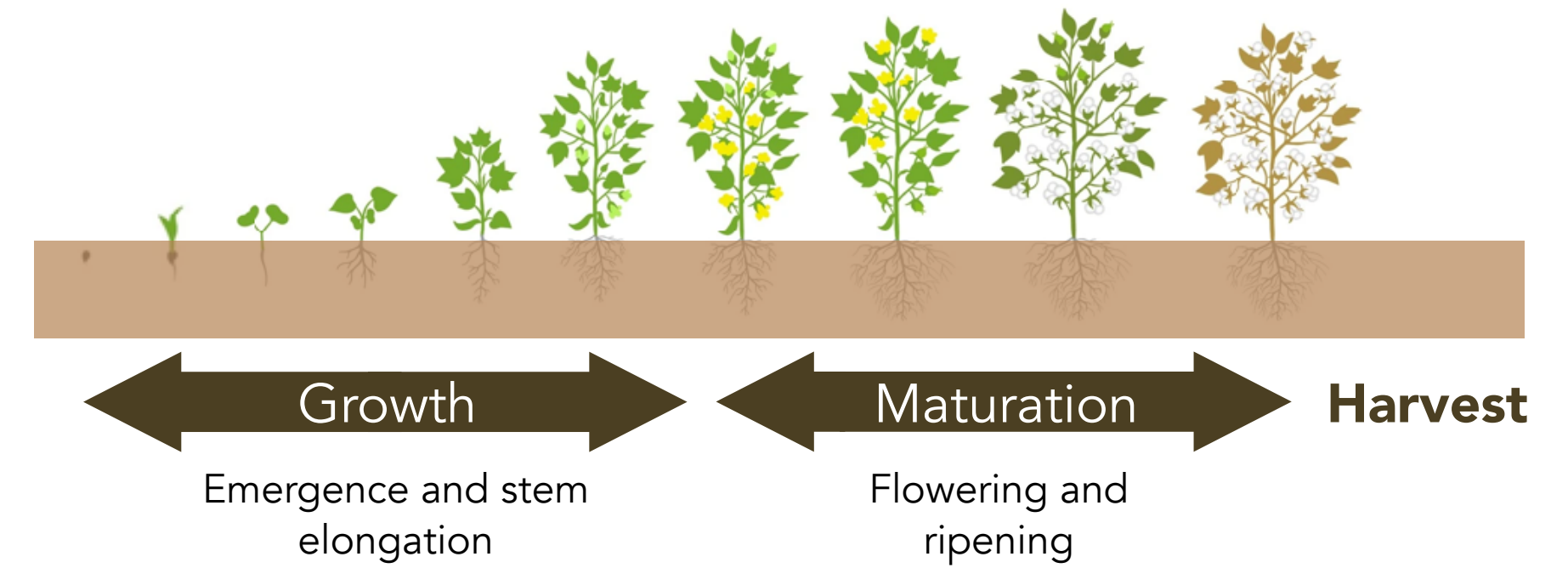
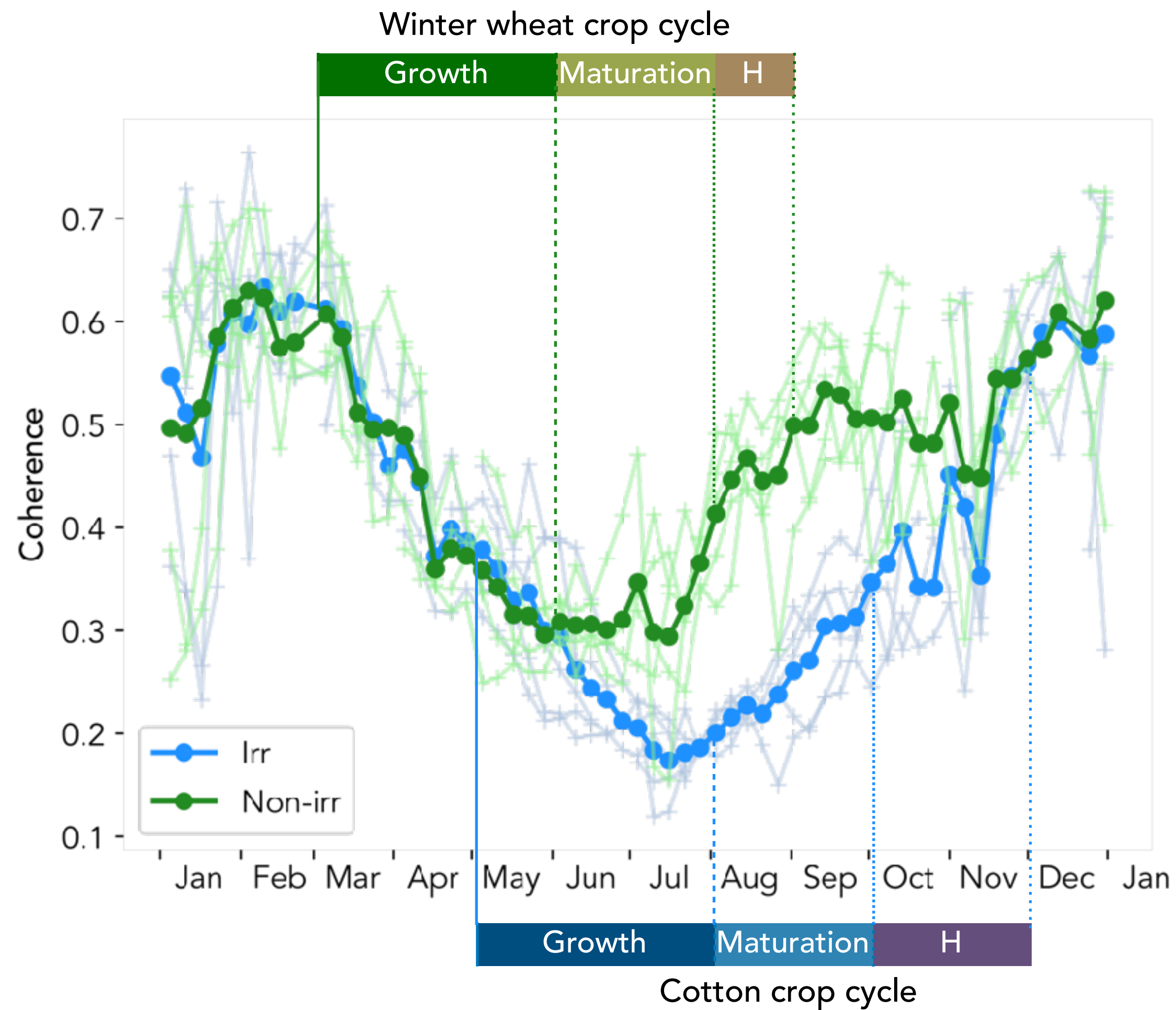
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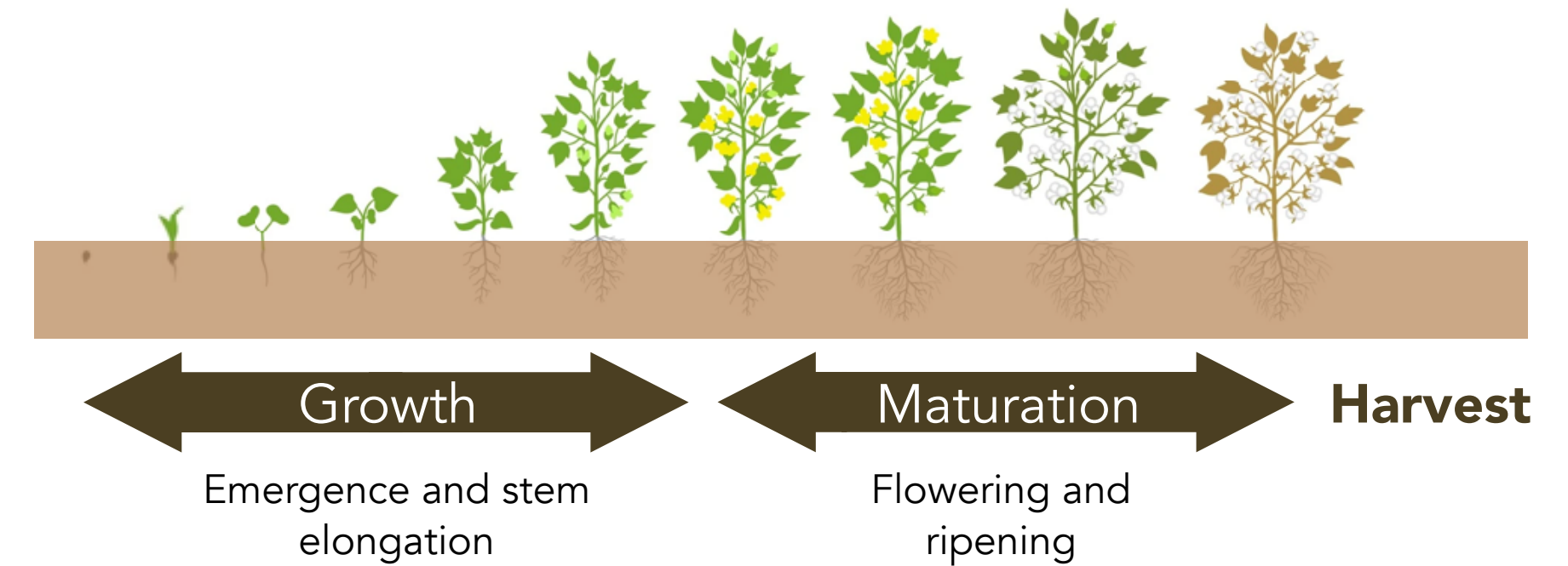
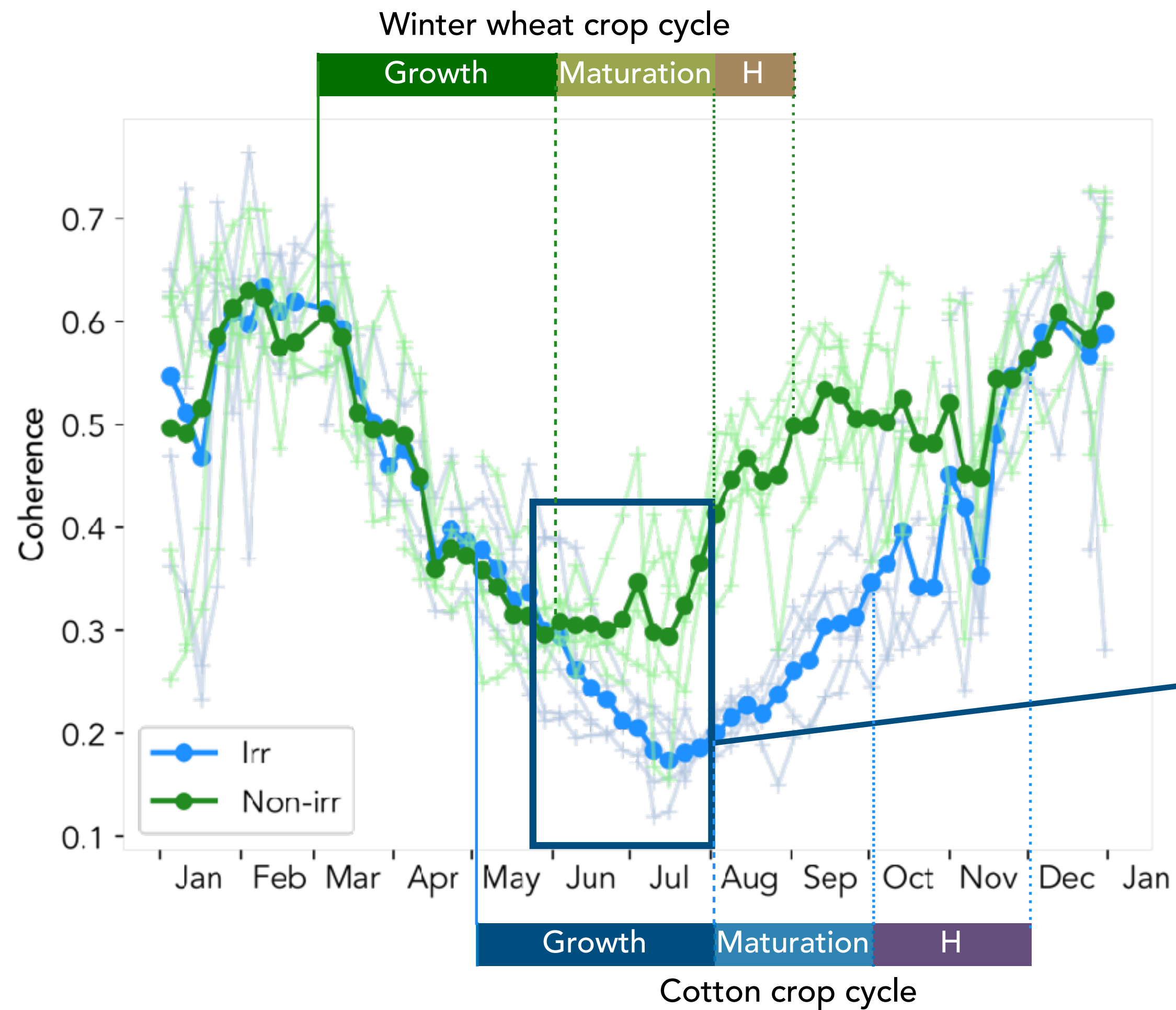
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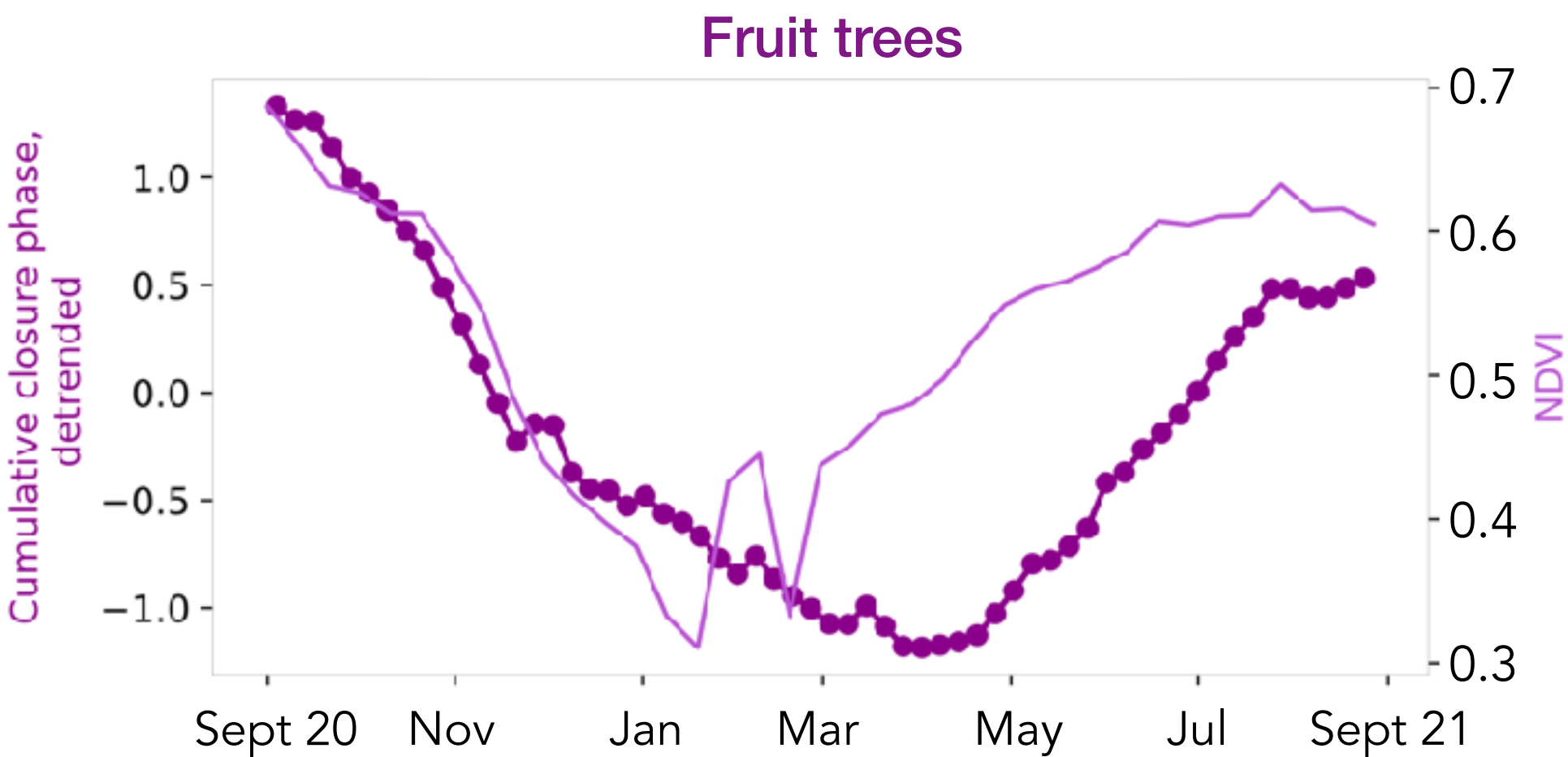
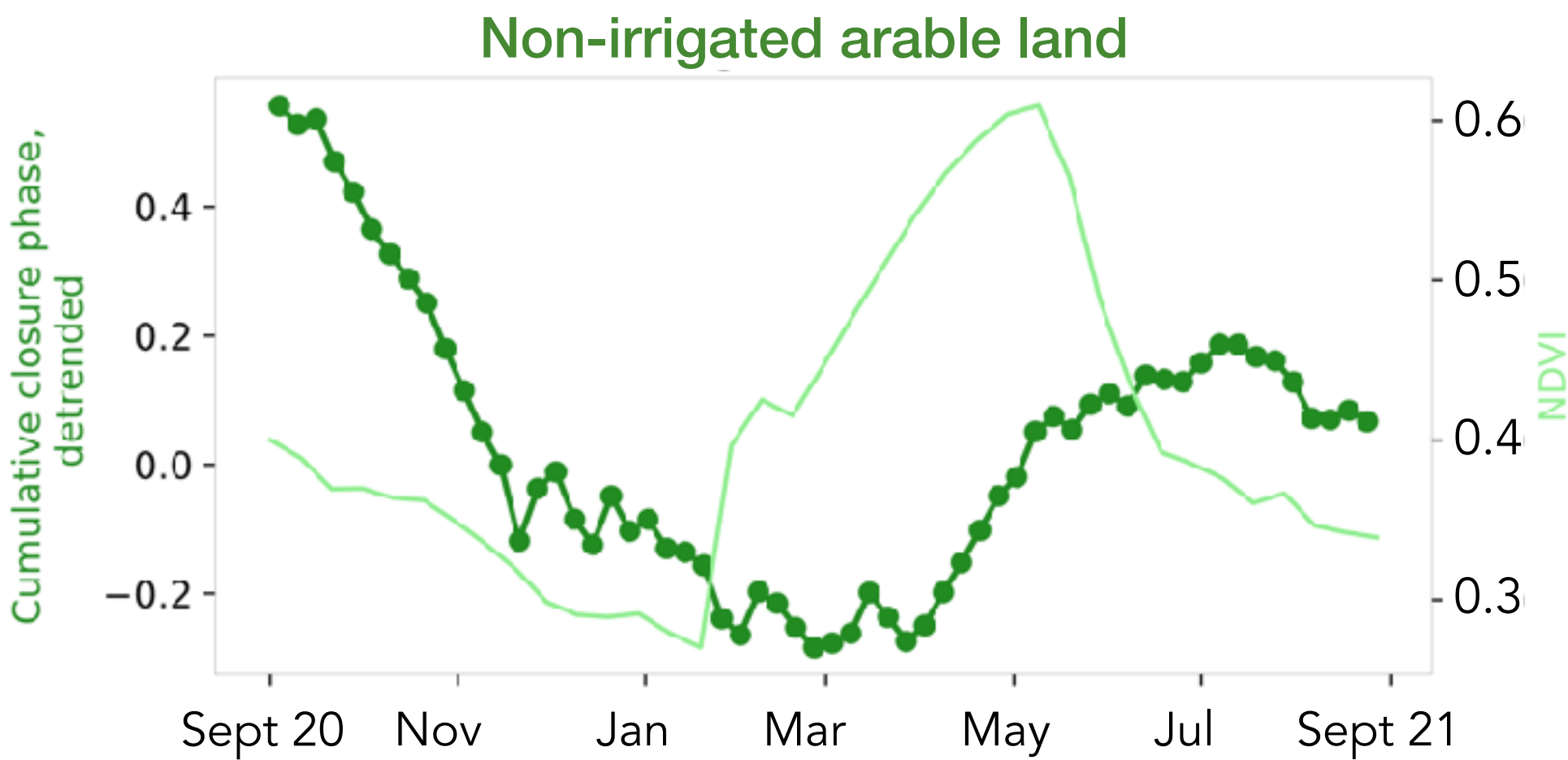
## Relation to the crop cycle



Coherence drop for plant growth during hottest summer months when more irrigation is needed

# NDVI and closure phase

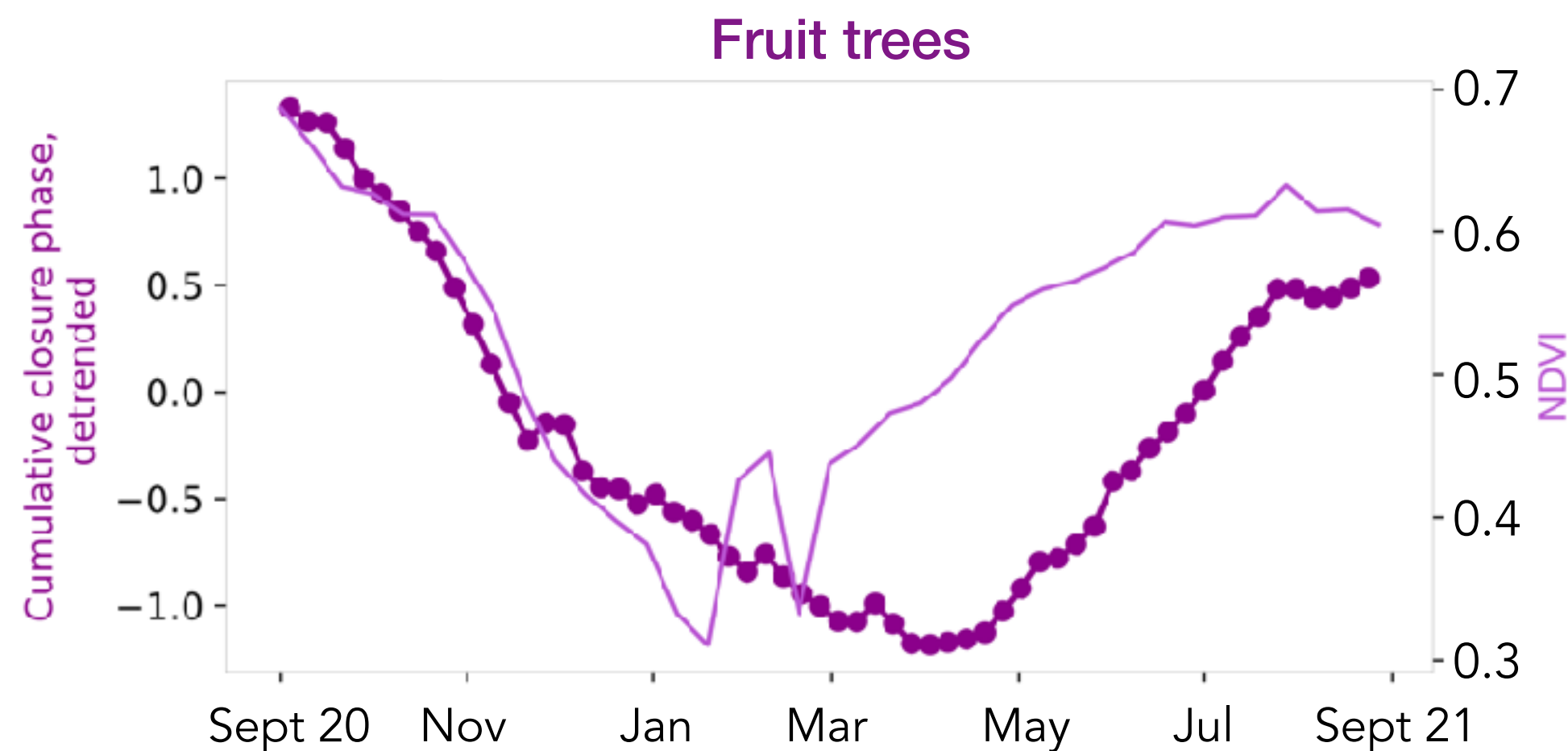
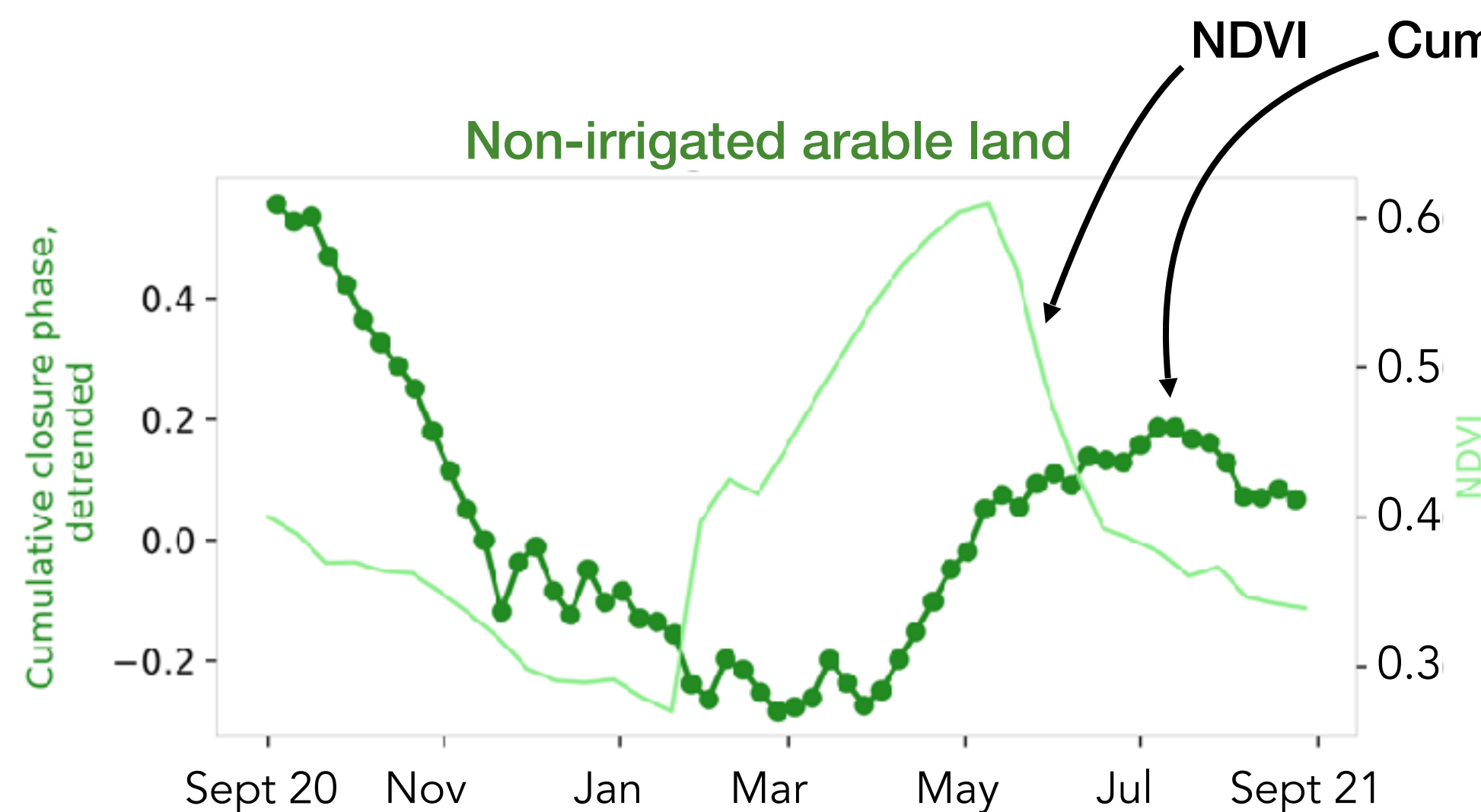
Interpolated data from S. Ferrant (CESBIO)





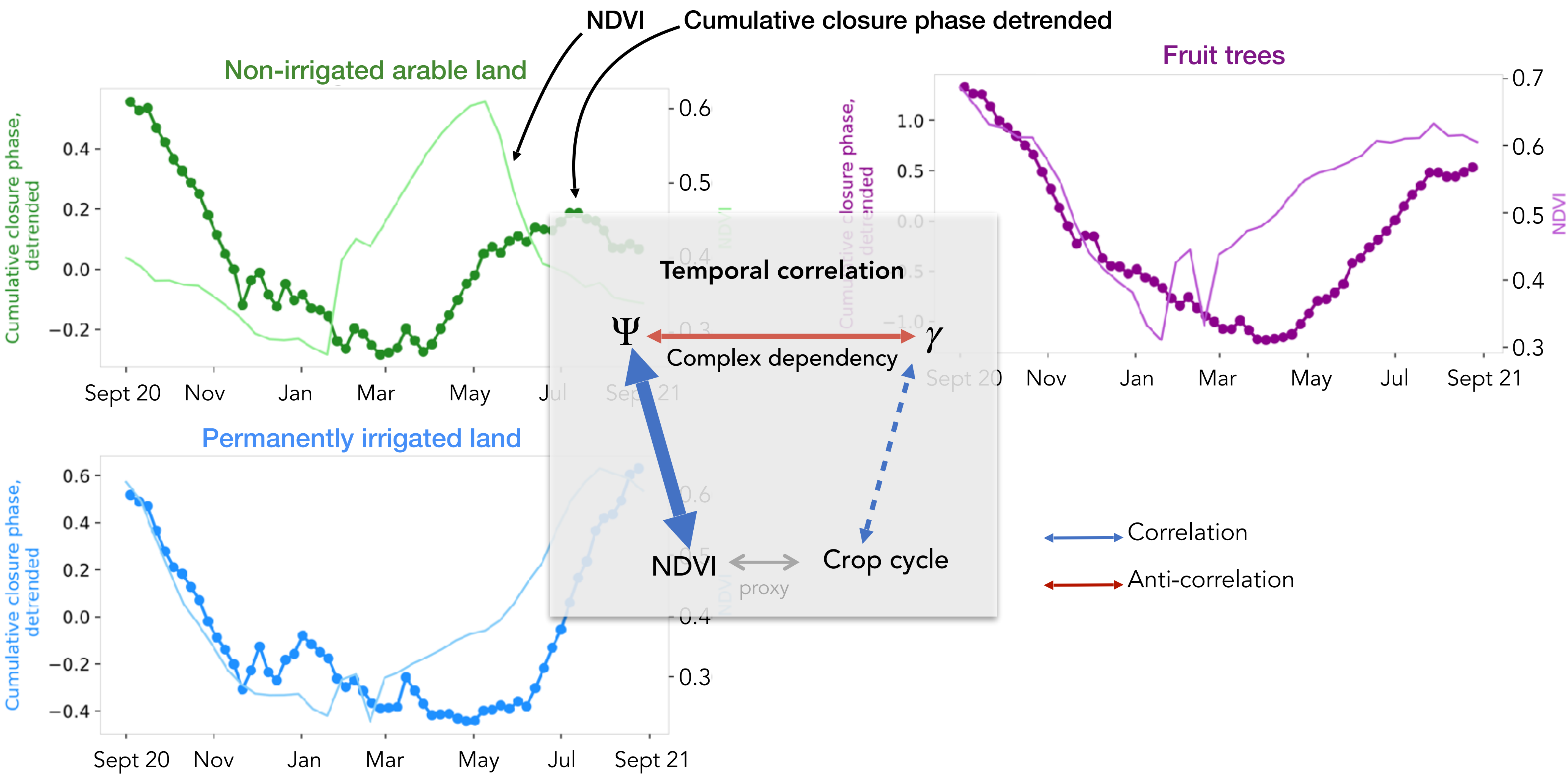
# NDVI and closure phase

Interpolated data from S. Ferrant (CESBIO)



# NDVI and closure phase

Interpolated data from S. Ferrant (CESBIO)





What about the velocity bias ? Why do we want to characterize it ?

# From phase error to velocity bias

Several methods for bias mitigation :

- ▶ **masking** biased pixels
- ▶ for better coverage : methods mostly based on **long baseline stability** (Ansari 2022, Zheng 2020, Maghsoudi 2022). Issues arise in regions with no long term coherence (typically temperate regions).
- ▶ **weighting** the spatial averaging. (SNO ISDeform, M.-P. Doin)



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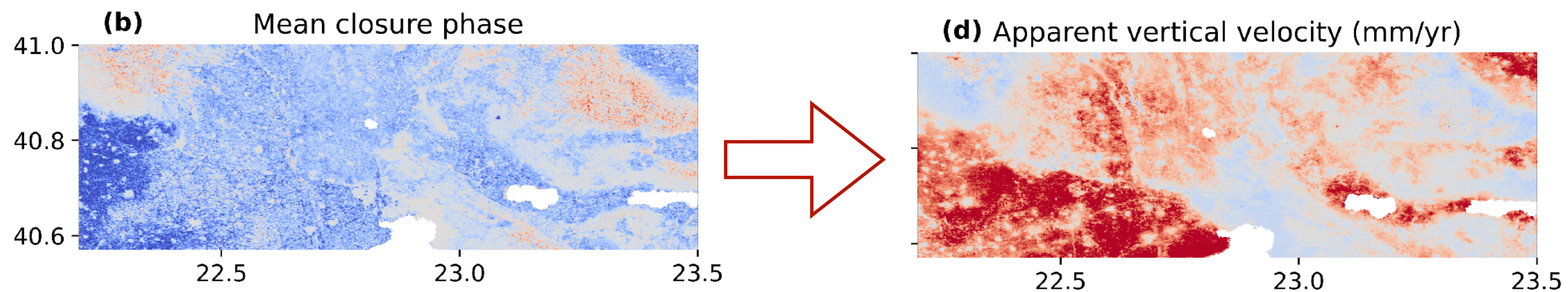
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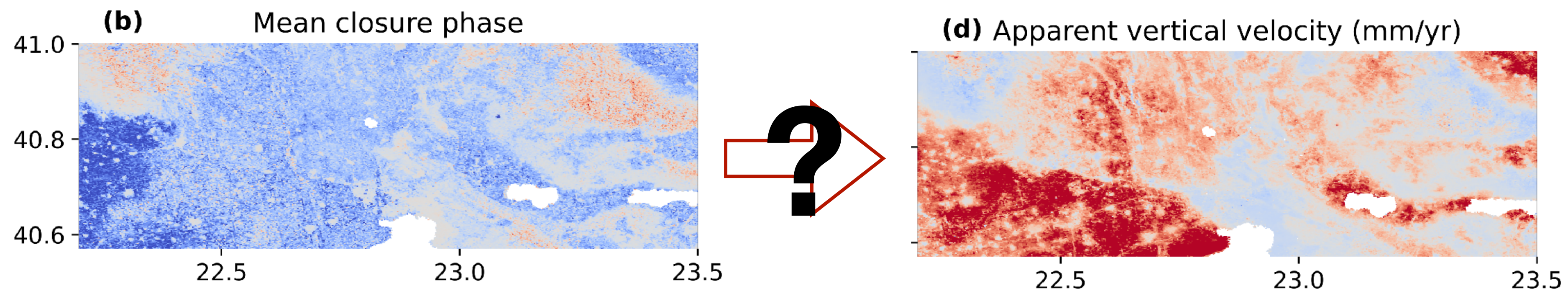


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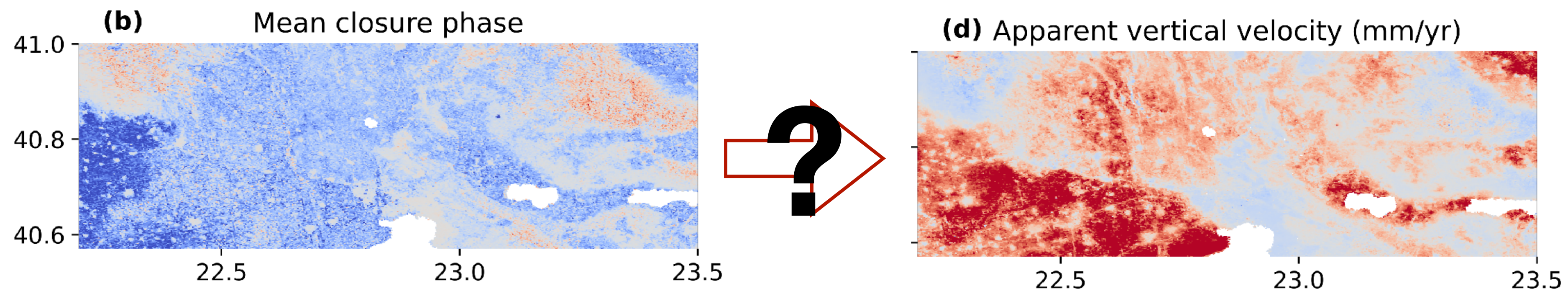


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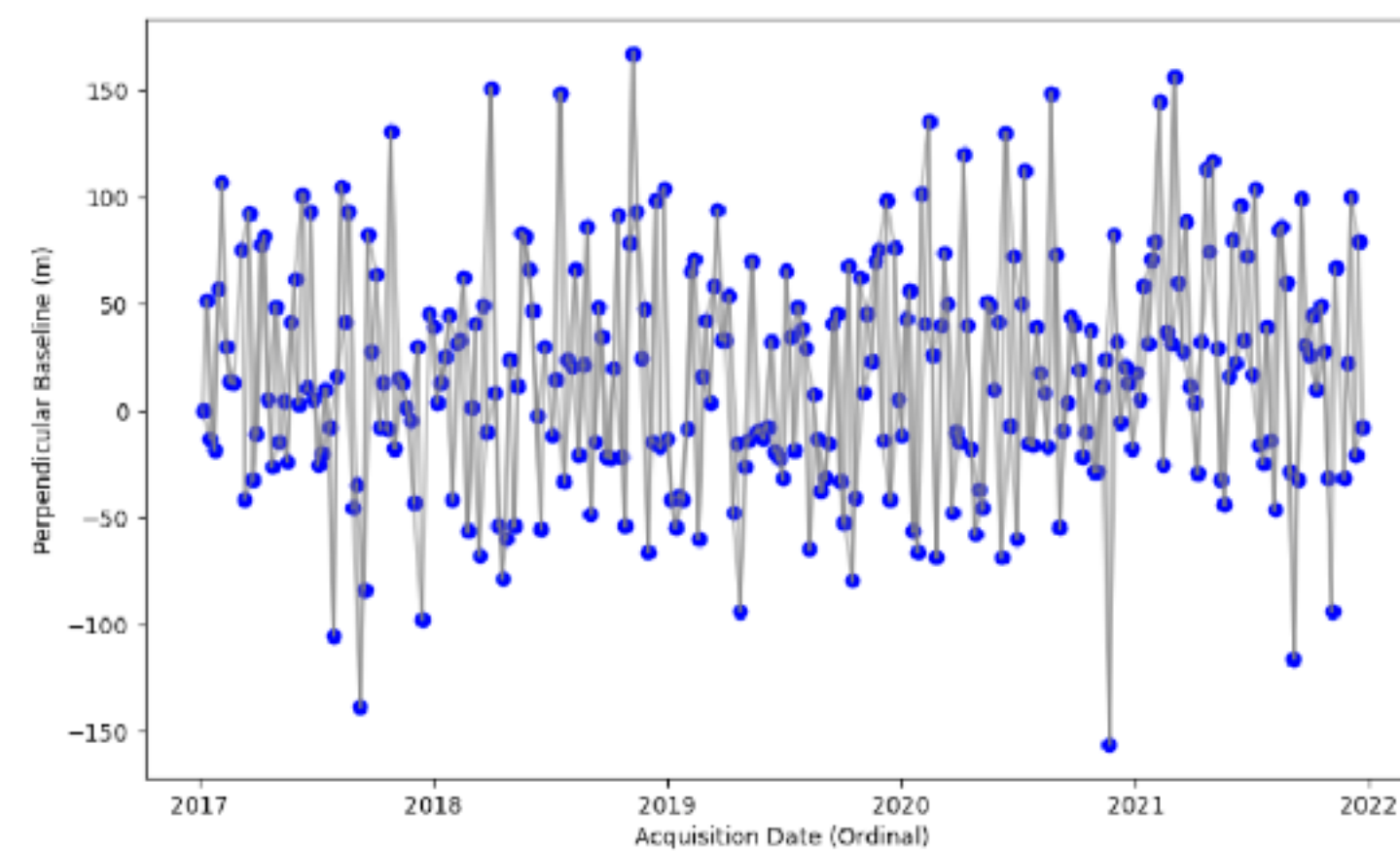
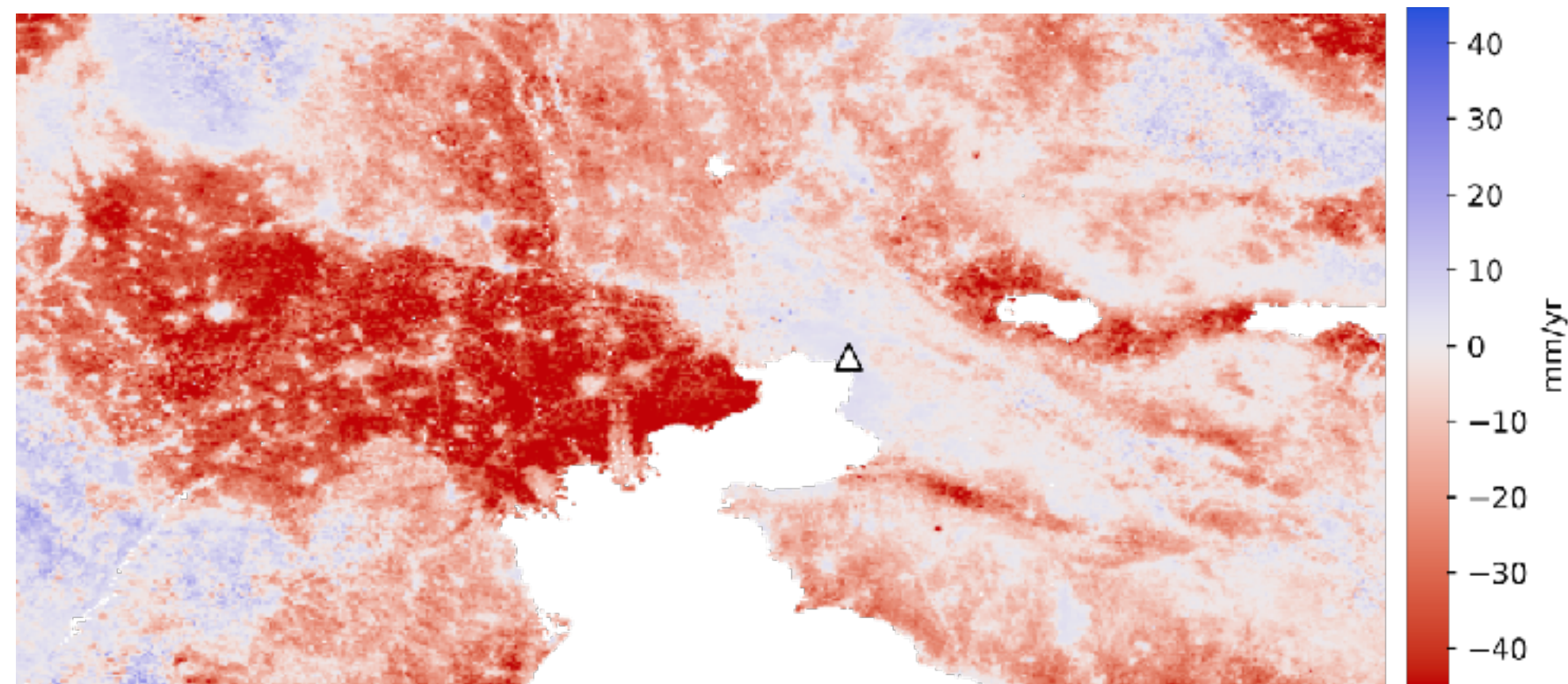


Prediction and correction of the bias based on its physical understanding ?



# Influence of the network

Bias minimizing with longer baselines



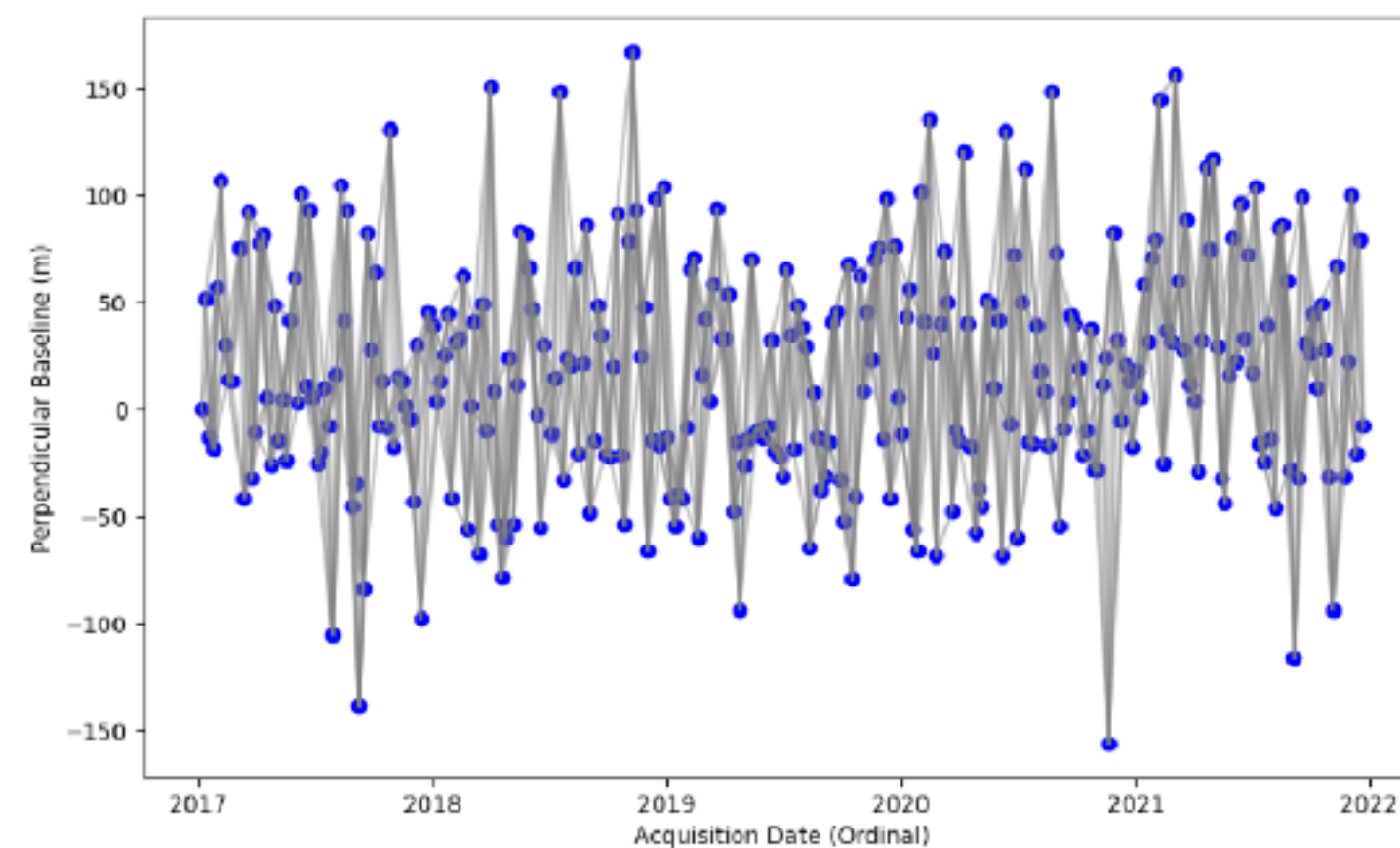
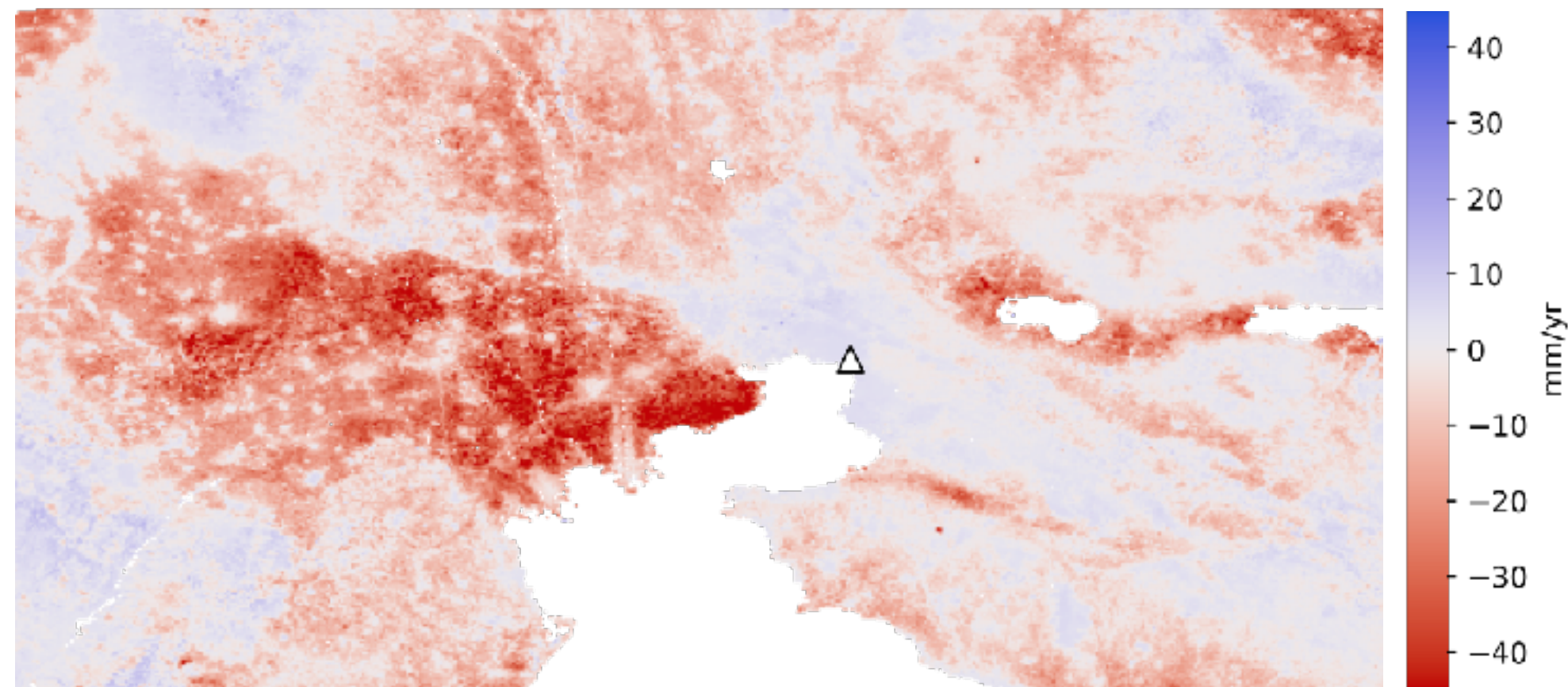
**Temporal baselines**

6 and 12 days



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Bias minimizing with longer baselines



**Temporal baselines**

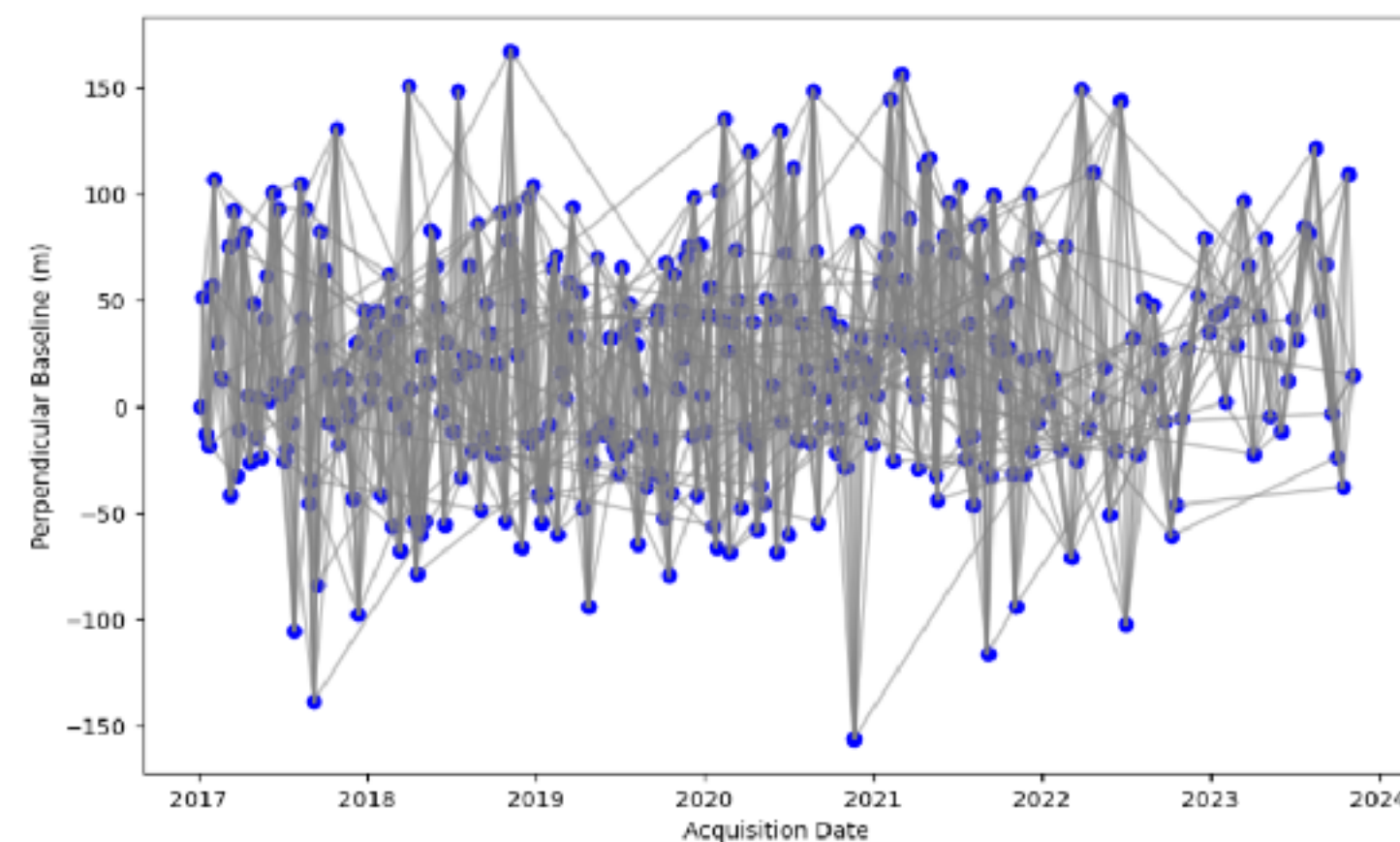
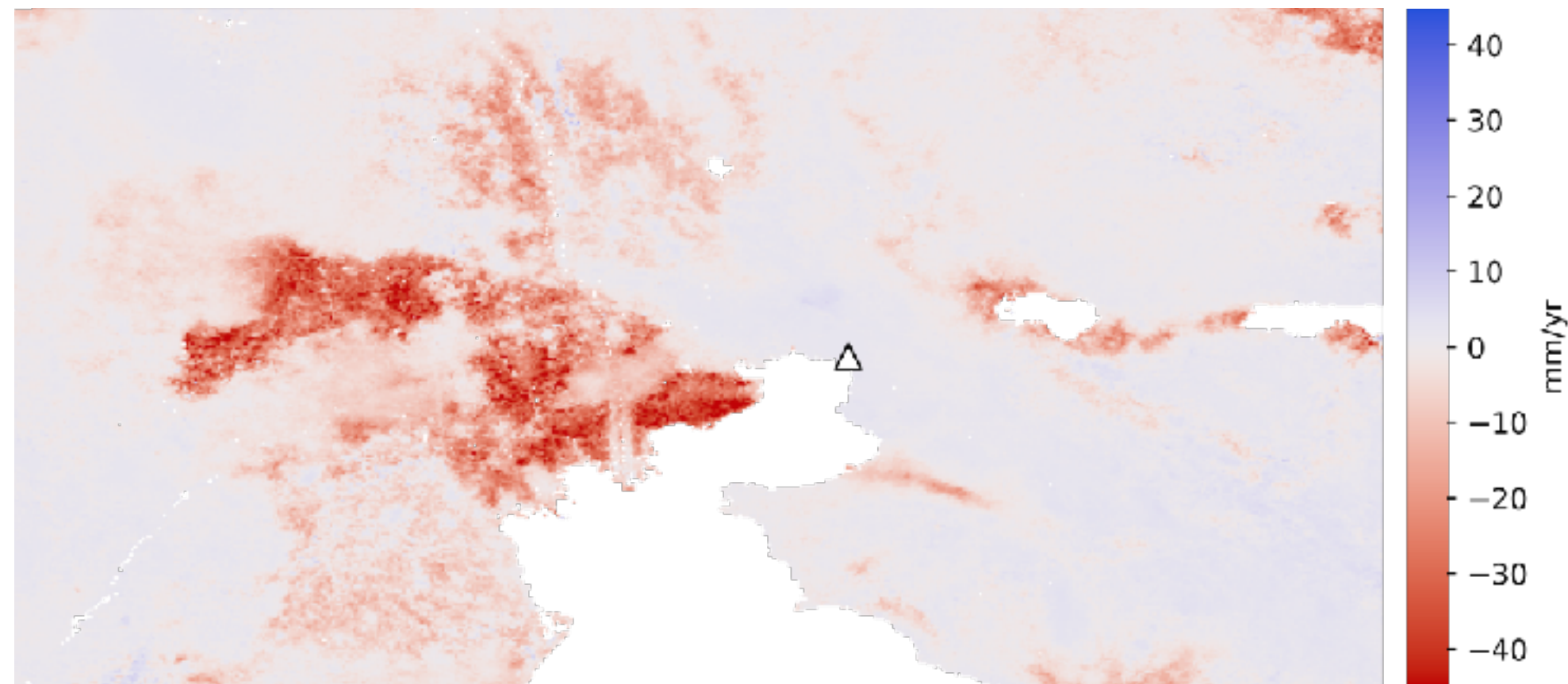
6 and 12 days

+ 18 and 24



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## Temporal baselines

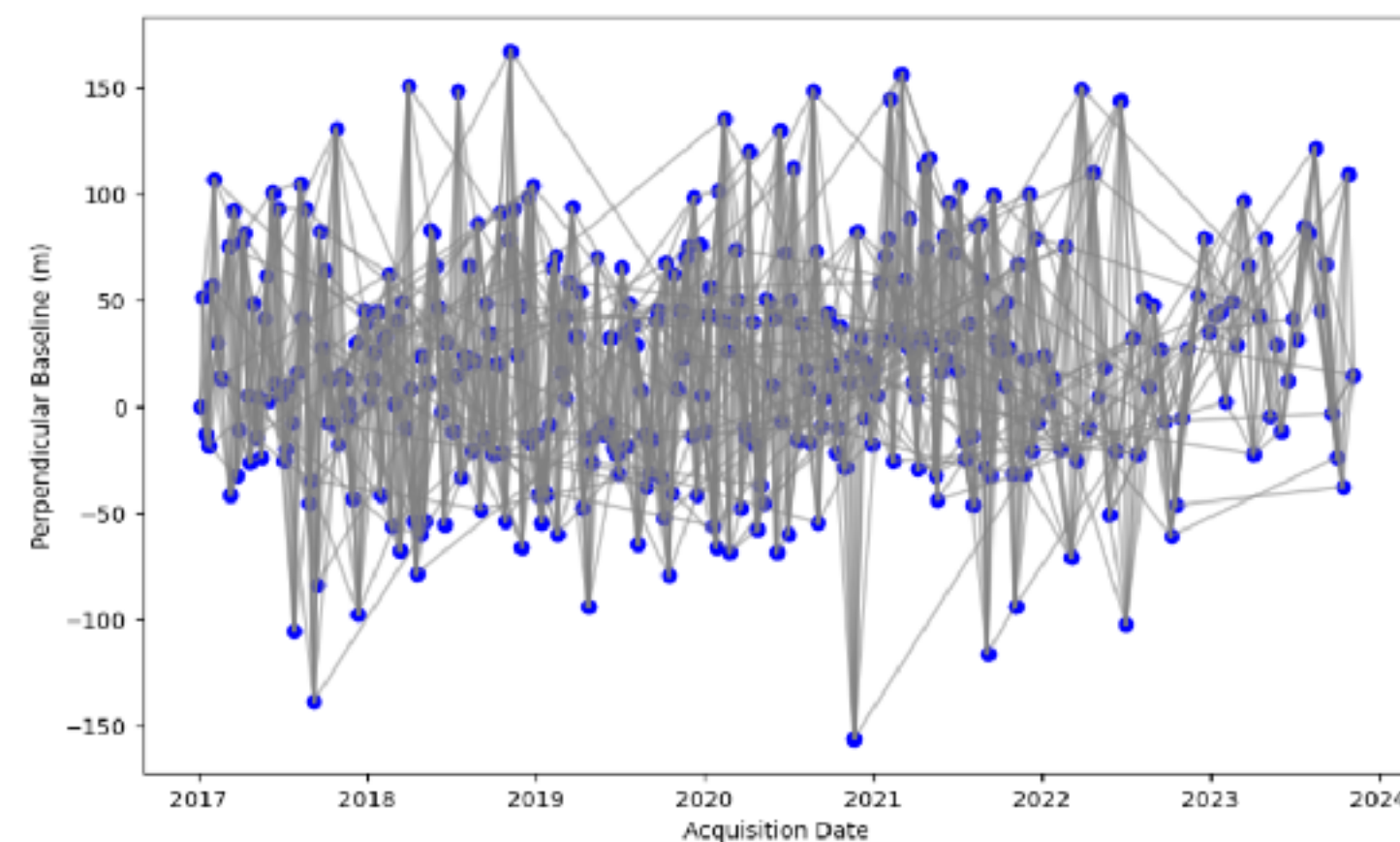
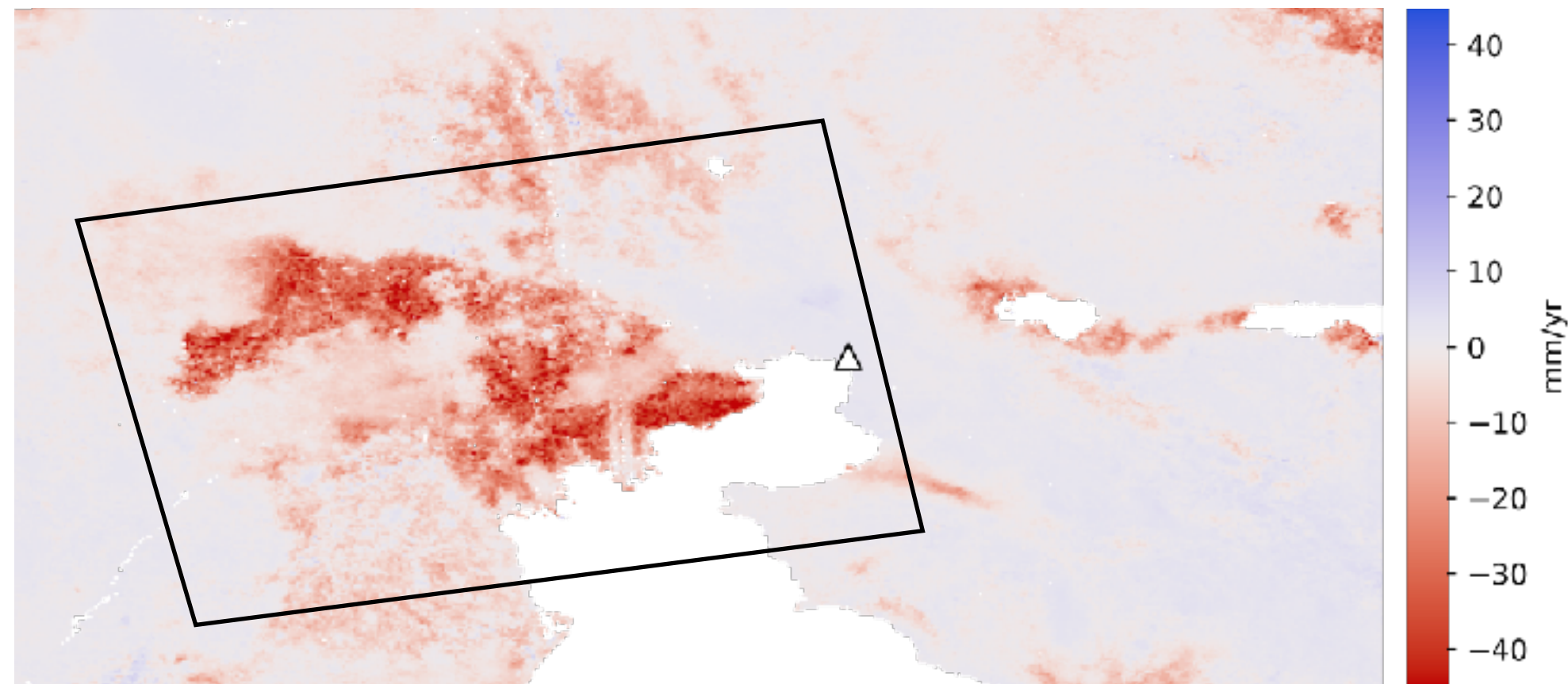
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+ 1, 2, 3, 6 months and 1 year

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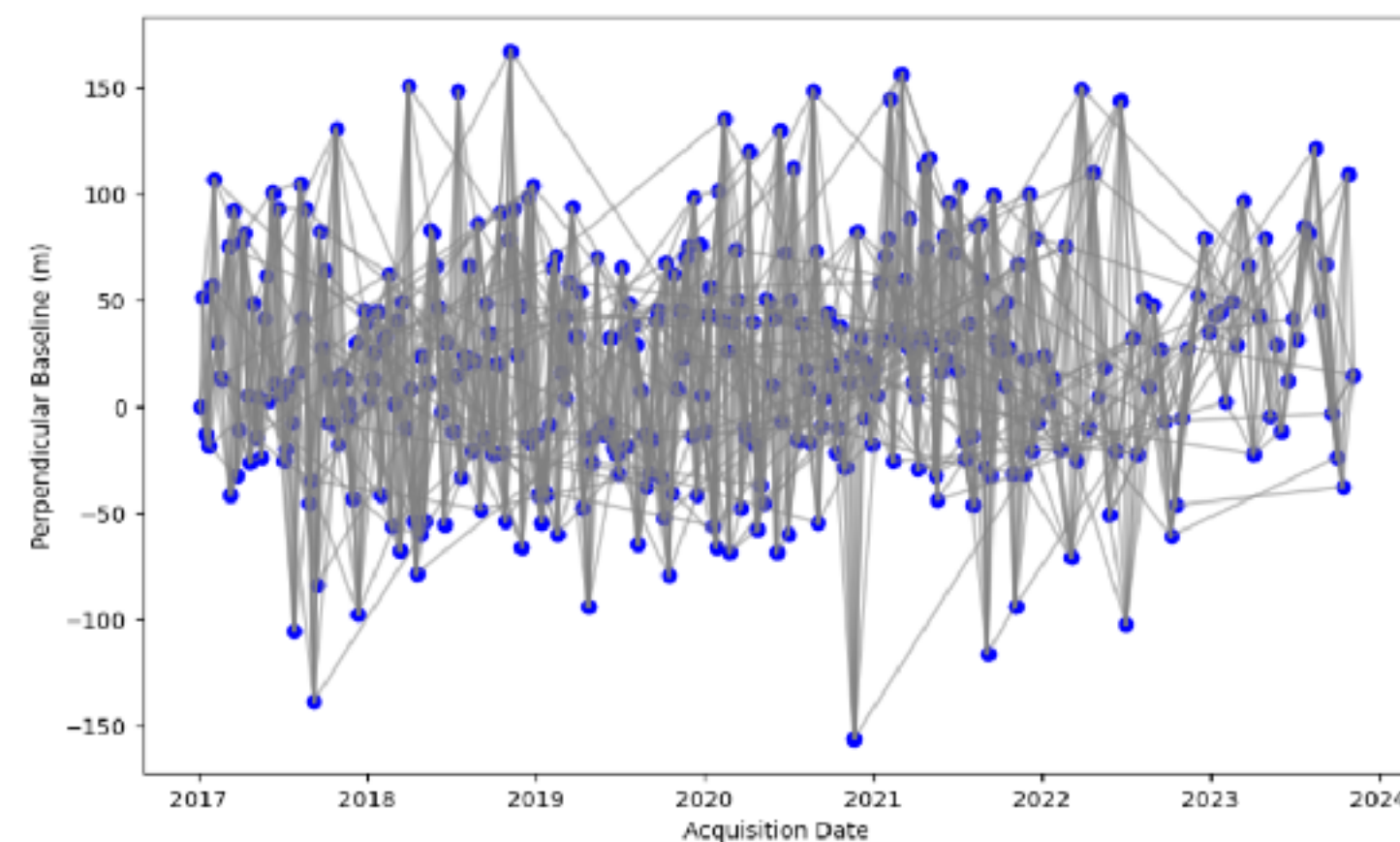
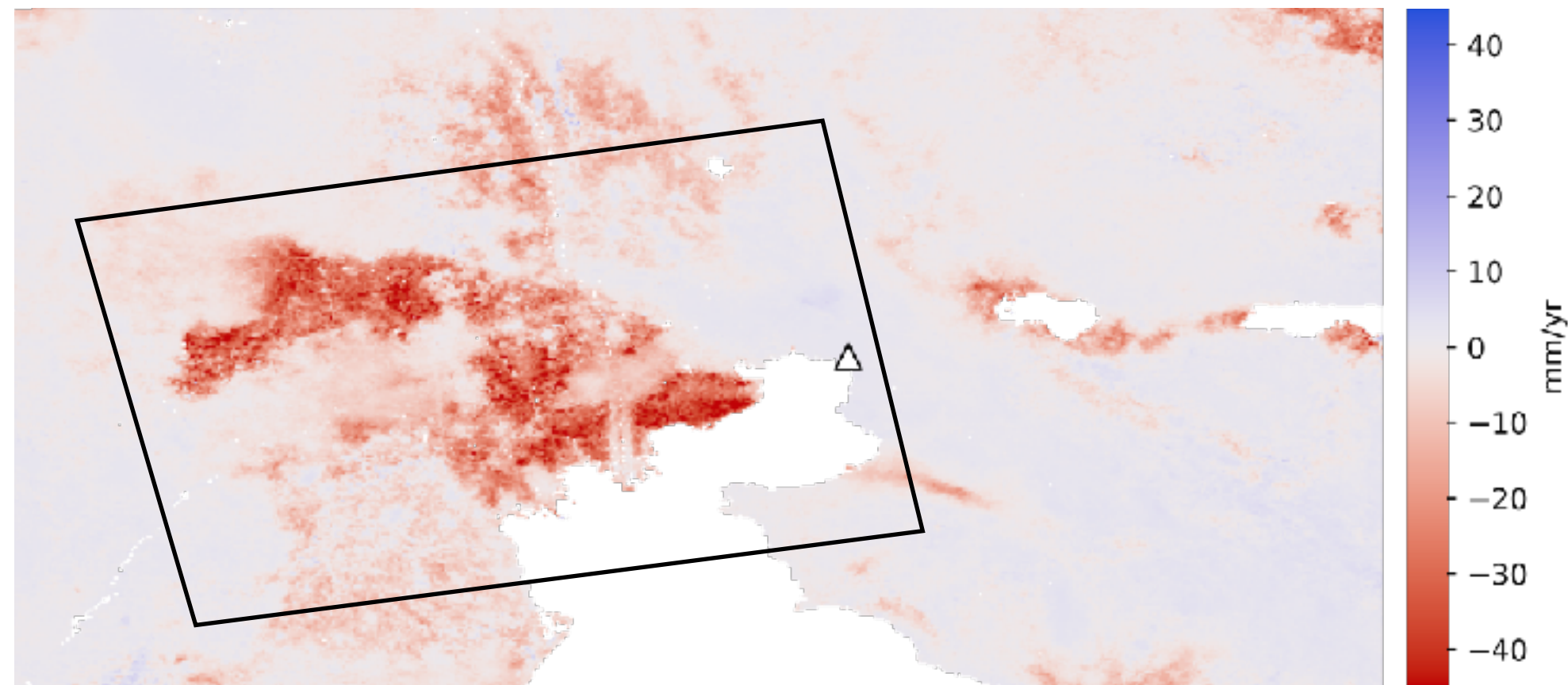
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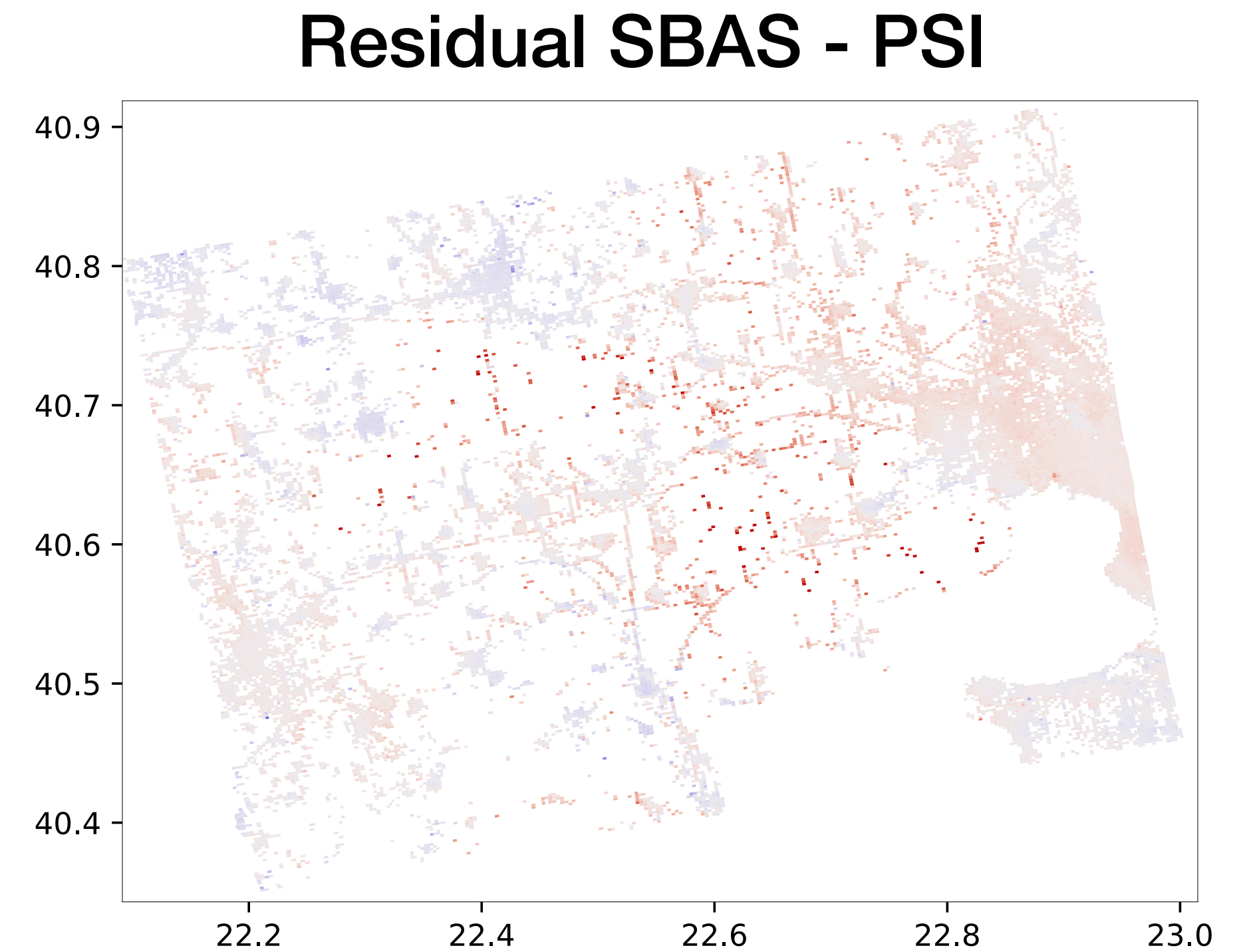
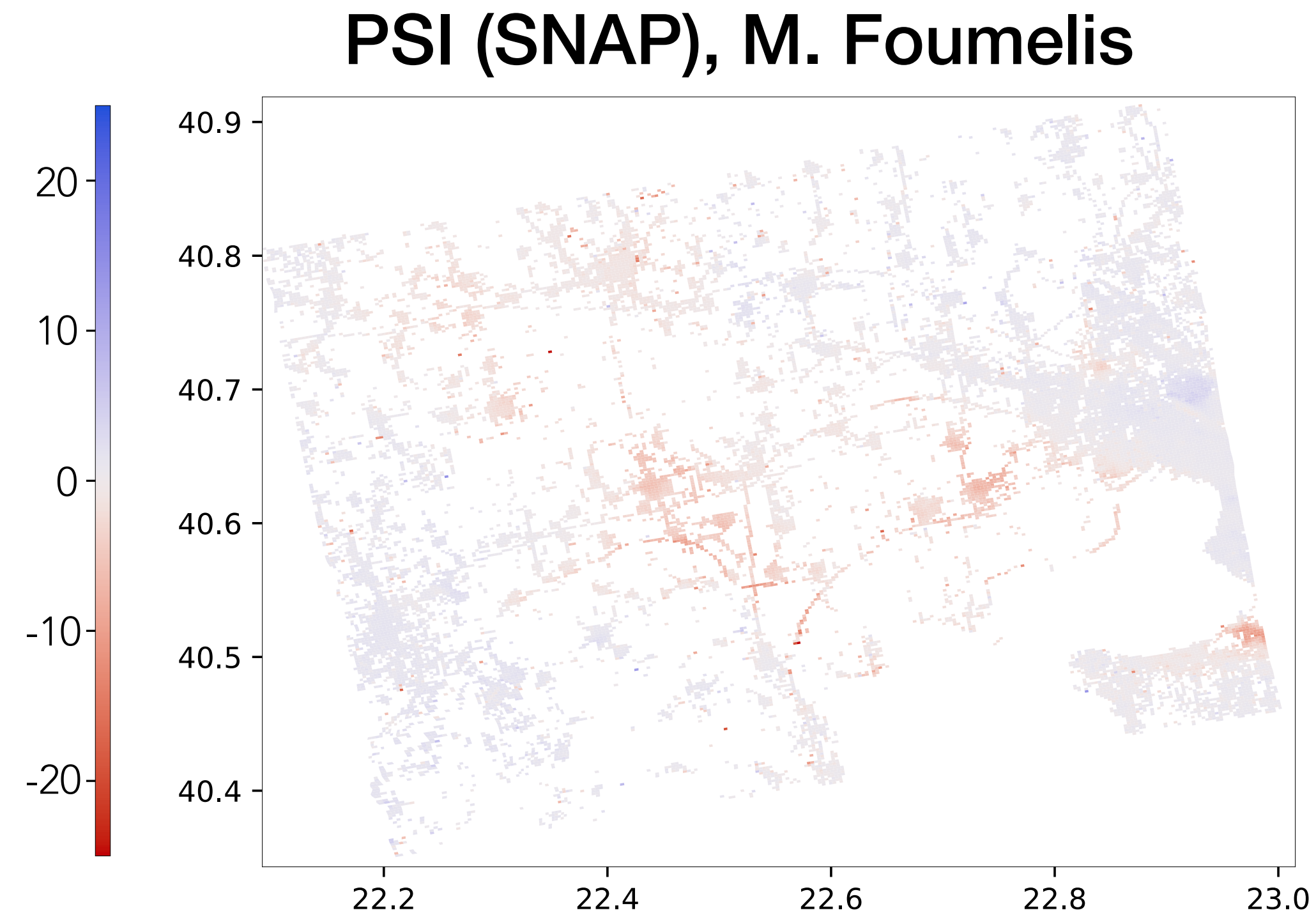
+ 18 and 24

+ 1, 2, 3, 6 months and 1 year

Bias has a crop-specific component and may remain after minimizing

# Estimating the residual bias

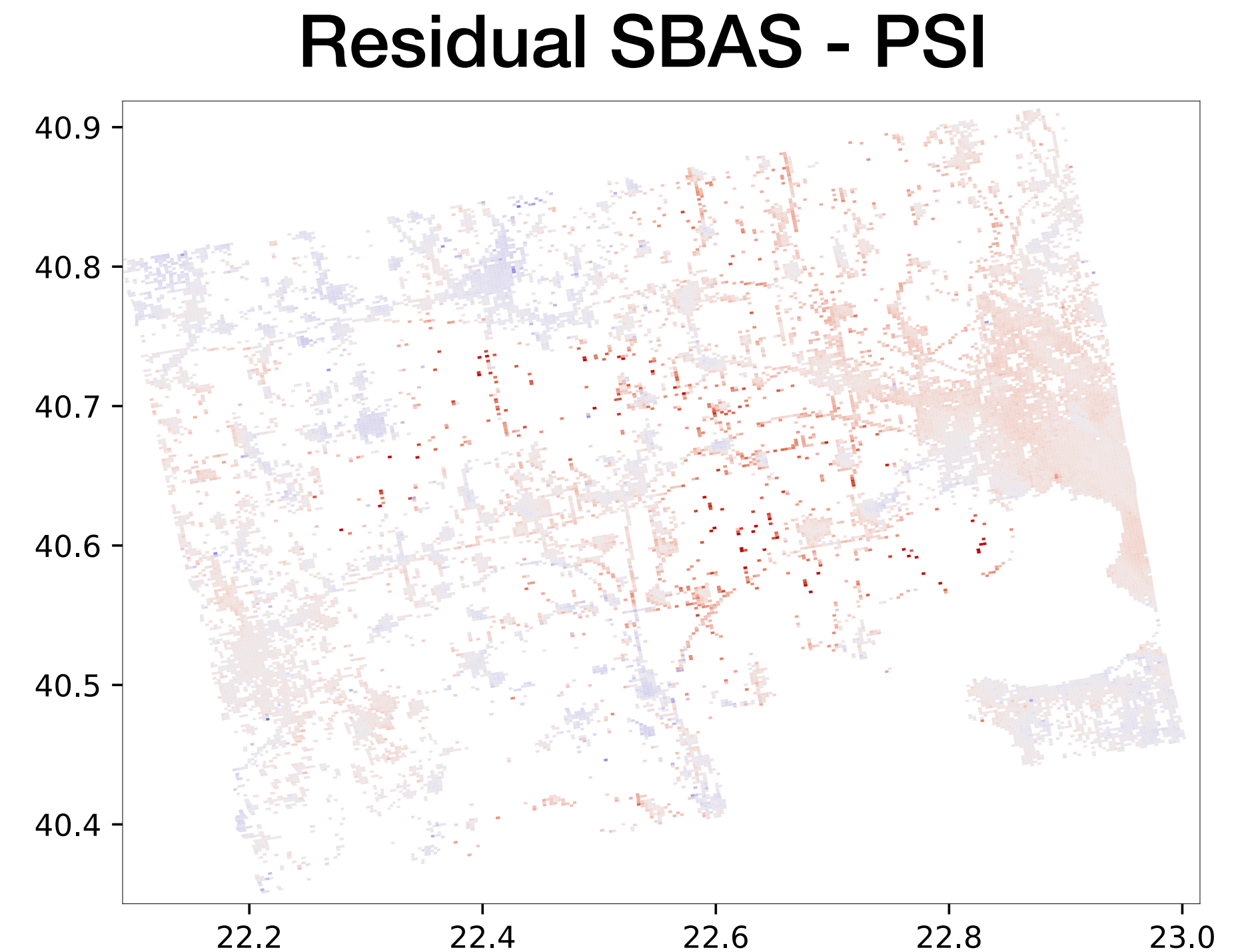
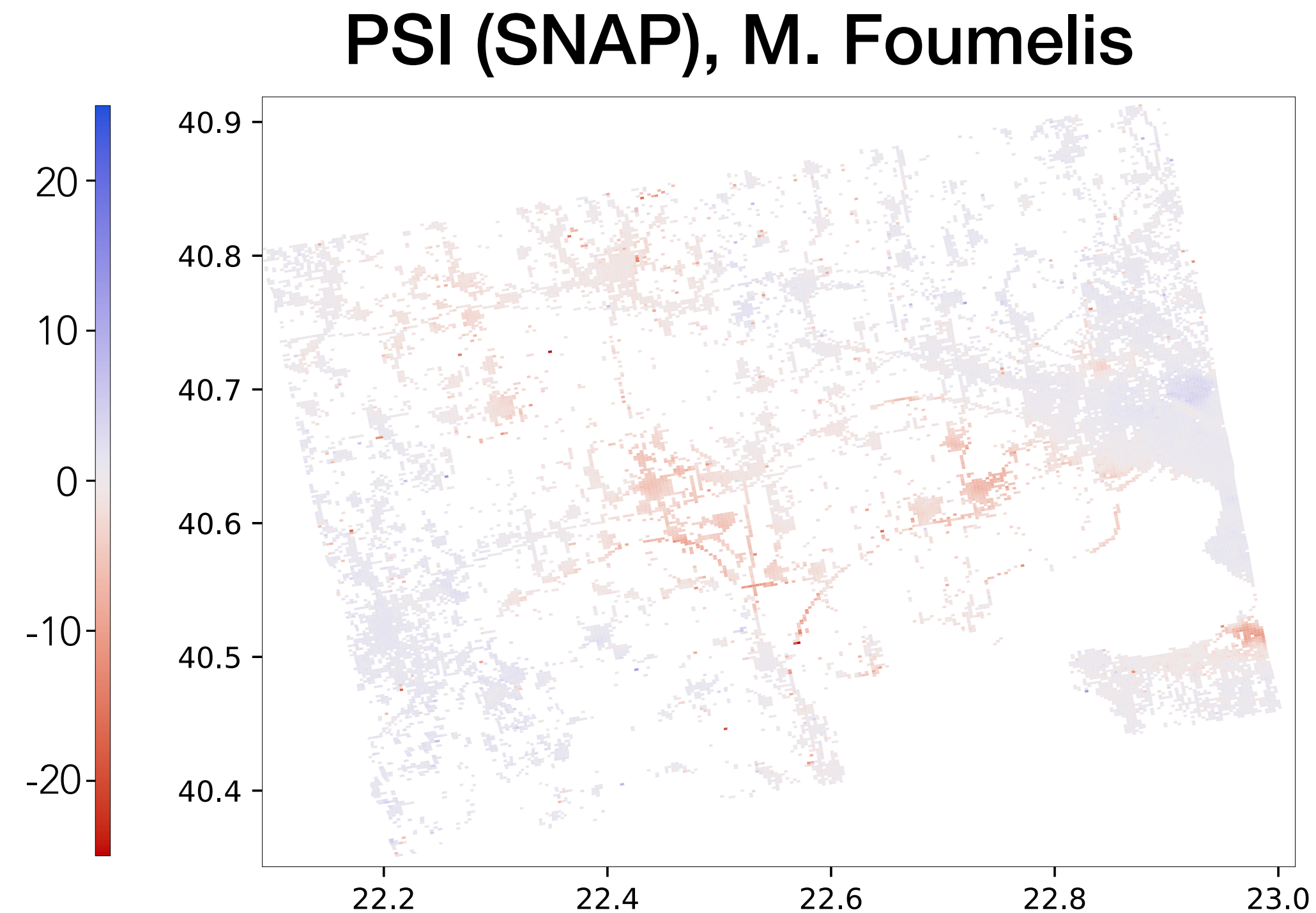
## Comparison to more stable time series





# Estimating the residual bias

## Comparison to more stable time series

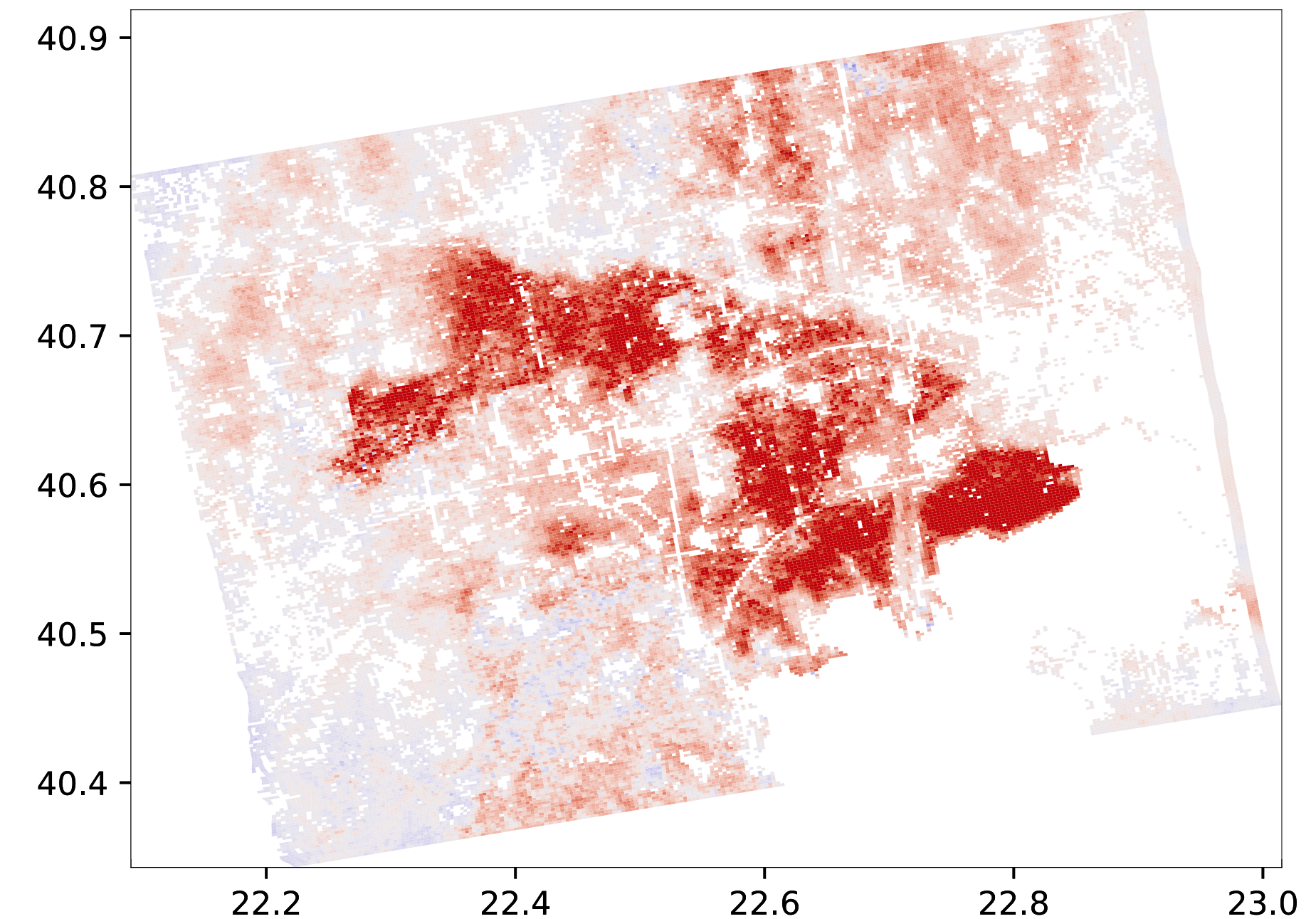
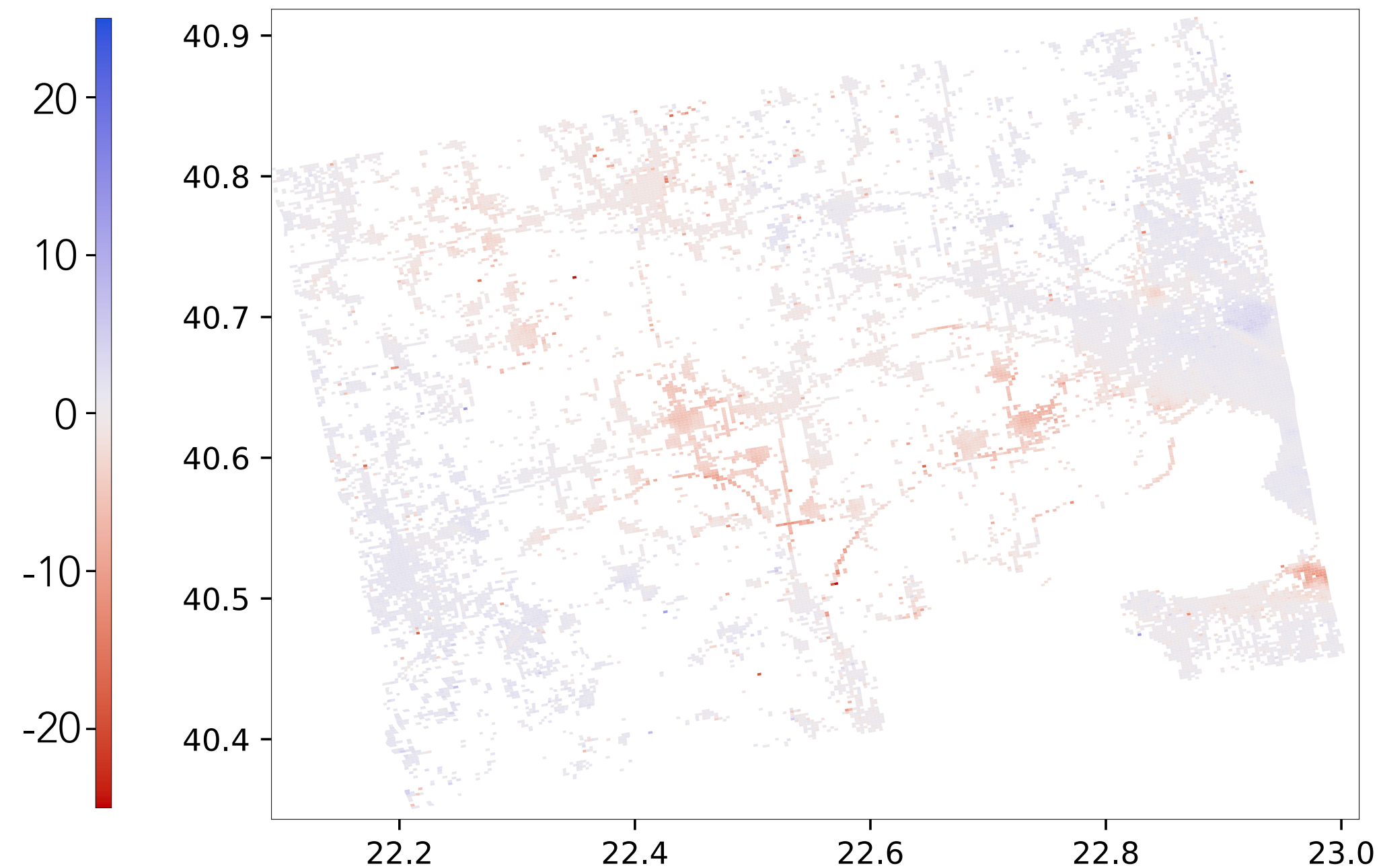


- ▶ Subsidence in PSI-derived deformation.
- ▶ SBAS estimate higher values.

# Estimating the residual bias

## Comparison to more stable time series

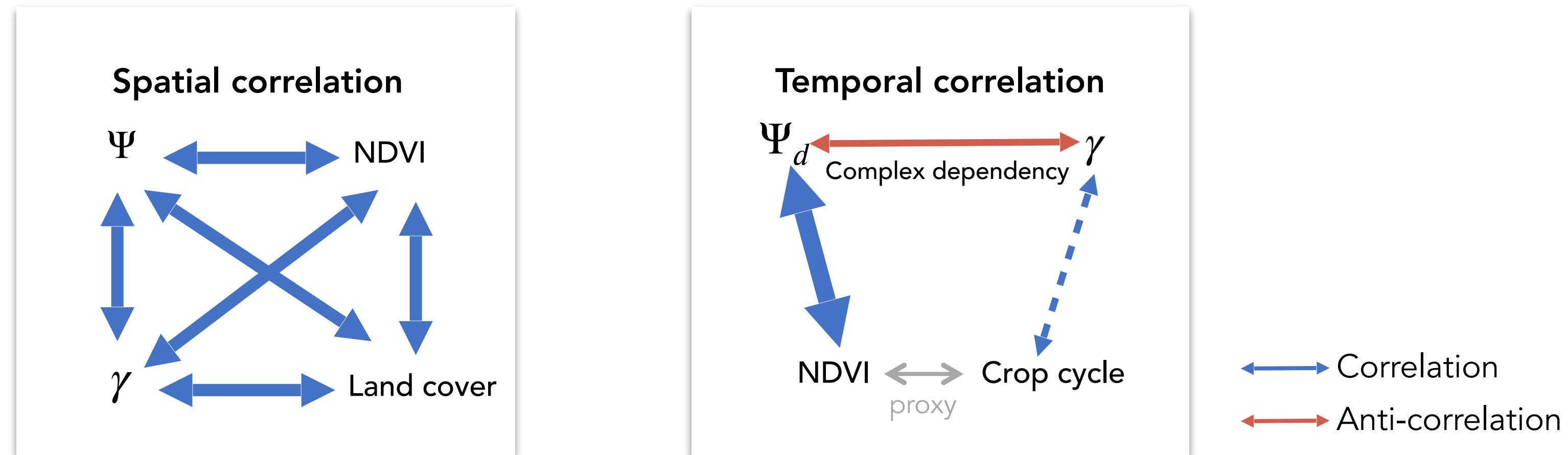
PSI (SNAP), M. Foumelis



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# Conclusions



Positive trend and seasonal accelerations in cumulative closure phase on crops in agreement with the local crop growth cycle.

➡ Closure phase = quantity that gives information about plant growth, beyond coherence only.

The cumulative error may translate as a **velocity bias with a seasonal component** in deformation time series.

The physical meaning behind the closure phase could help extending the coverage of InSAR-derived information to agricultural areas. Work in progress...

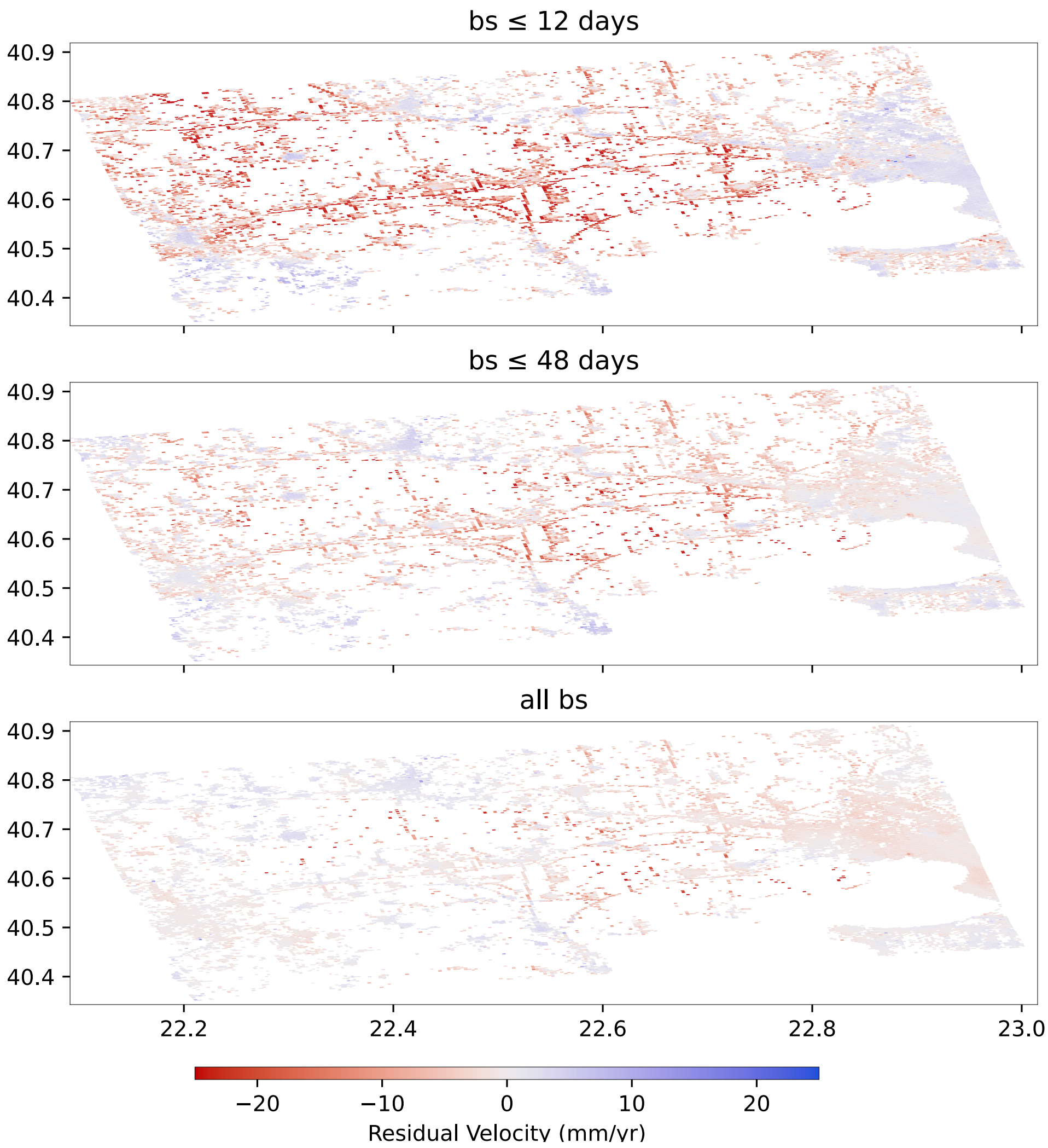
**Thank you !**



We received funding from the INSU PNTS with the project OptInSAR (AAP 2024). Numerical computations were performed on CPUs on the S-CAPAD/DANTE platform, IPGP, France.

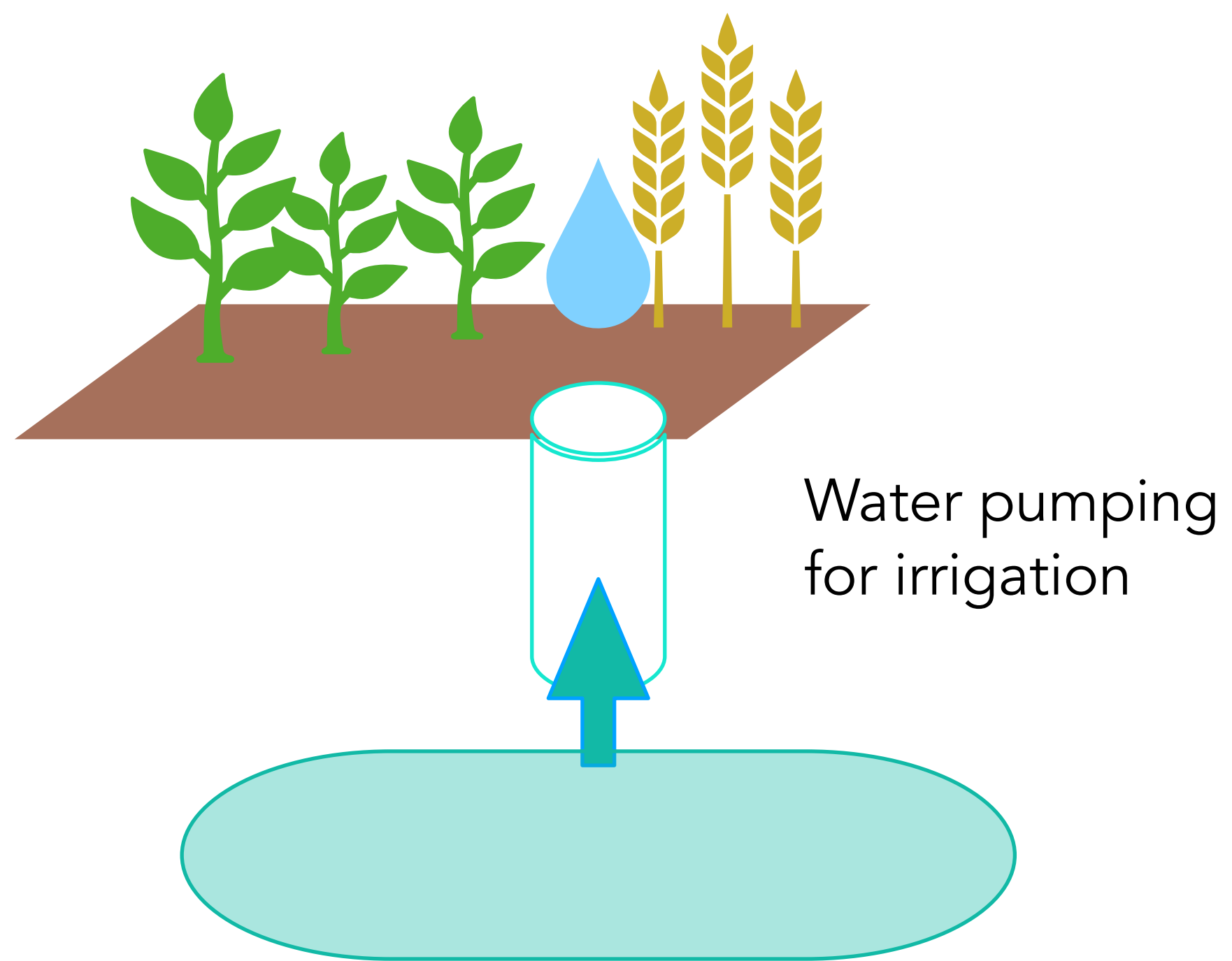
- P. A. Rosen, E. Gurrola, G. F. Sacco and H. Zebker, 'The InSAR scientific computing environment,' \textit{EUSAR 2012}, pp. 730-733, 2012
- Corine Land Cover 2018. European Union's Copernicus Land Monitoring Service information, Available online: <https://land.copernicus.eu/en/products/corine-land-cover/clc2018-> (accessed on 12/06/2025)
- P. Psimoulis, M. Ghilardi, E. Fouache and S. Stiros, 'Subsidence and evolution of the Thessaloniki Plain, Greece, based on historical leveling and GPS data,' *Engineering Geology*, vol. 9, pp.55-70, 2007
- F. De Zan, M. Zonno, and P. Lopez-Dekker, "Phase inconsistencies and multiple scattering in SAR interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 12, pp. 6608–6616, 2015
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- H. Ansari, F. De Zan, and A. Parizzi, 'Study of systematic bias in measuring surface deformation with SAR interferometry,' *IEEE Trans. Geosci. Remote Sens.*, vol. 59, no. 2, pp. 1285–1301, 2021.
- F. De Zan, F. Rocca, A. Ferretti, P. Lopez-Dekker and M. Eineder, 'Comments on "Influence of the Statistical Properties of Phase and Intensity on Closure Phase"', *IEEE Trans. Geosci. Remote Sensing*, vol. 59, no. 7, pp. 6277-6278, 2021
- A. Maghsoudi, J. Hooper, T. J. Wright, M. Lazecky, and H. Ansari, 'Characterizing and correcting phase biases in short-term, multilooked interferograms,' *RSE*, vol. 275, 113022, 2022
- A. Villarroya-Carpio, J. Lopez-Sanchez and M. Engdahl, 'Sentinel-1 interferometric coherence as a vegetation index for agriculture,' *RSE*, vol. 280, 113208, 2022
- F. De Zan, P. Saporta and G. Gomba, "Spatiotemporal Analysis of C-band interferometric Phase Anomalies over Sicily," *EUSAR 2022; 14th European Conference on Synthetic Aperture Radar*, Leipzig, Germany, pp. 1-4, 2022.
- M. Dalaison, B. Pinel-Puysségur, R. Jolivet, B. Rimbault, and L. Drique 'Relationship between closure phase error and interferometric coherence in multilooked InSAR' *AGU Fall Meeting*, G34A-08, 2024
- Y. Yuan, M. Kleinherenbrink, and P. López-Dekker, 'On Crop Growth and InSAR Closure Phases', *IEEE Trans. Geosci. Remote Sensing*, vol. 62, pp. 1–12, 2024
- N. C. Mira, J. Catalão, and G. Nico, 'On the Mitigation of Phase Bias in SAR Interferometry Applications: A New Model Based on NDWI,' *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, vol. 17, pp. 3850-3859, 2024
- E. Wig, R. Michaelides, and H. Zebker, 'Fine-resolution measurement of soil moisture from cumulative {InSAR} closure phase' *IEEE Trans. Geosci. Remote Sensing*, vol. 62, pp. 1-15, 2024.

Residual Velocity maps (PSI - raw)

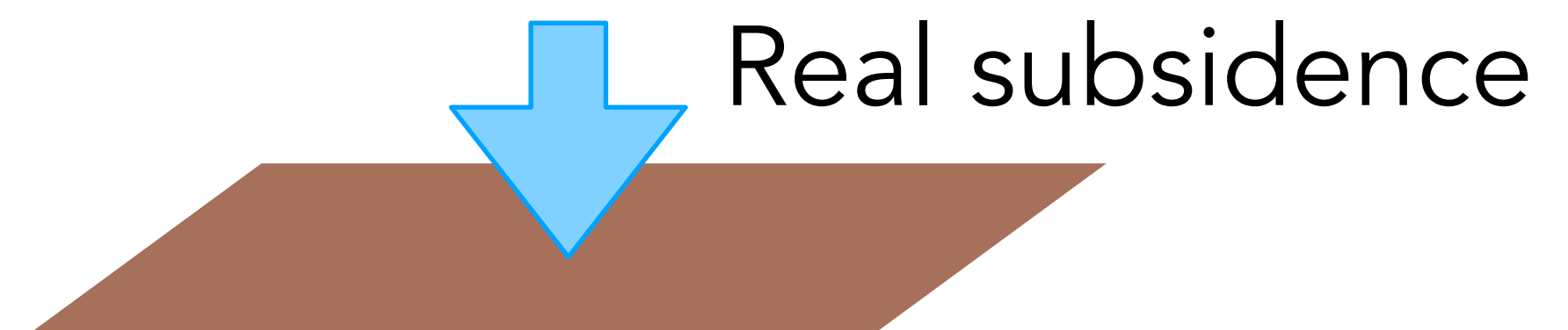
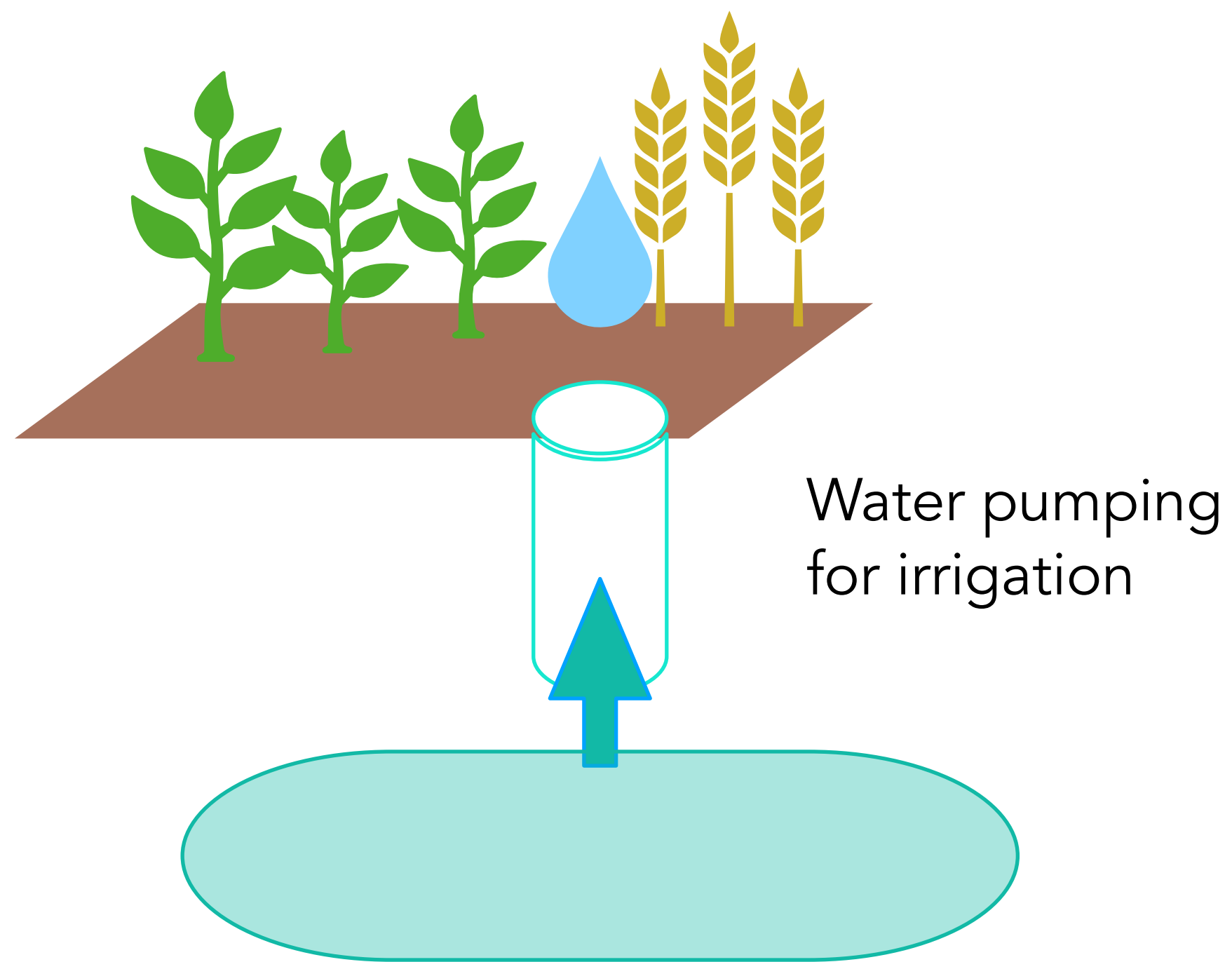


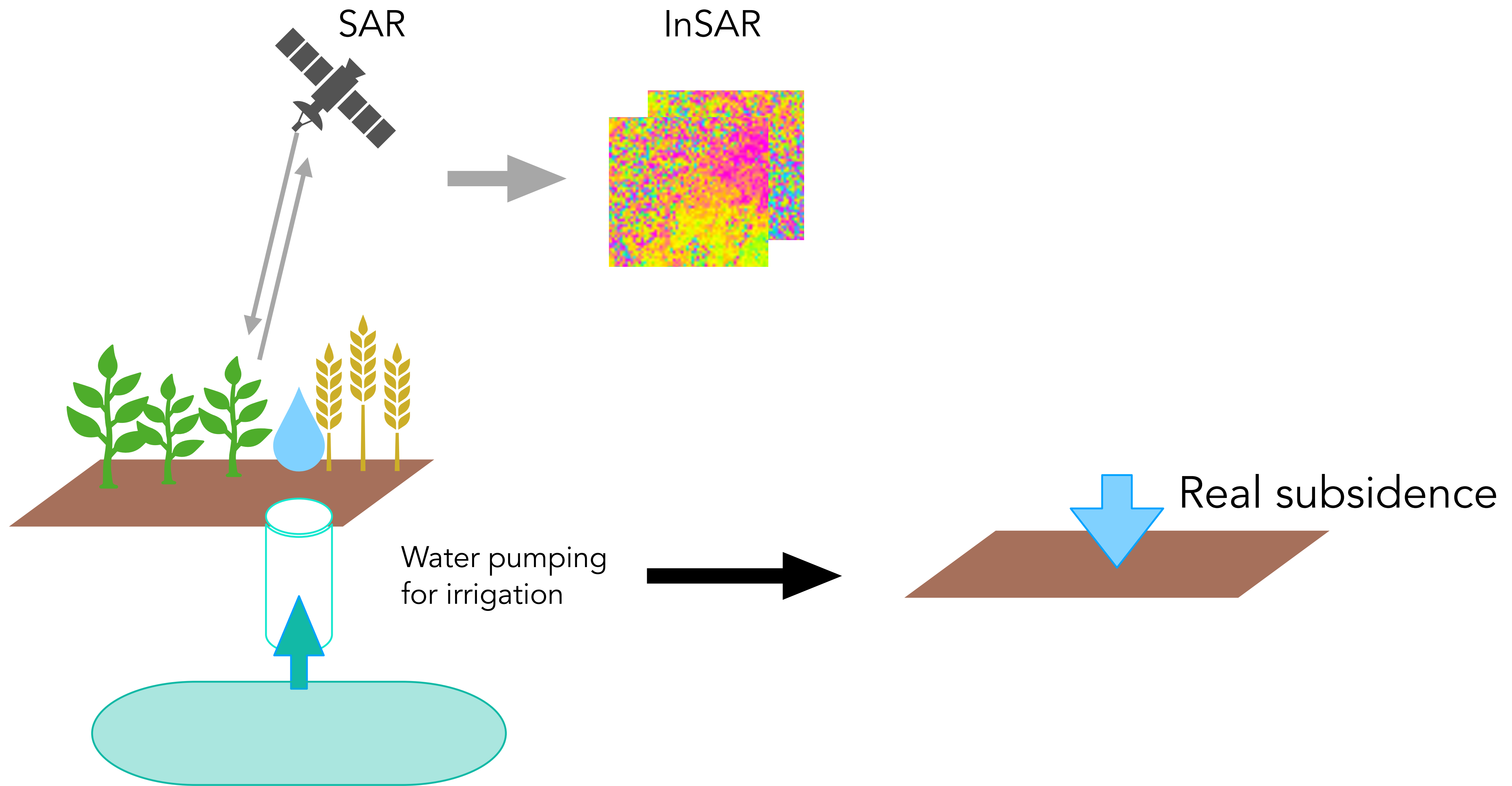




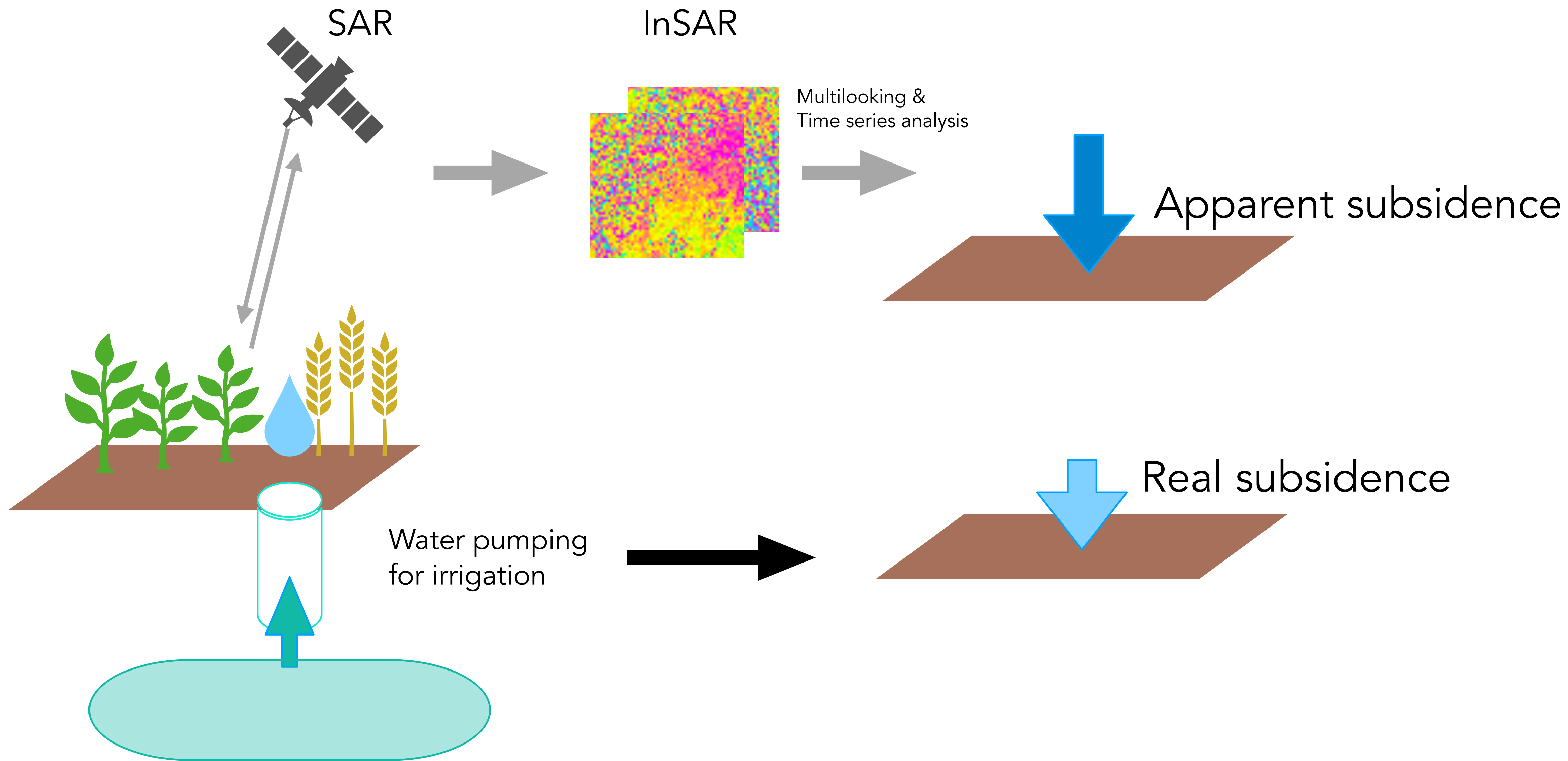


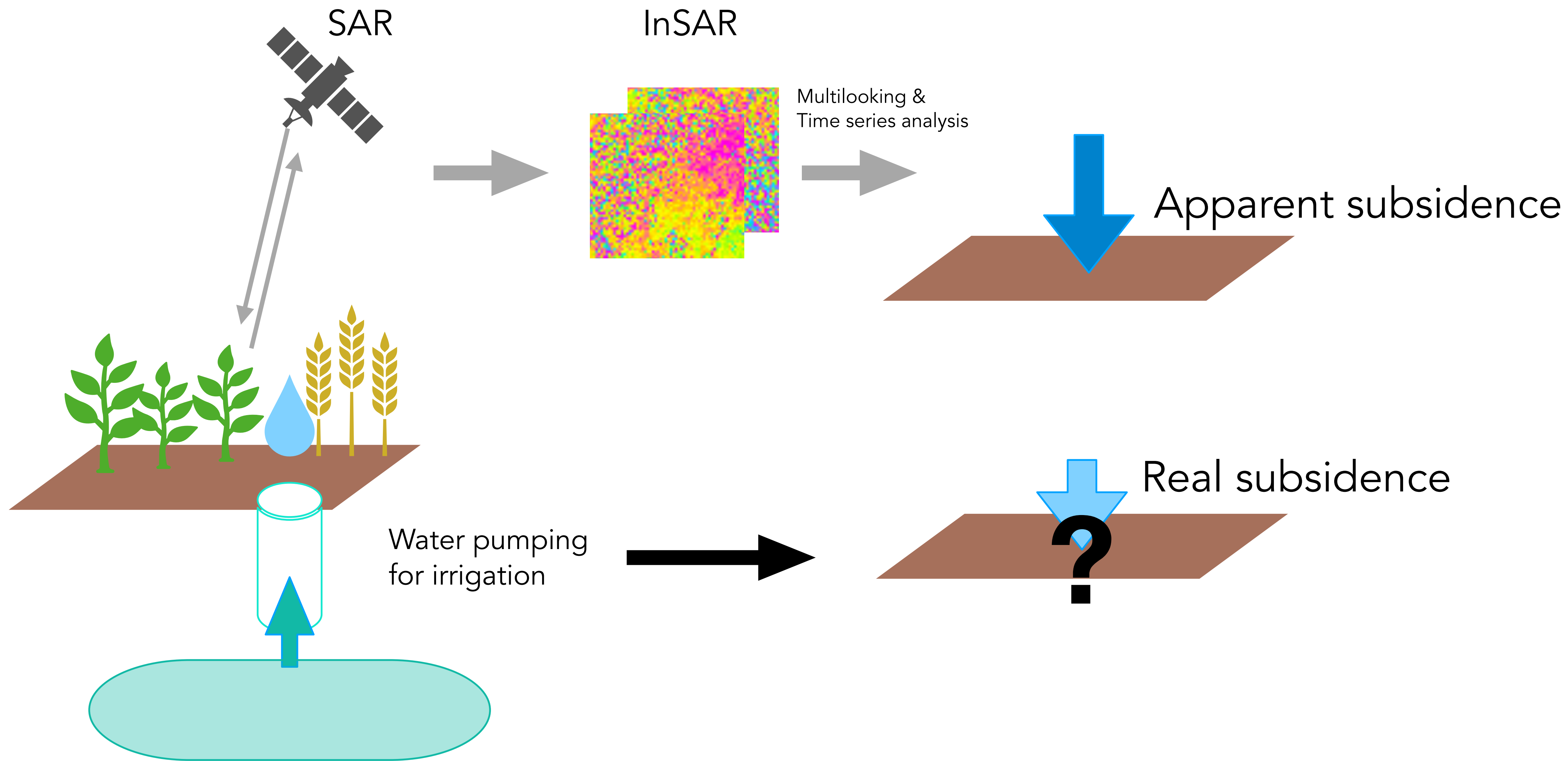




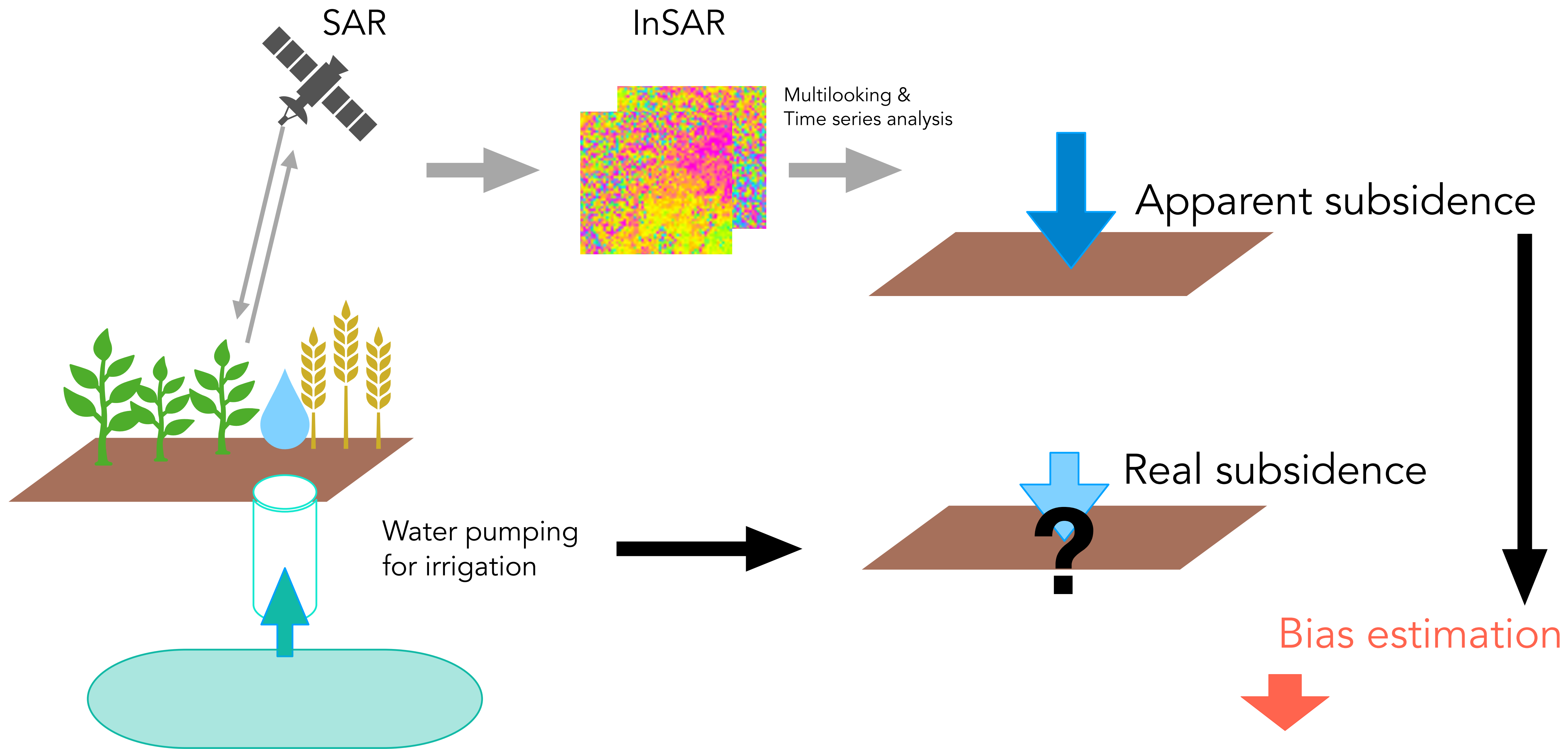


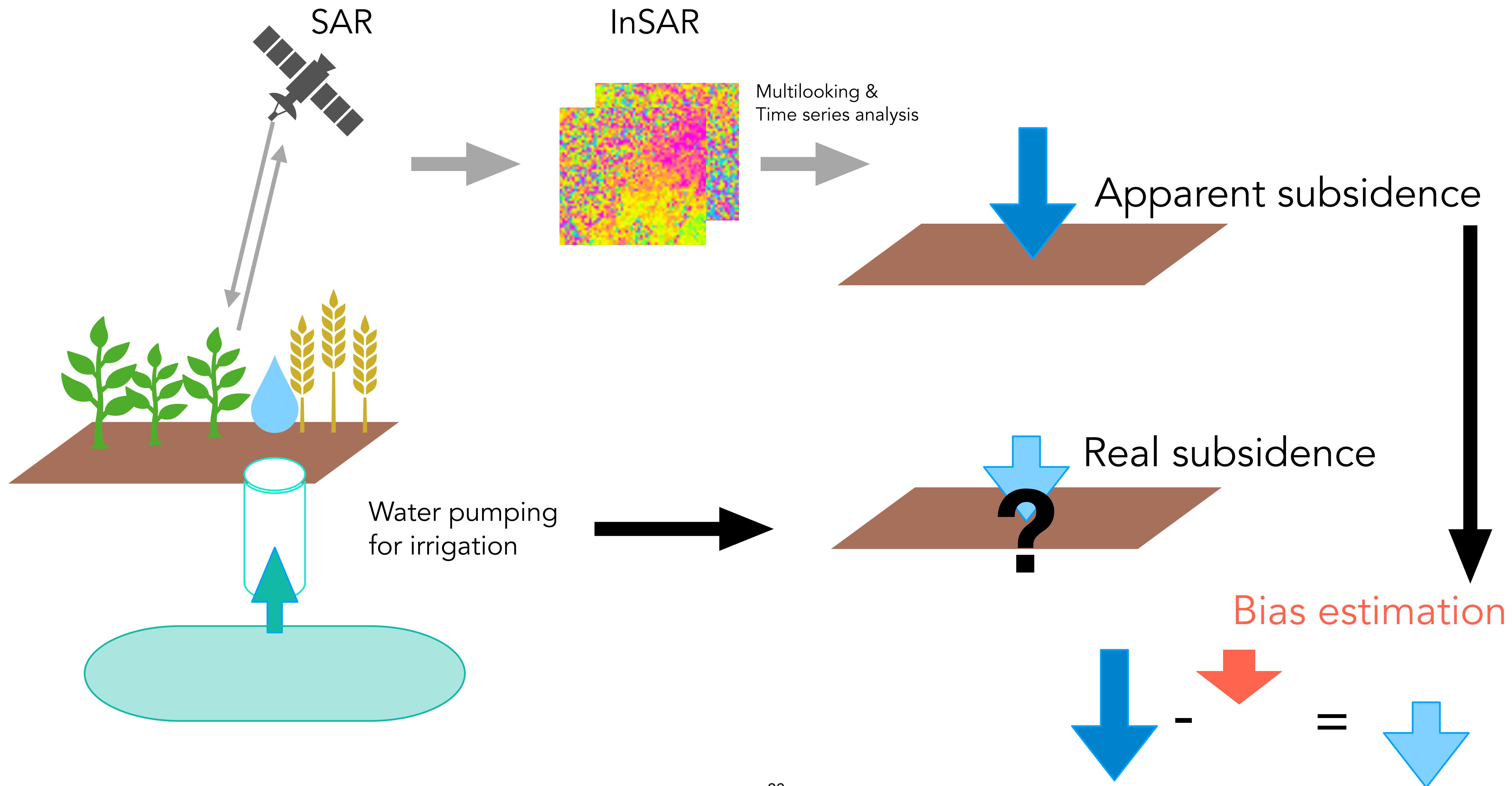














# Crop types in the Thessaloniki region, gathered from existing statistics

Table 2. Crop plan of the region of Central Macedonia for 2018 [49].

| Crop           | Irrigated (I)<br>Non Irrigated (N) | Area<br>(ha) | Percentage<br>% |
|----------------|------------------------------------|--------------|-----------------|
| Rice           | I                                  | 24,279       | 5.45            |
| Hard Wheat     | N                                  | 101,718      | 22.83           |
| Sunflower      | I                                  | 23,452       | 5.26            |
| Soft Wheat     | N                                  | 45,220       | 10.15           |
| Maize          | I                                  | 29,596       | 6.64            |
| Barley         | N                                  | 31,634       | 7.10            |
| Cotton         | I                                  | 76,330       | 17.13           |
| Alfalfa        | I                                  | 43,963       | 9.87            |
| Set Aside (SA) |                                    | 69,355       | 15.57           |
| Total          |                                    | 445,547      | 100             |

The distribution of each crop in the crop plan of the region of Central Macedonia is presented in Figure 2. This distribution of crops is used as the crop plan of the average farm in the region. This is the base for all the calculations and results for the crop plans in this study, and it is assumed to be 100 ha.

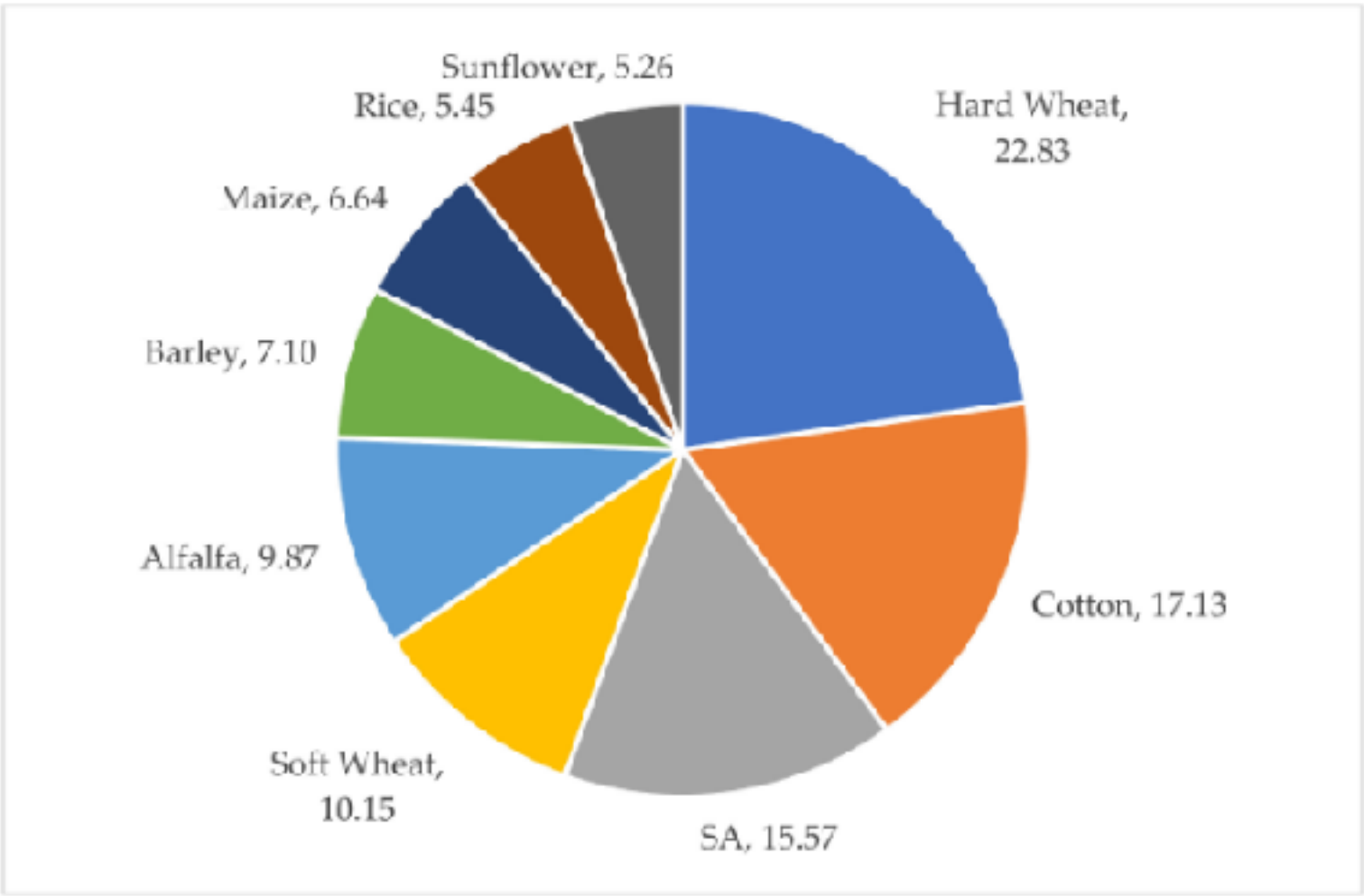
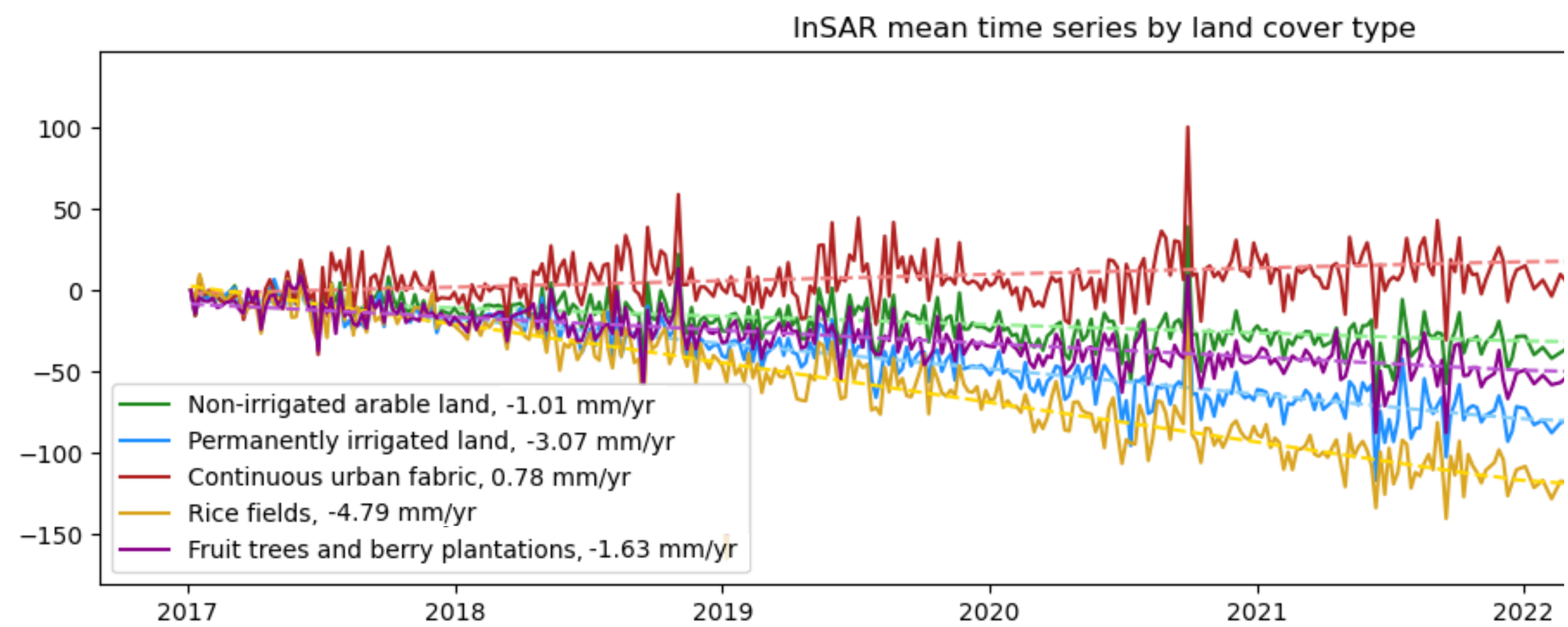
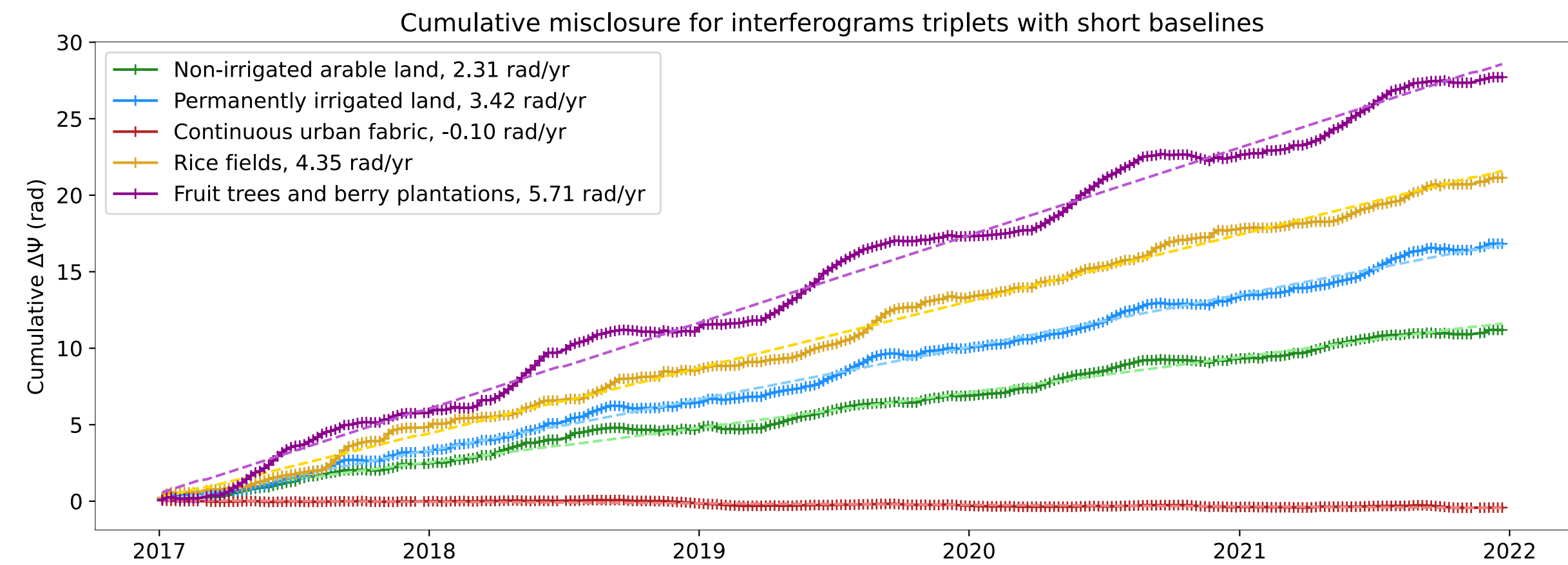


Figure 2. Distribution (%) of the main crops of the region of Central Macedonia (2018) [48].

Georgilas et al (2021) dans *Agronomy*

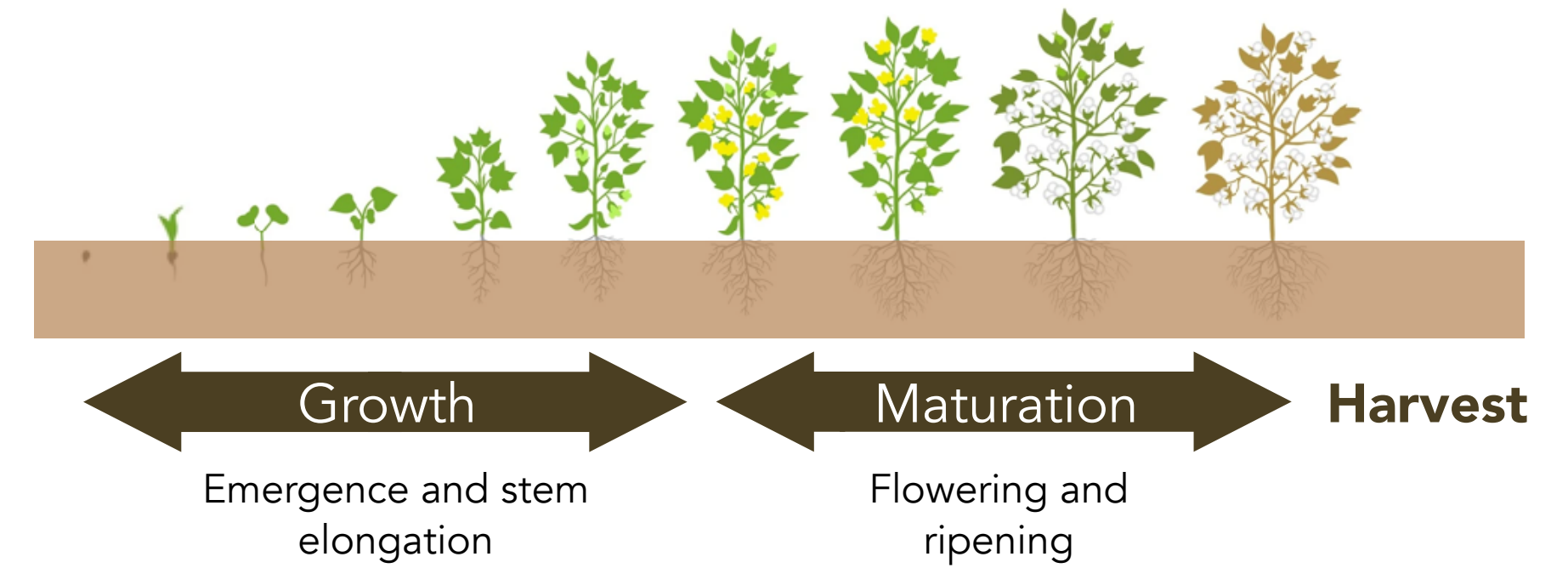
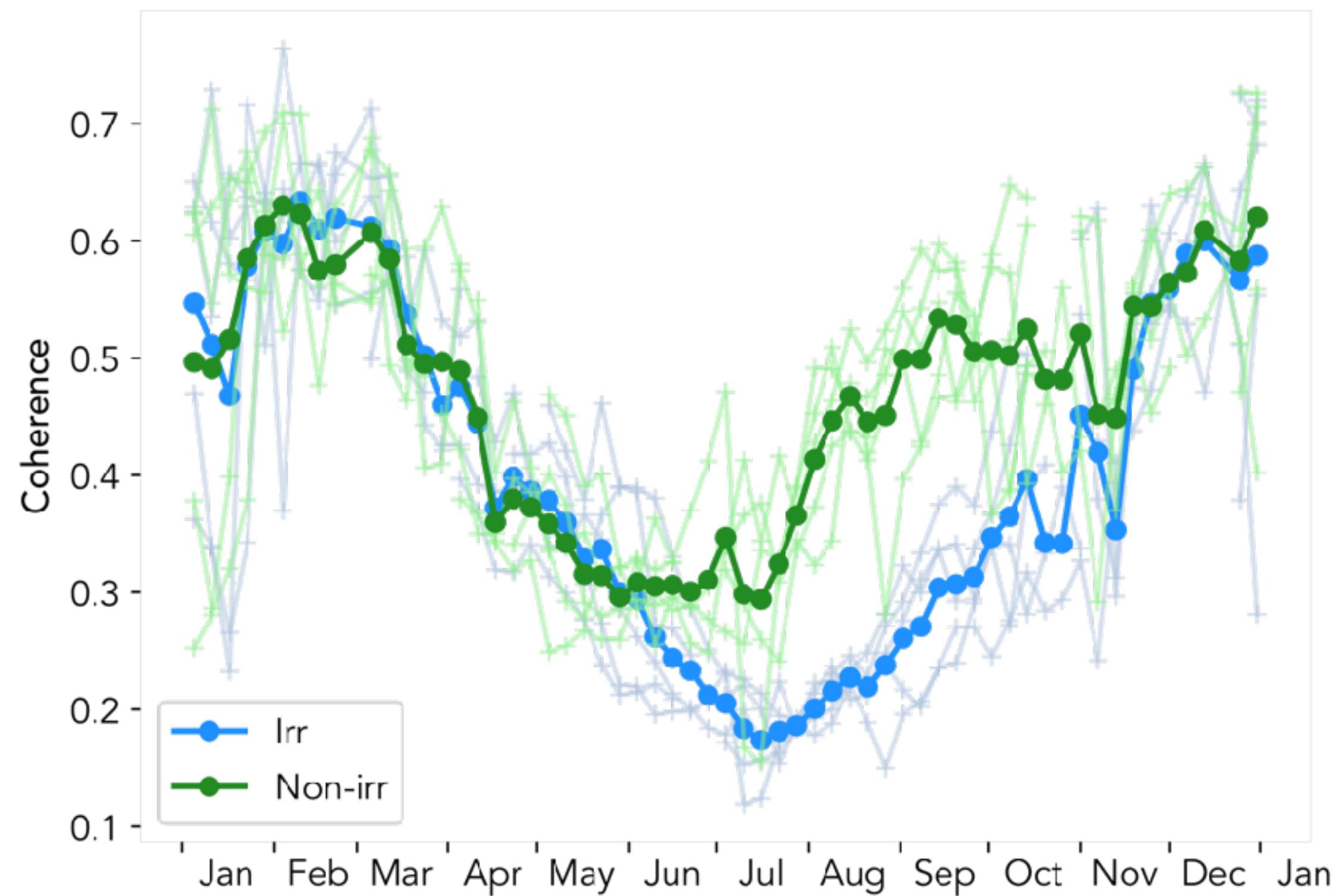
| IRRIGATED                                                                                                                                                                                                  | NOT IRRIGATED                                                                                        |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| <div>1. Cotton (~20%)</div> <div>2. Alfalfa (~10%)</div> <div>3. Corn (~7%)</div> <div>4. Rice/Sunflowers (10% tt)</div> <div>ie cotton &gt;40% off all irrigated (rice is a Corine class in itself)</div> | <div>1. Wheat (~30%)</div> <div>2. Barley (~7%)</div> <div>ie. Wheat ~70% of all not irrigated</div> |





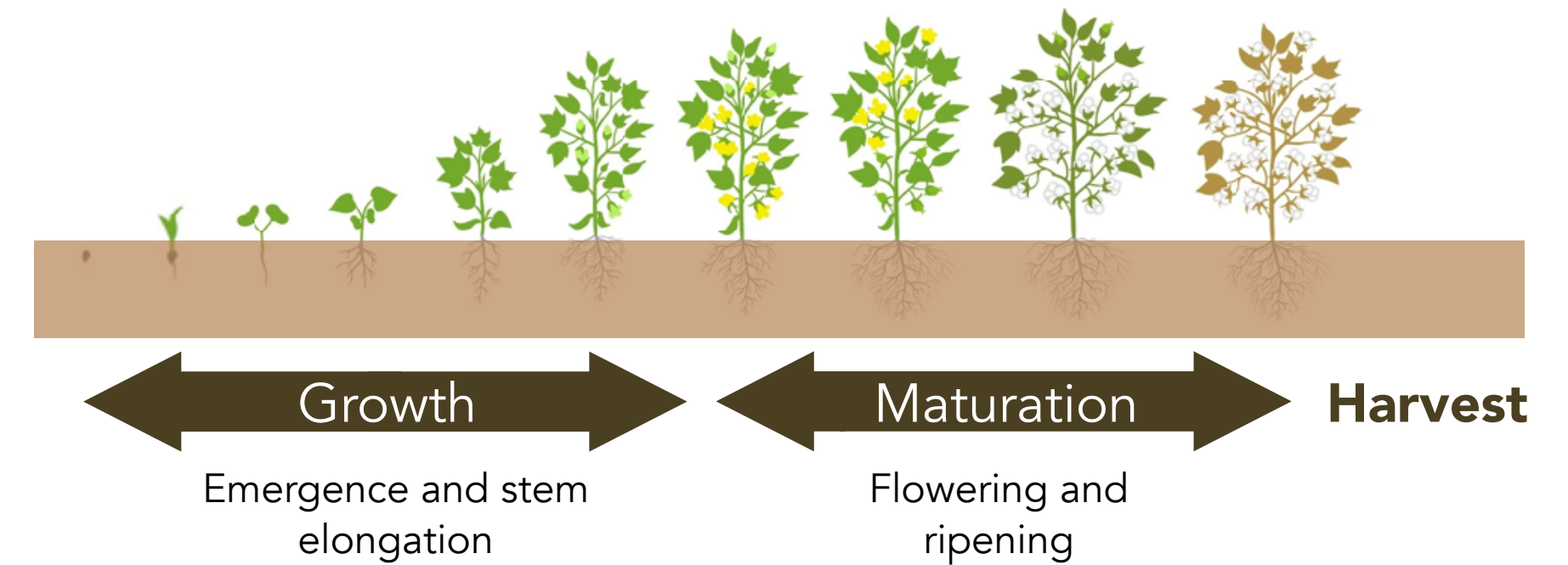
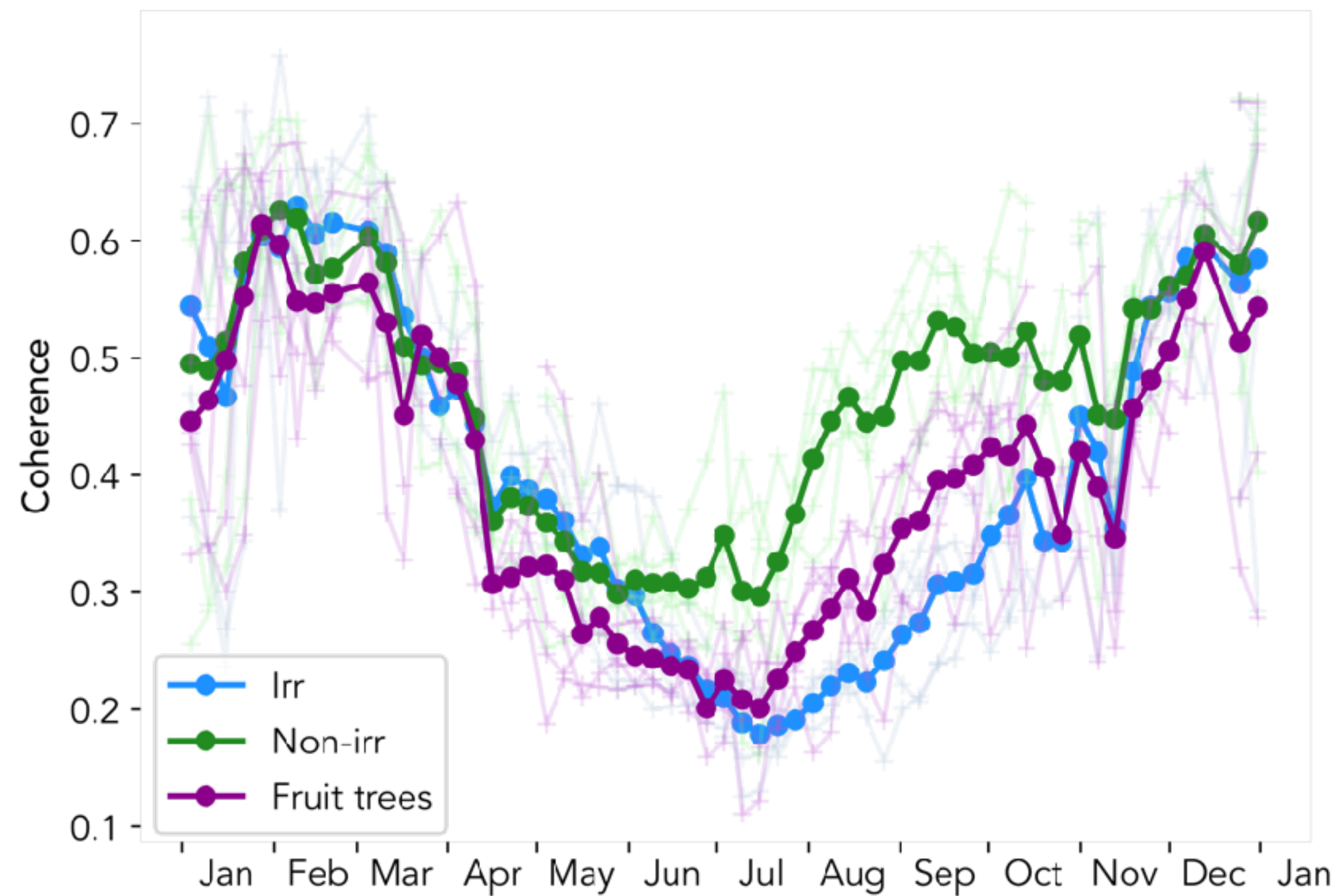
# The annual coherence

## Relation to the crop cycle



# The annual coherence

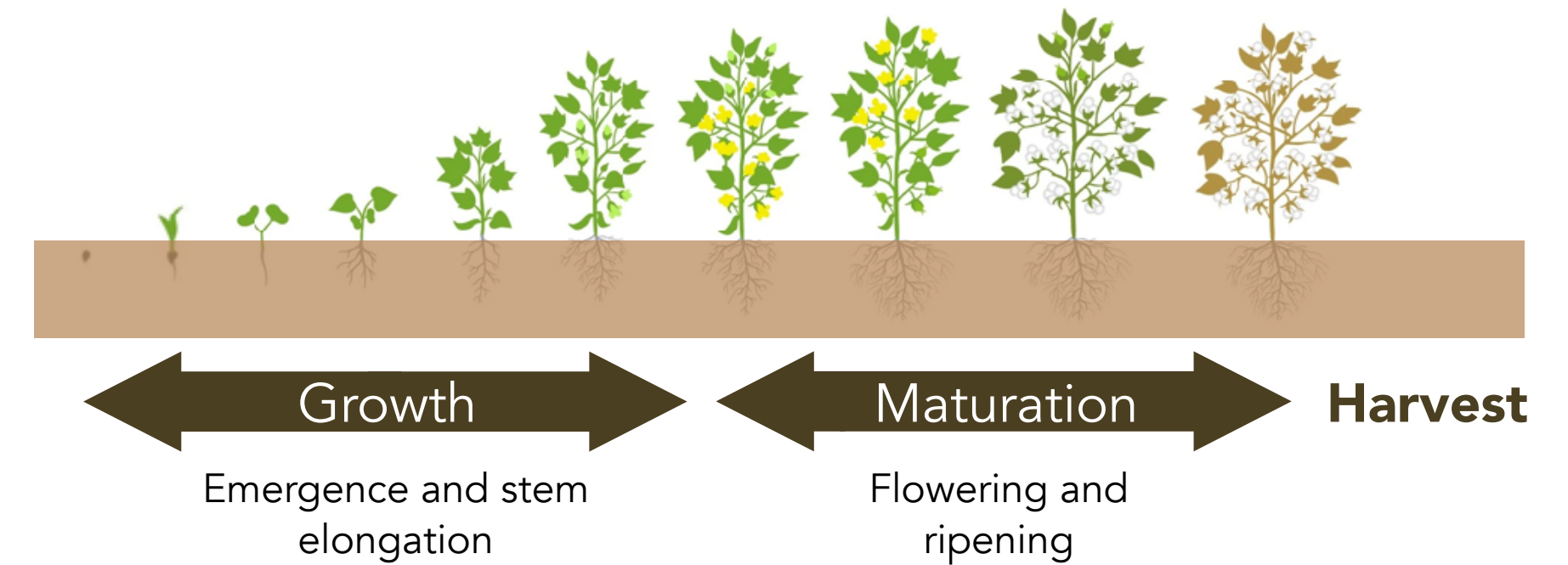
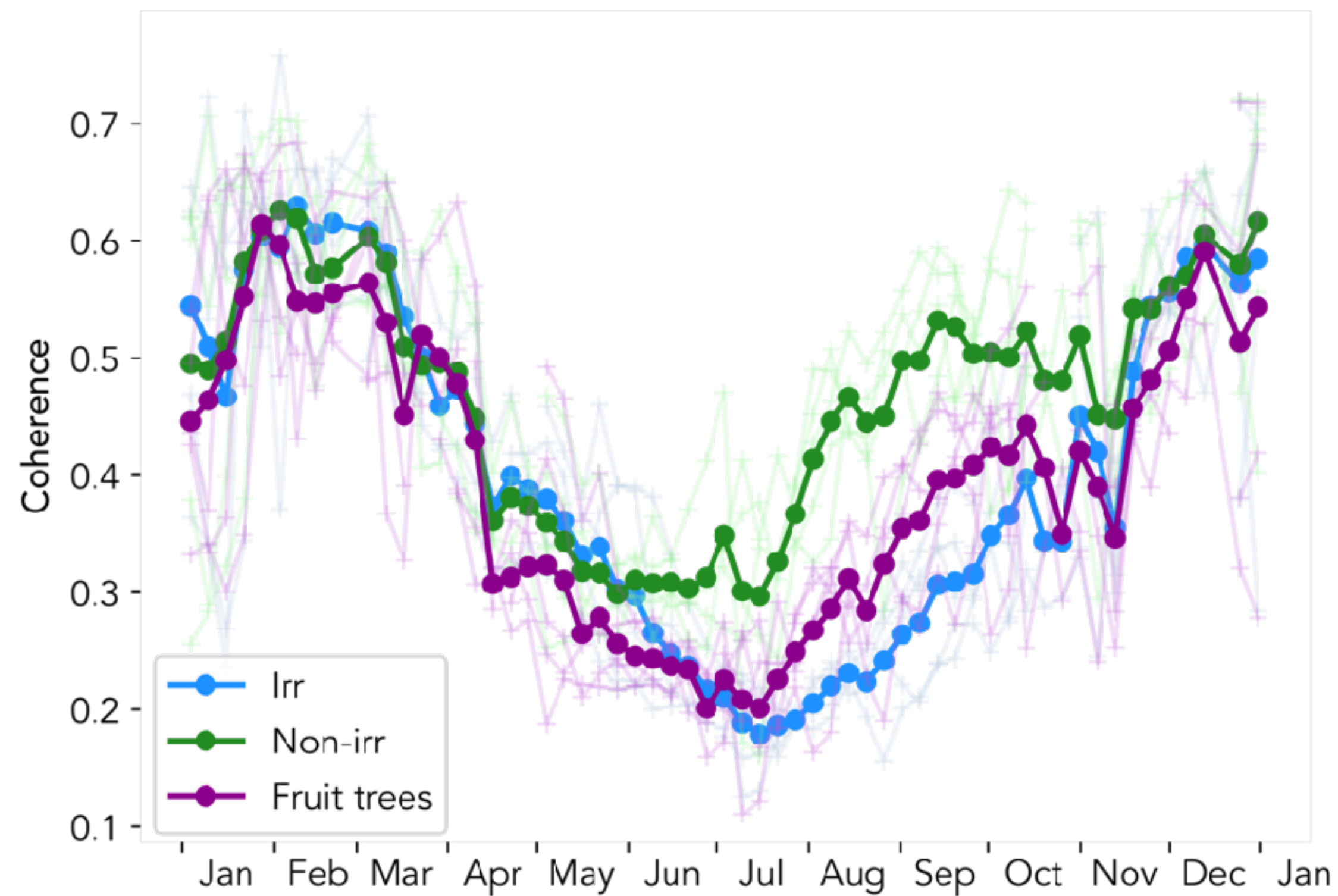
## Relation to the crop cycle



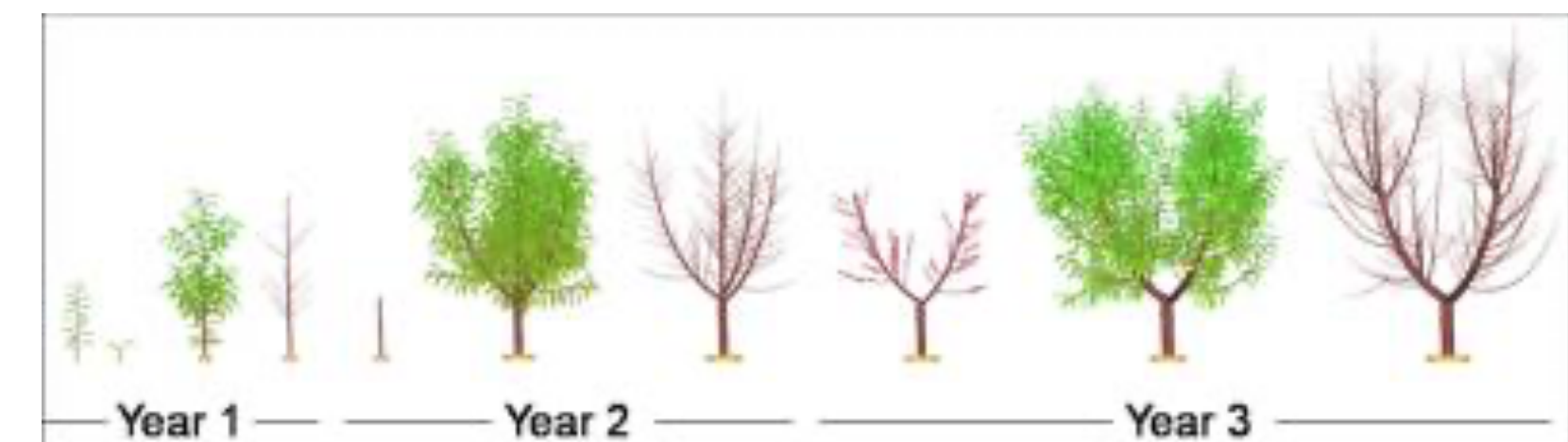


# The annual coherence

## Relation to the crop cycle



Fruit trees =  
complex  
growth cycle

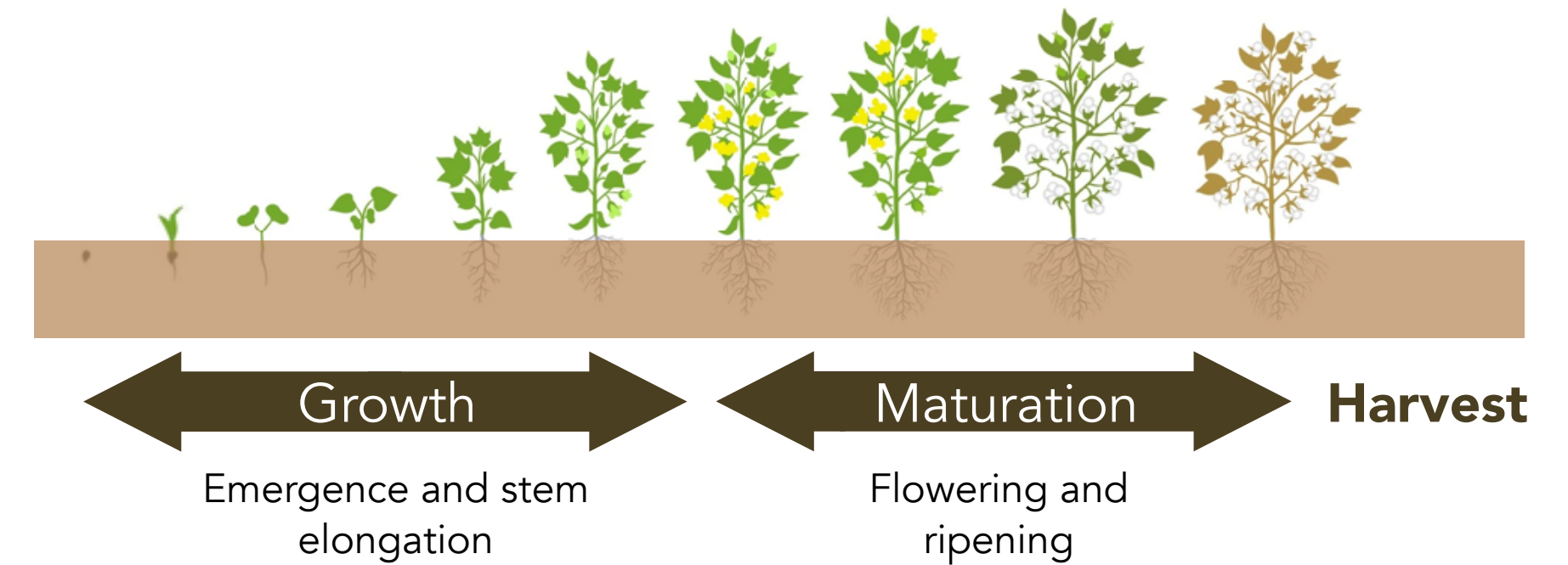
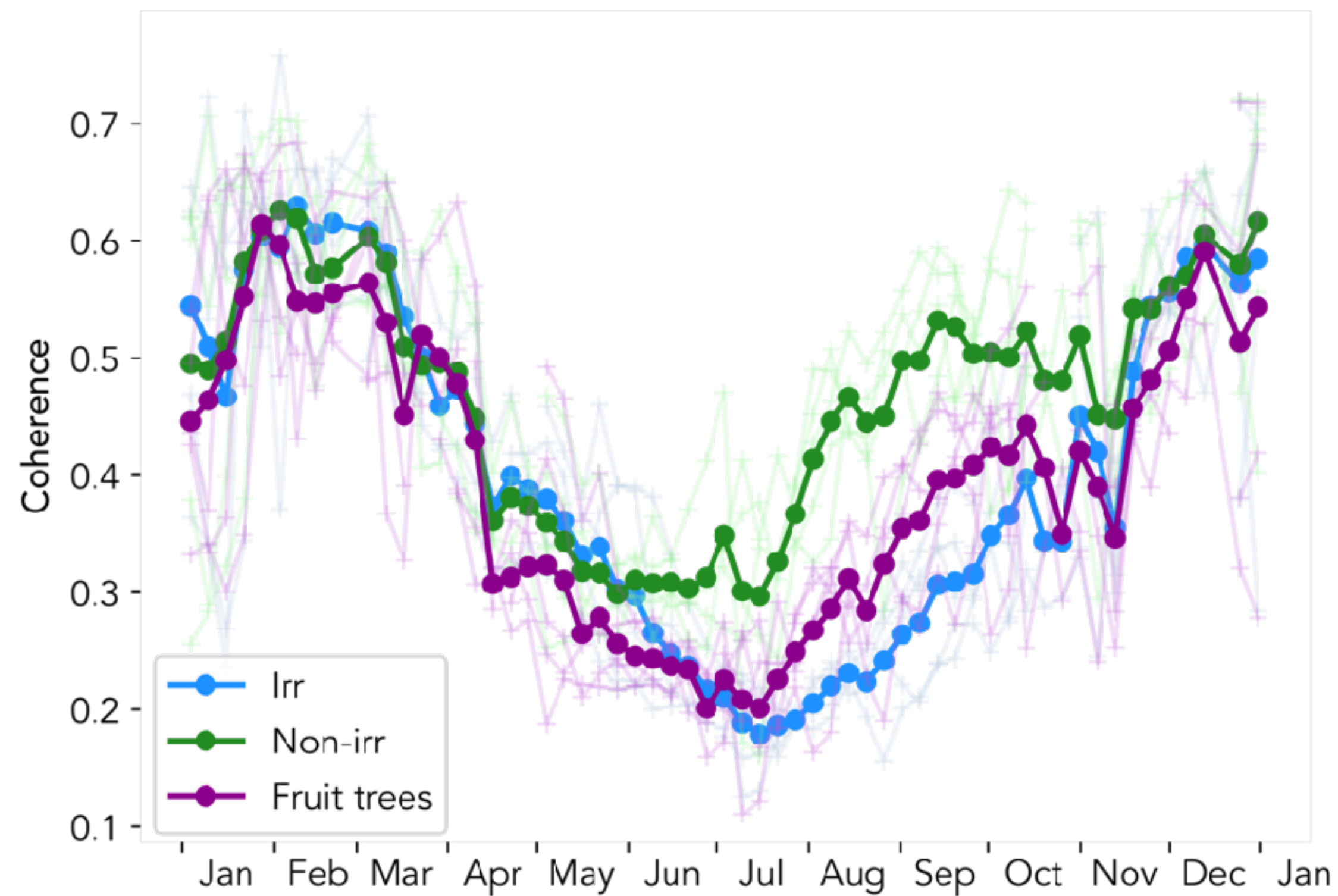


Lopez Velasco et al. 2008

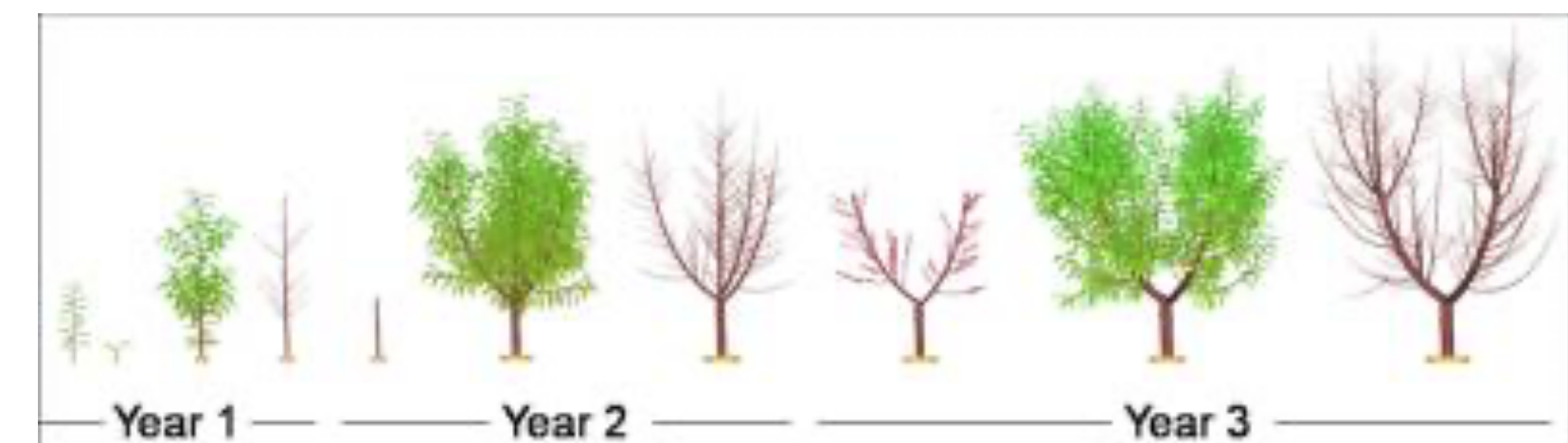


# The annual coherence

## Relation to the crop cycle



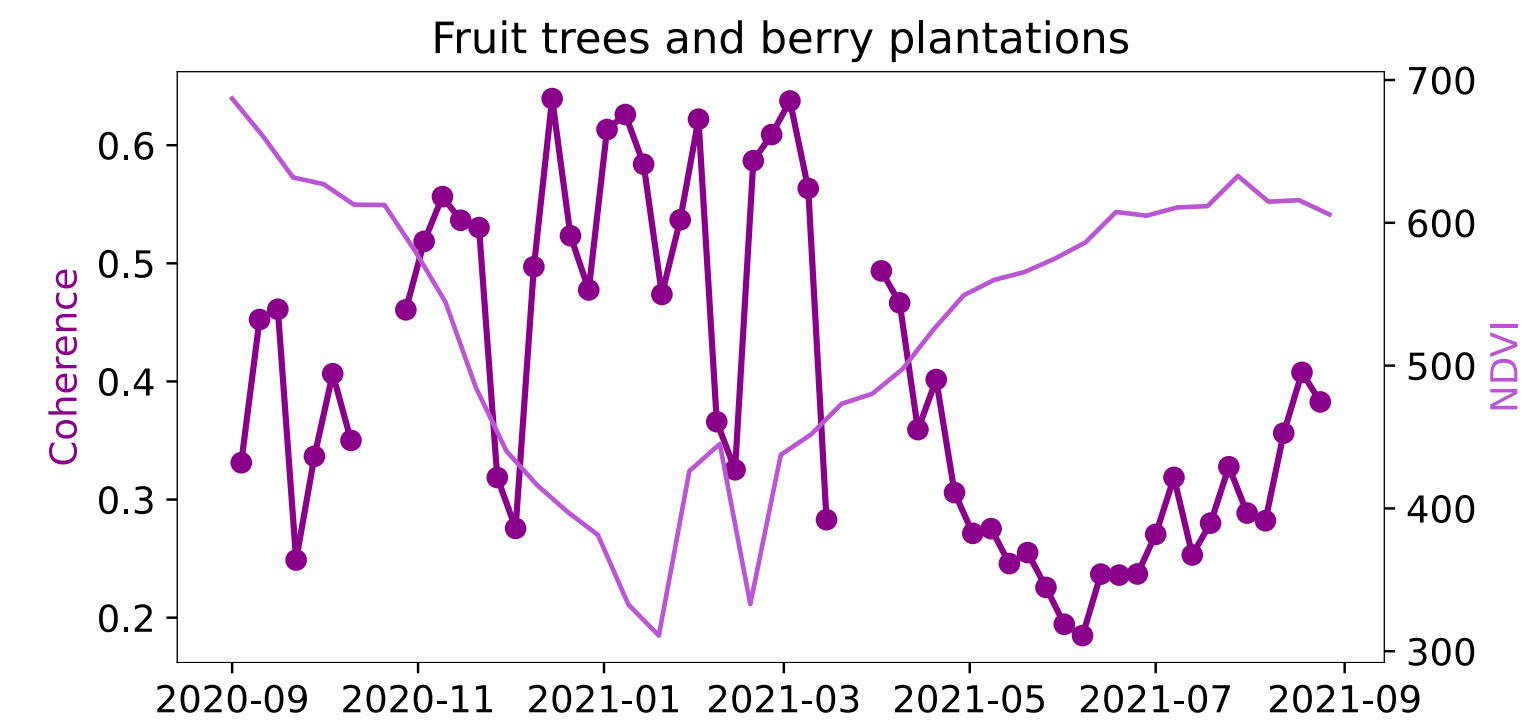
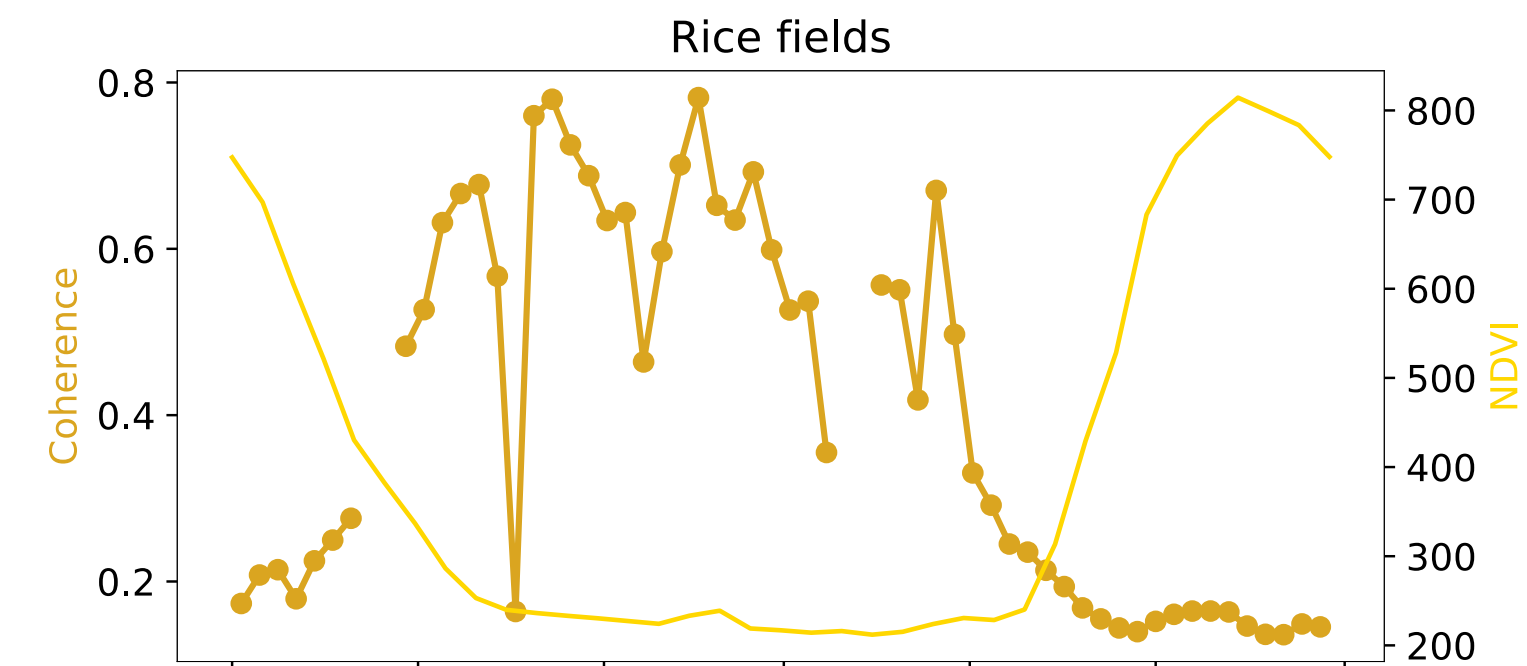
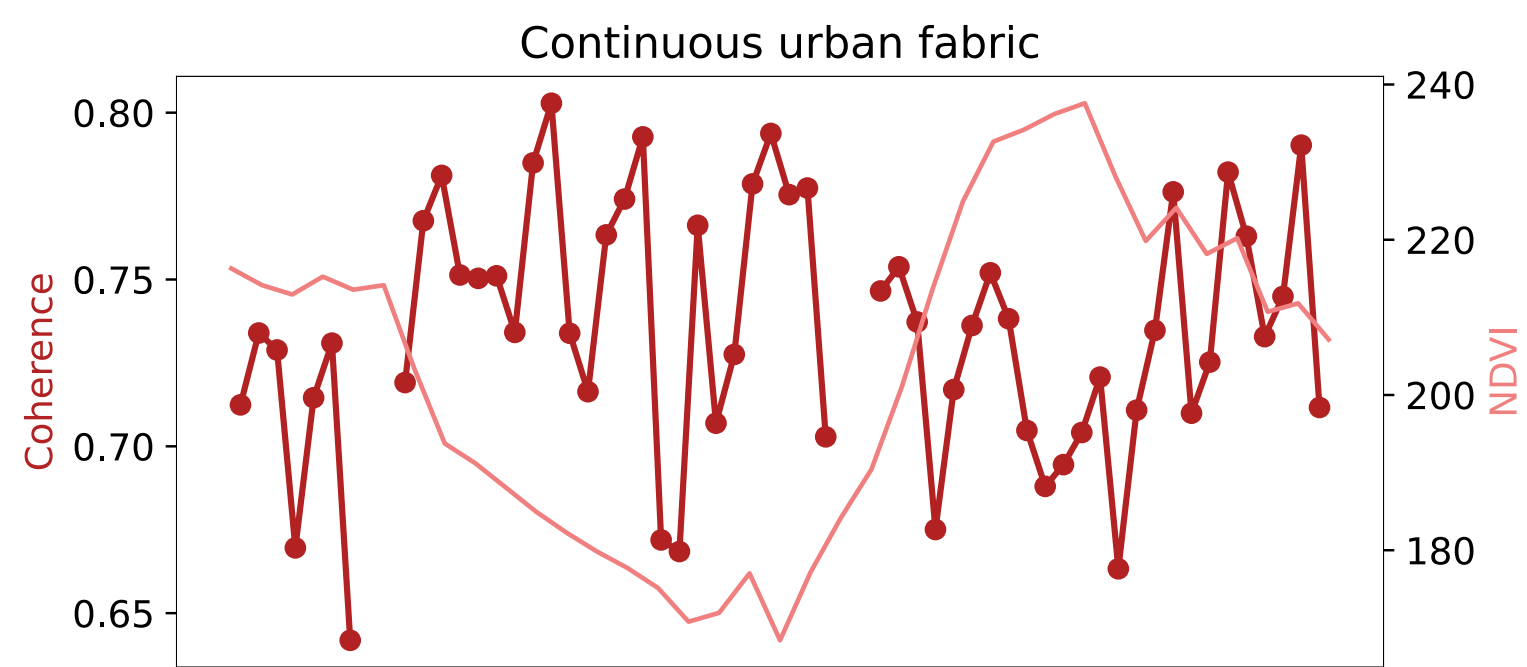
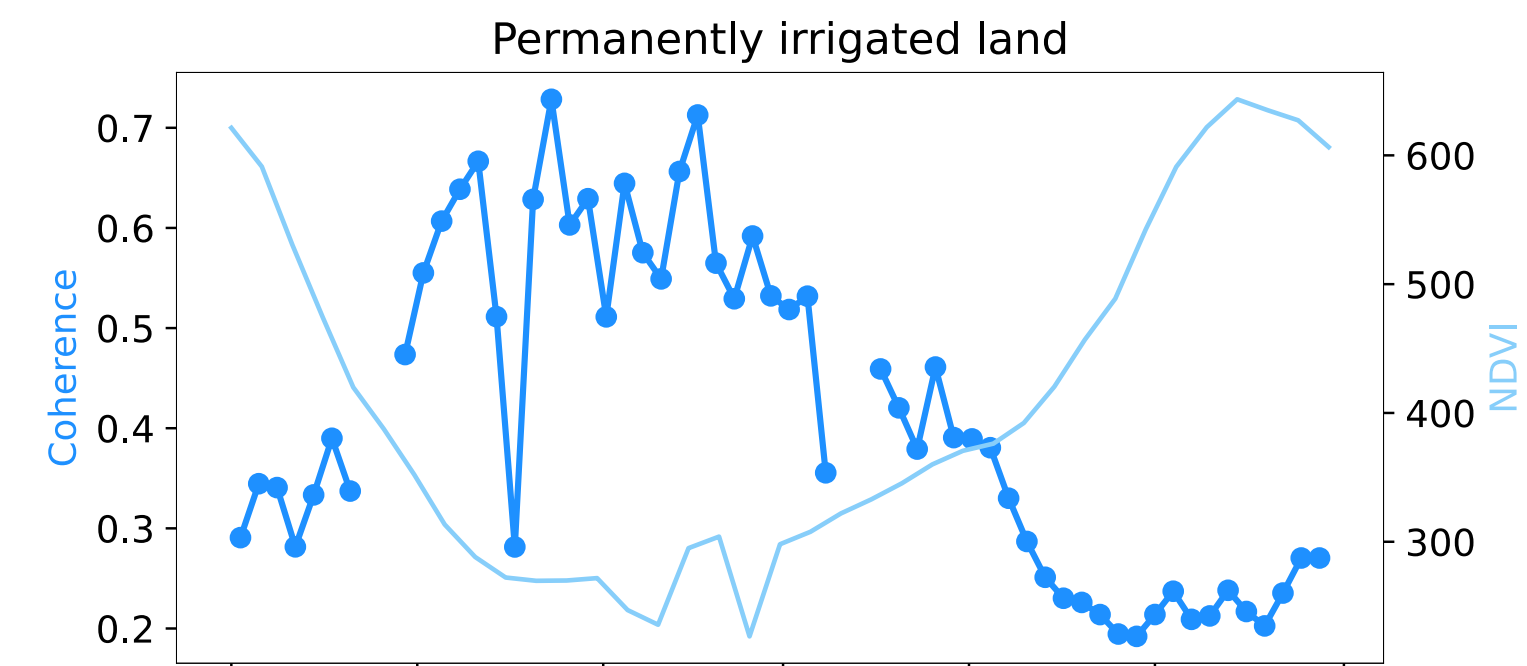
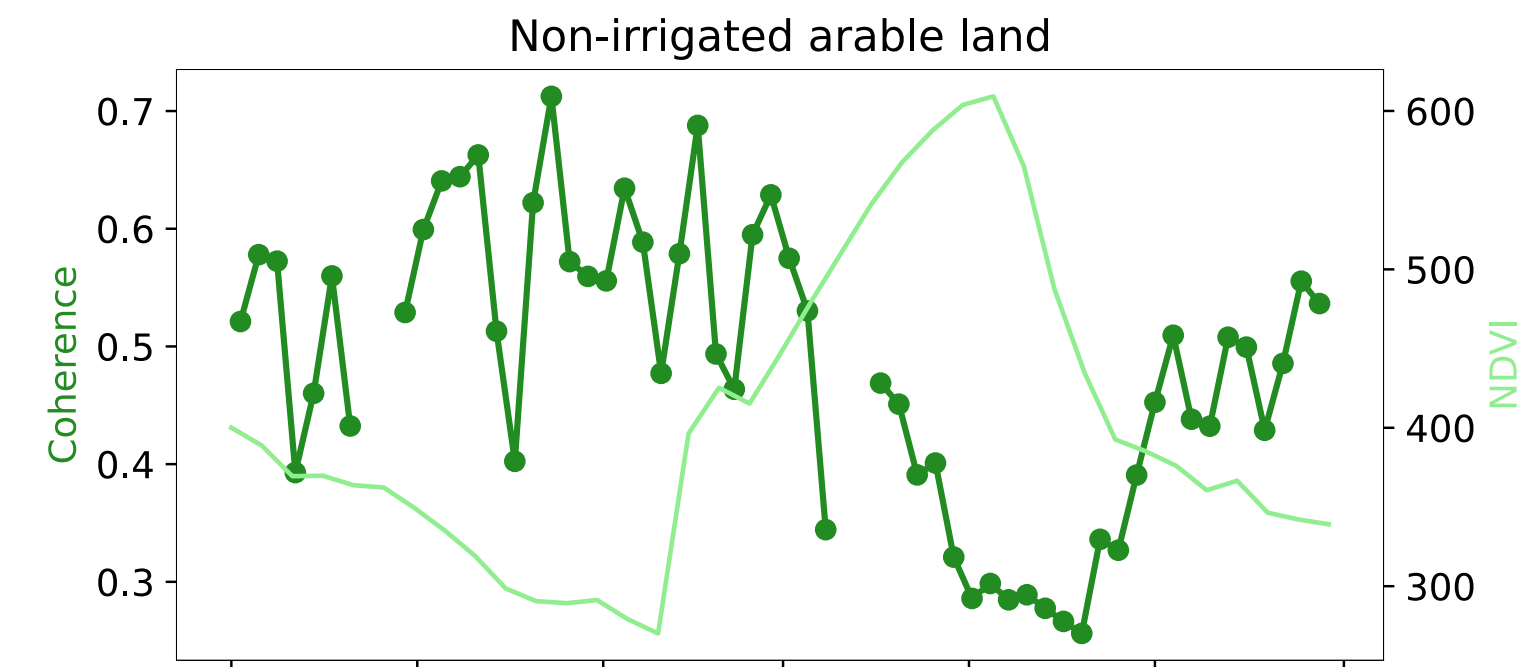
Fruit trees =  
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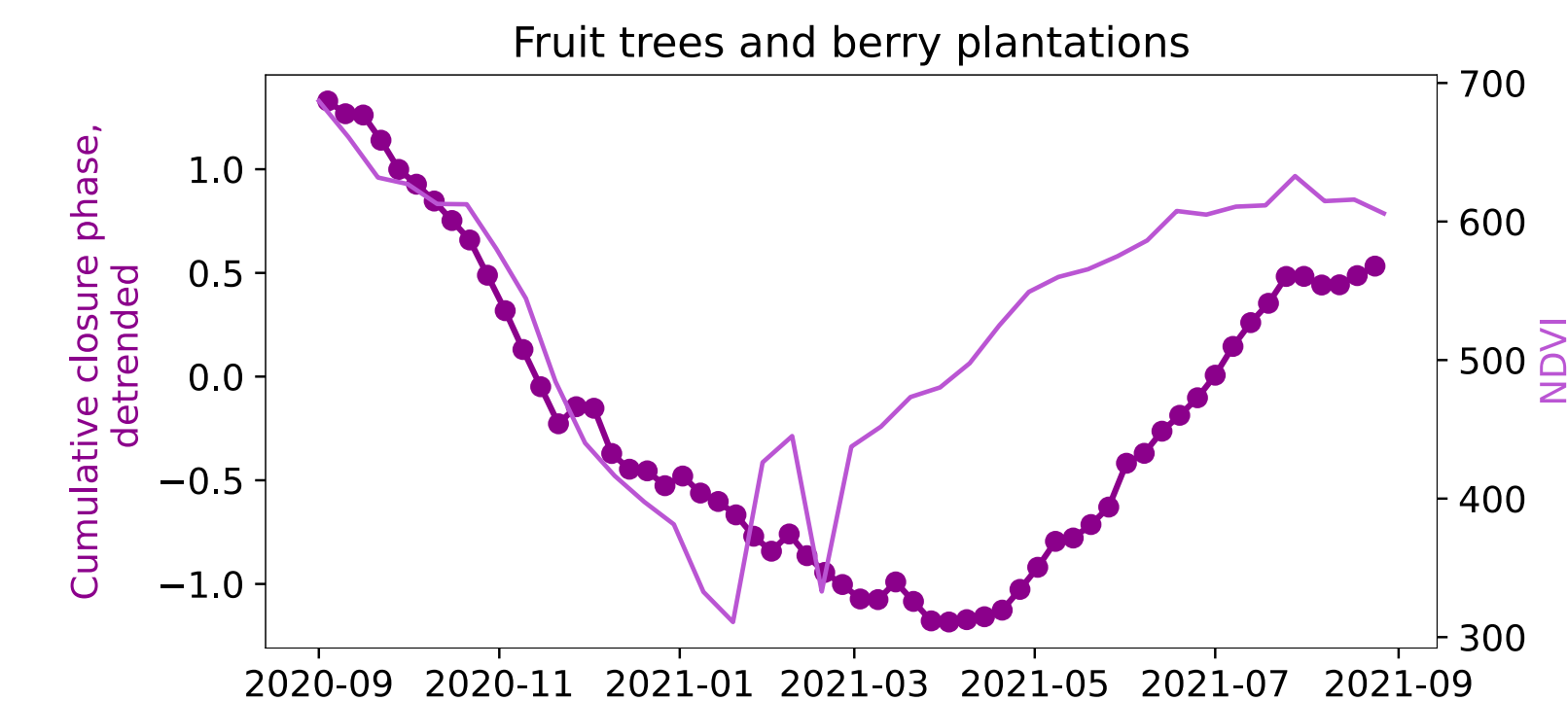
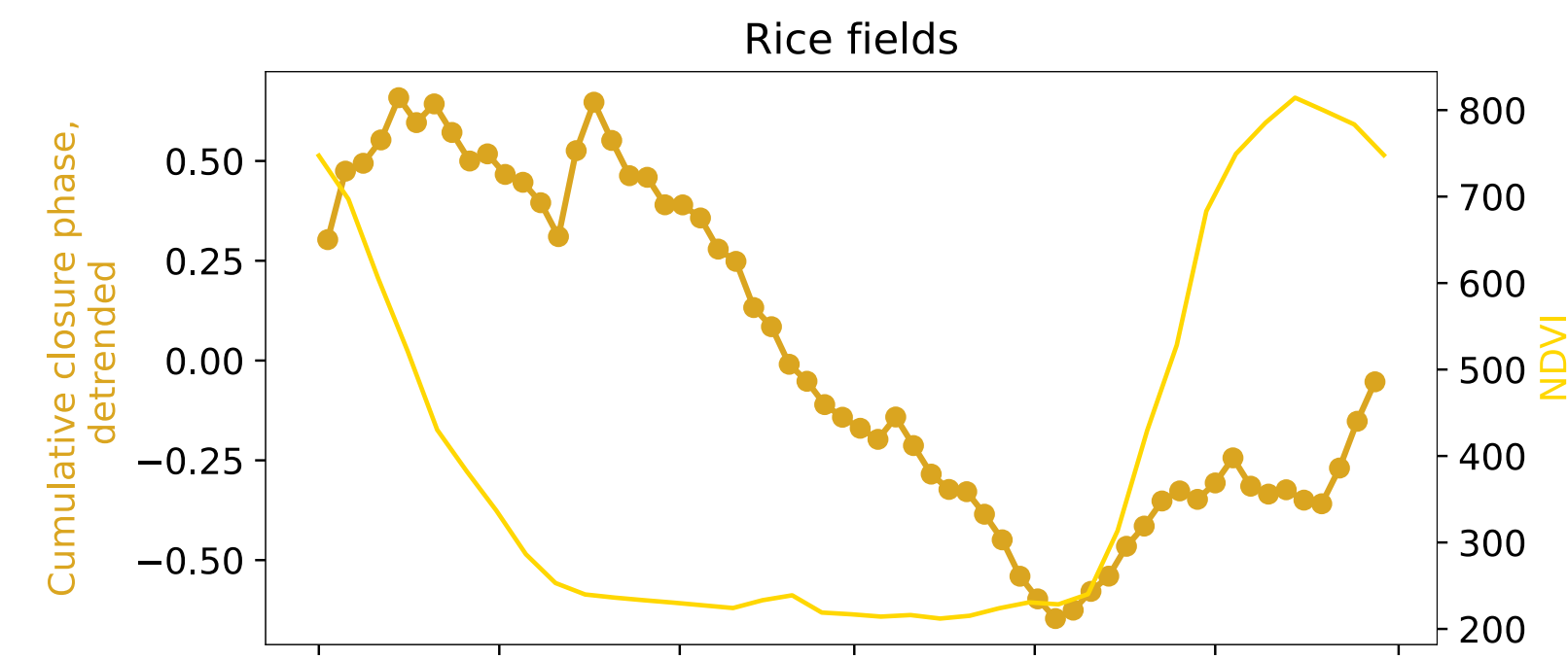
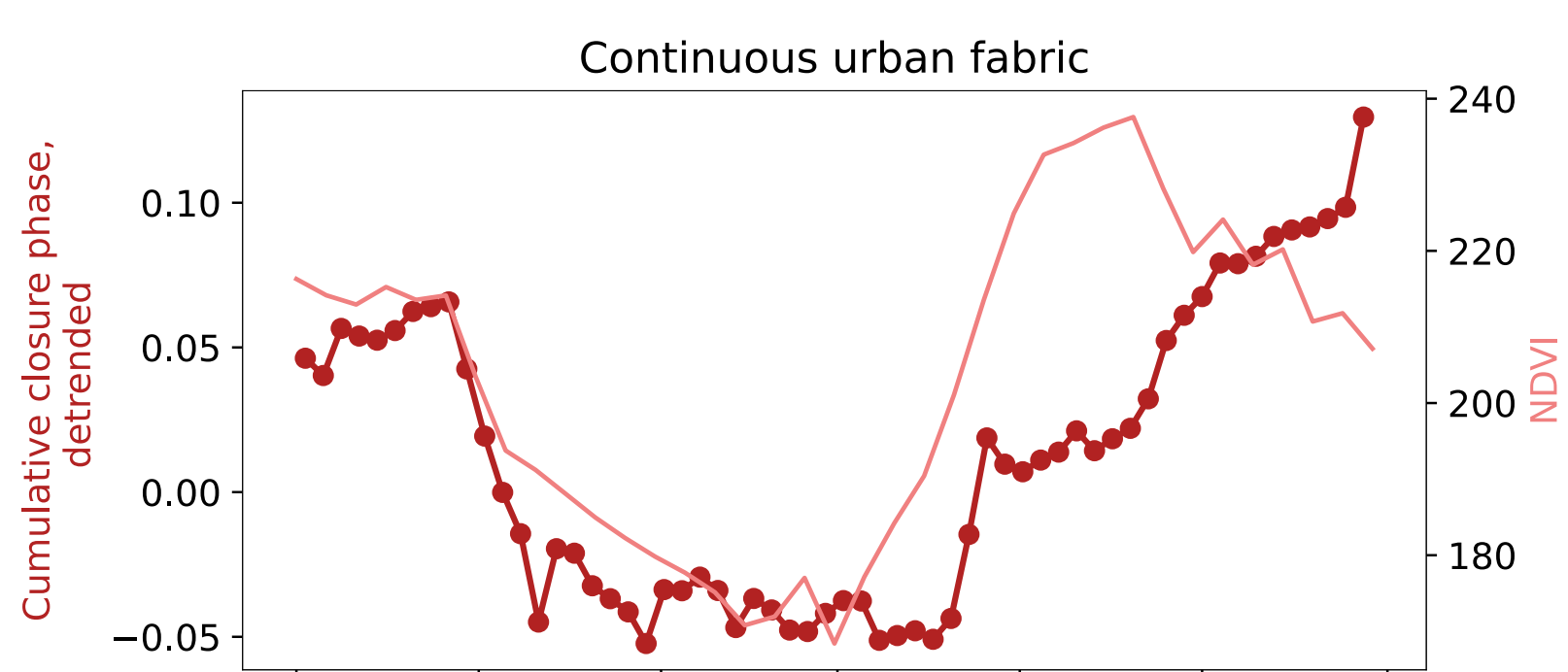
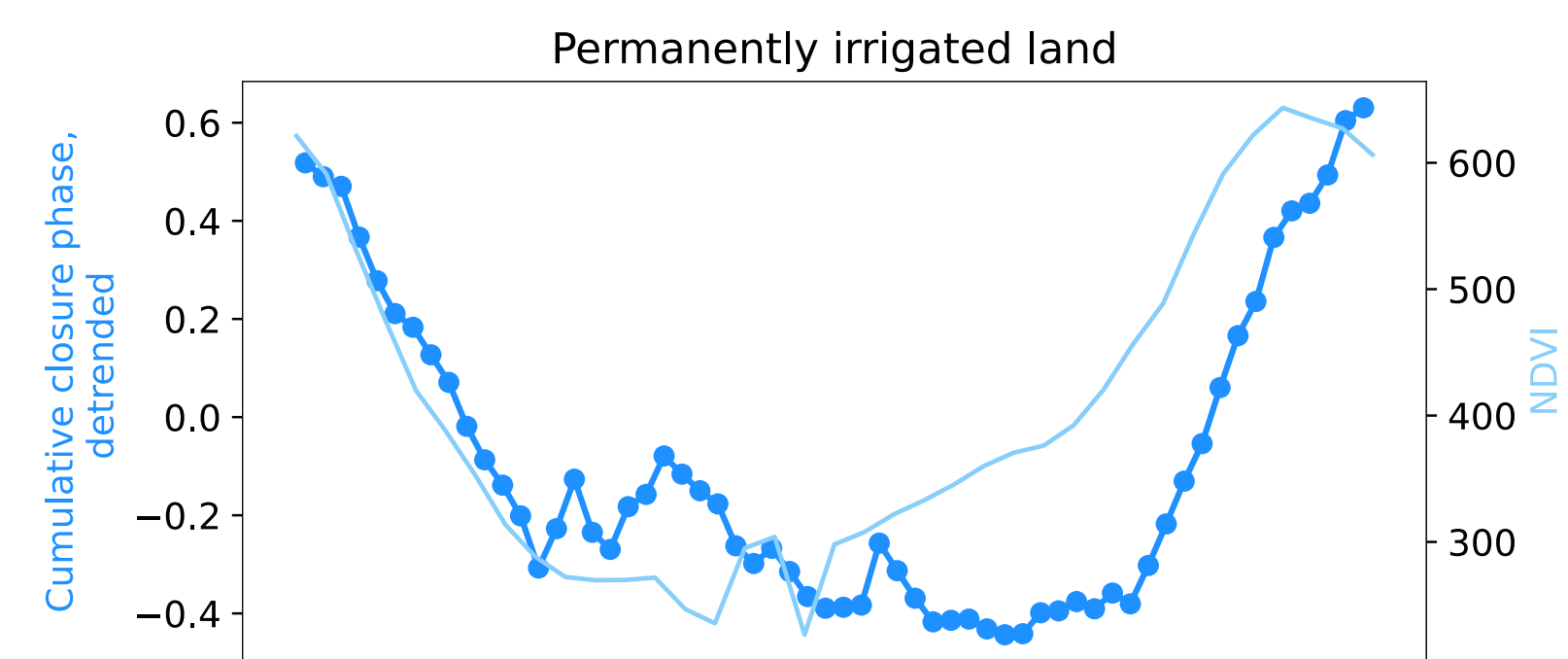
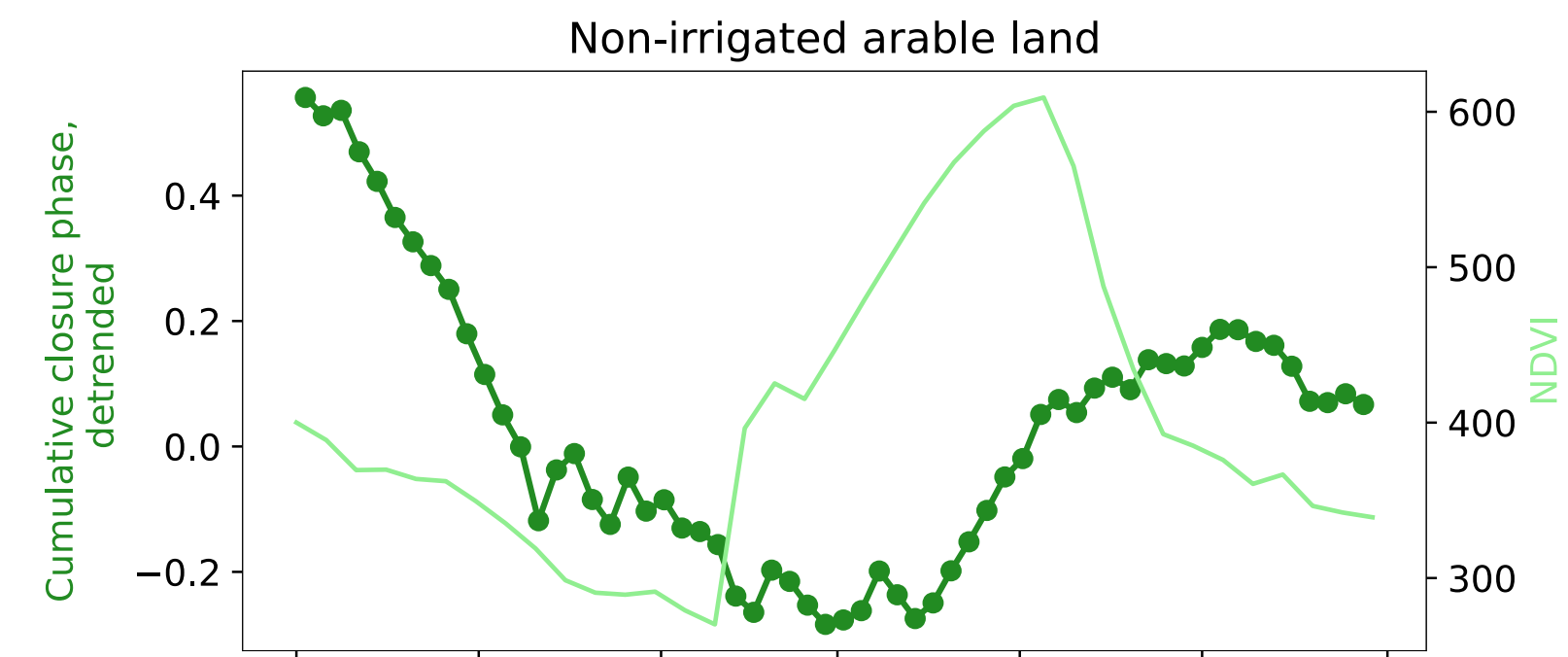


Lopez Velasco et al. 2008

More precision in crop distribution and cycle could help us identify the physical processes at play

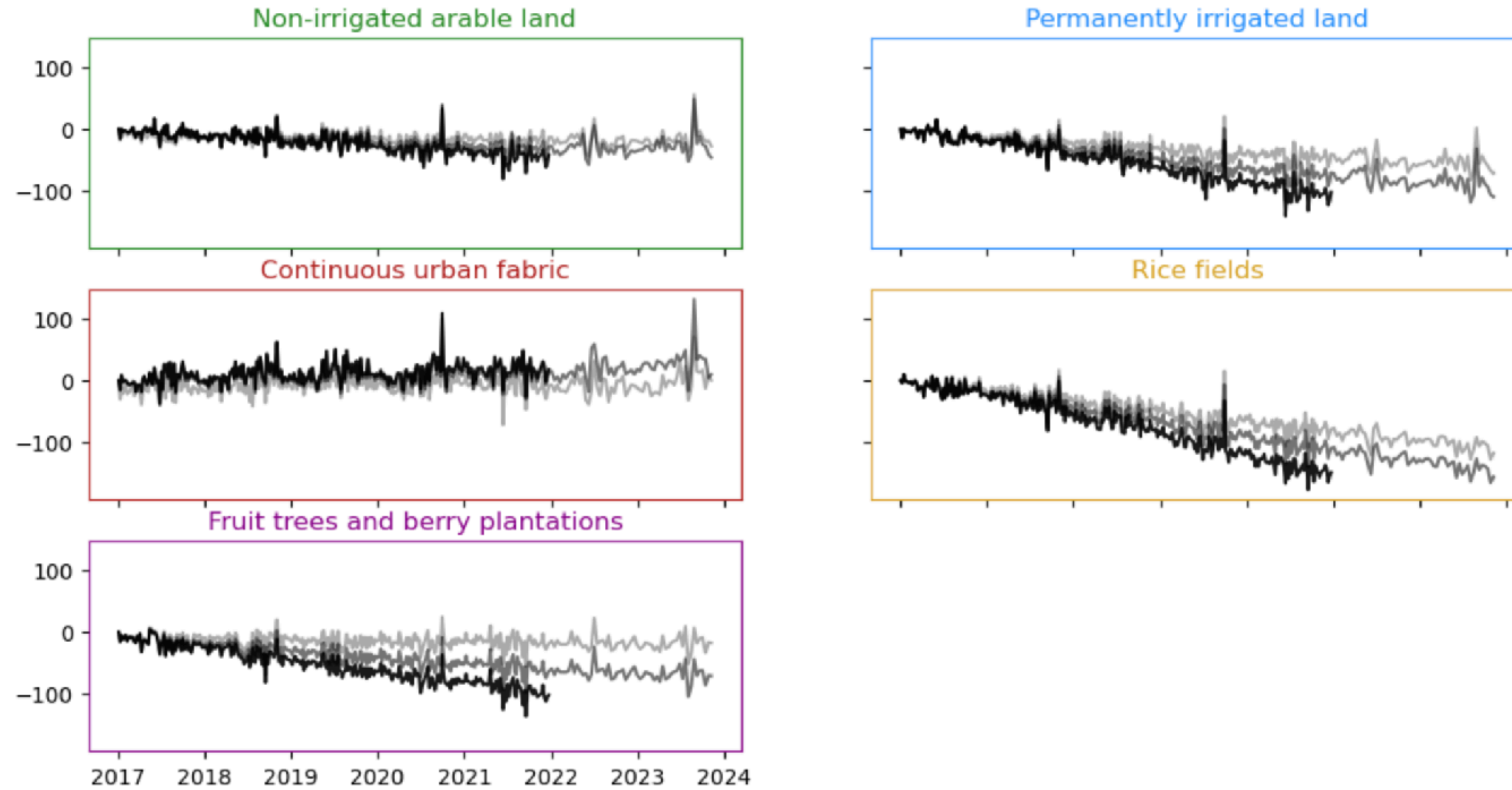


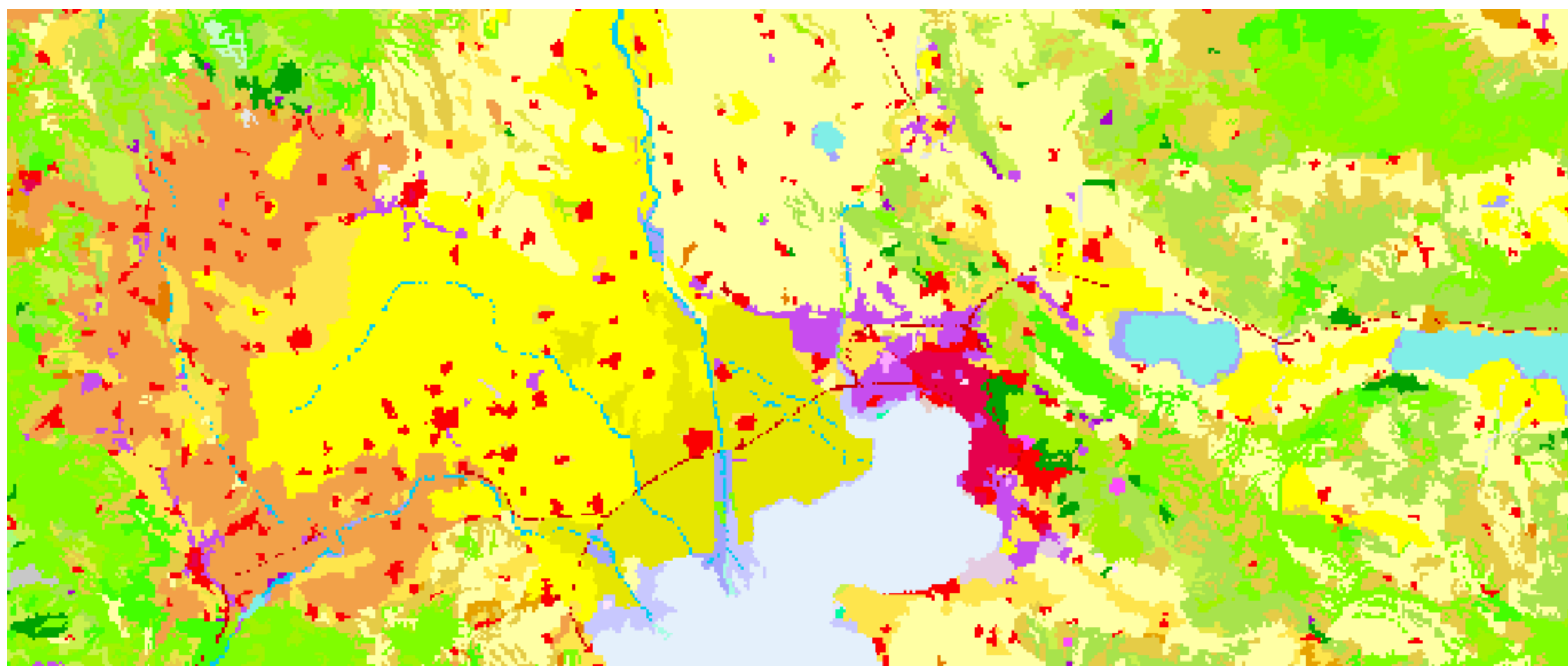




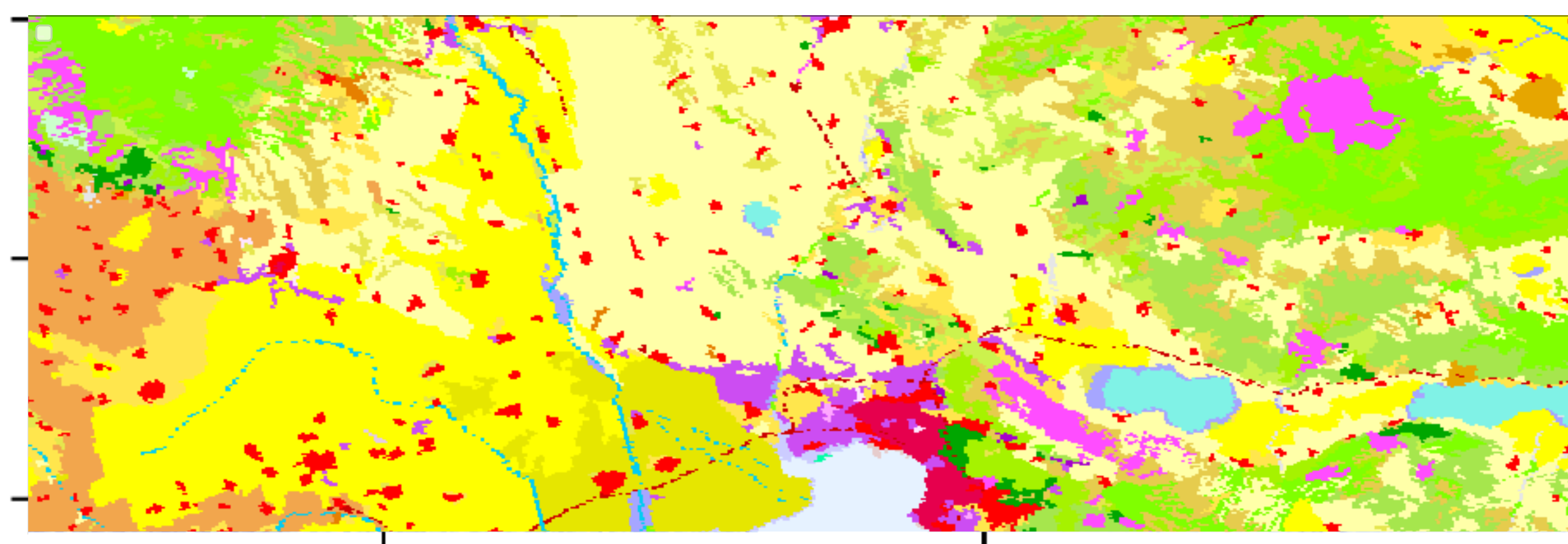


Mean timeseries for different land cover types  
(black:  $bs \leq 12$ , dark gray:  $bs \leq 48$ , light gray: all bs)





Land cover map, Corine 2018, ESA





# Yuan et al. 2024

