Assessing the Contribution of Urban Green Spaces to Atmospheric CO_2 Dynamics Using WRF-Chem in a Metropolitan Area

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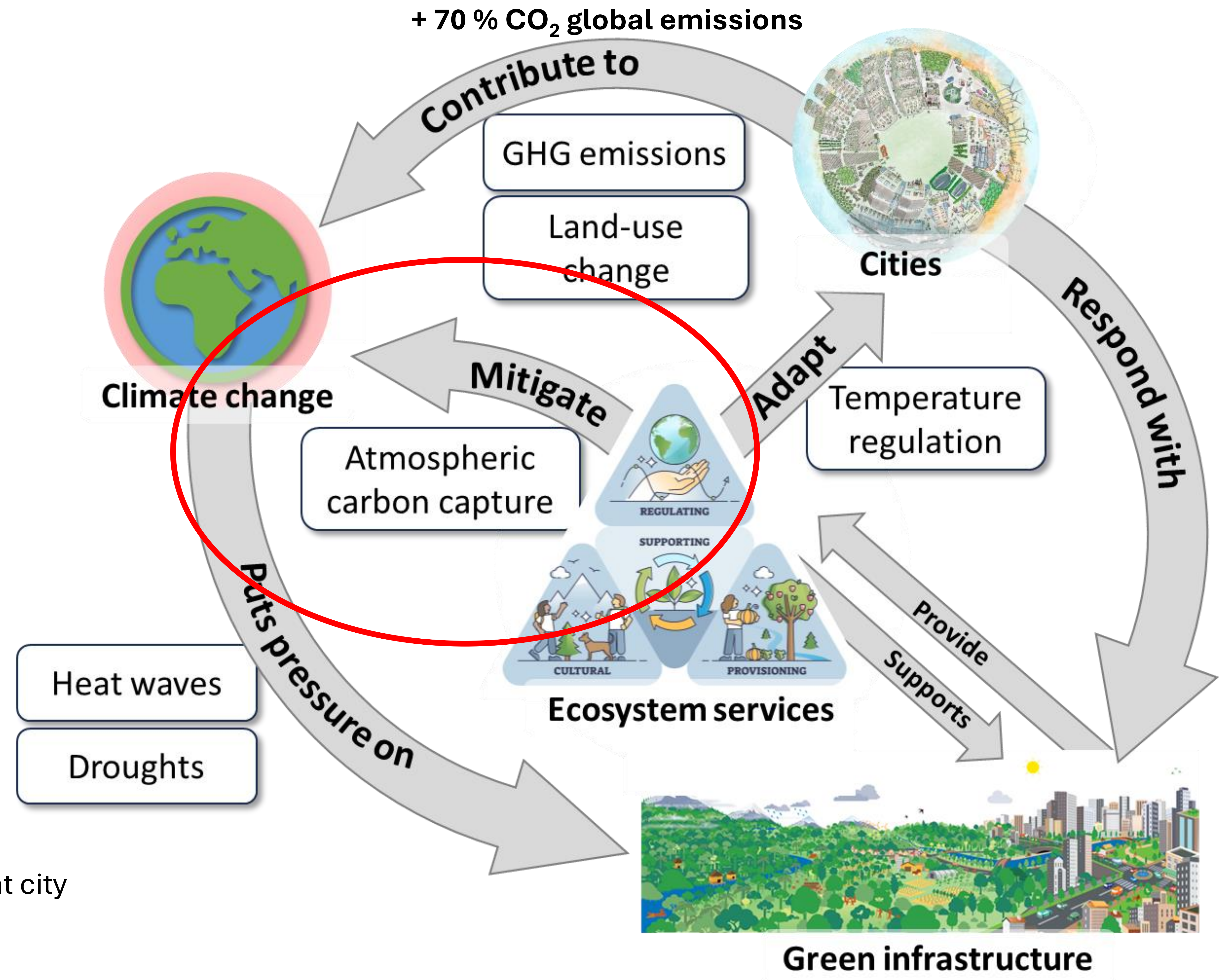
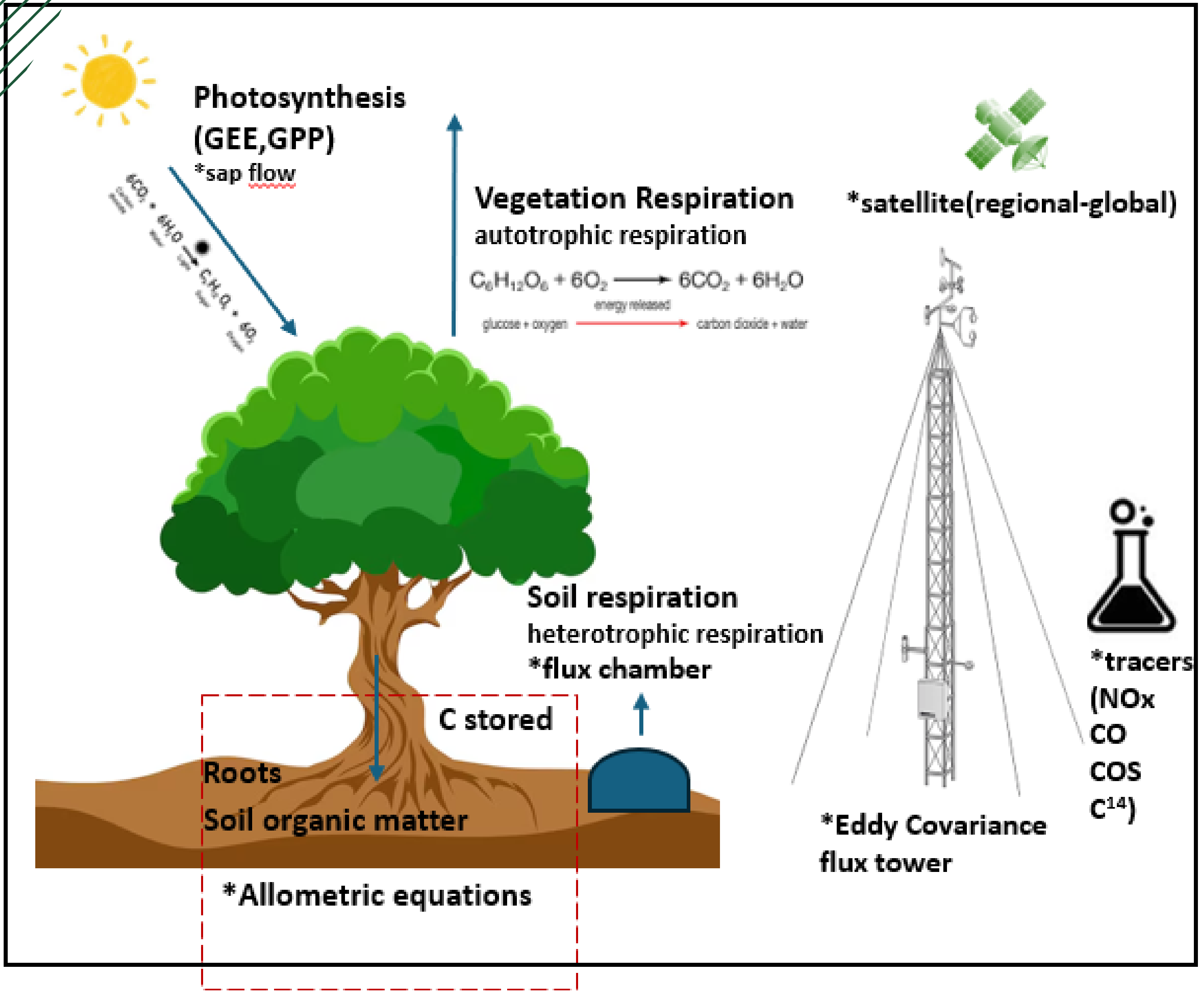
Green Infrastructure

Cities aiming to become more sustainable often turn to green infrastructure. Examples include vertical farming, rooftop greenhouses, green roofs, and public parks. But how well do we understand the impacts of these strategies? If we can understand the precise impact of different sustainability strategies, cities can engineer a combination of sustainability strategies to maximize positive effects.



Climate-resilient city

How to quantify the CO_2 signals from GI of a city?



Measurements

Light-Use-Efficiency Model

- VPRM
- diFUME
- SMUrF

- GPP is proportional to the amount of absorbed photosynthetically active radiation; LUE factors and parameterizations for respiration
- Low input data requirements
- Not account for long-term carbon stocks

Process-based Model

- SUEWS
- JSBATCH
- SURFEX

- rely on detailed mechanistic representations of photosynthesis, respiration, and water balance
- Extensive parameterization and data requirements

Modelling Approaches

Quantify biogenic CO_2 fluxes at the urban scale(10m-1km) is critical and challenging

Vegetation Photosynthesis and Respiration Model (VPRM)

Research Questions

To understand the role of urban green spaces on urban carbon budget(sink or source?), we need a high-resolution estimate of biogenic CO_2 fluxes

1) **Can we improve the resolution of biogenic CO_2 fluxes estimation?**

- Default VPRM normally combined with MODIS satellite data (500m)
- Incorporate high-resolution satellite data sentinel2 data (10m) to VPRM

->Biogenic CO_2 fluxes estimation at 10m in the Metropolitan Area of Barcelona (AMB)

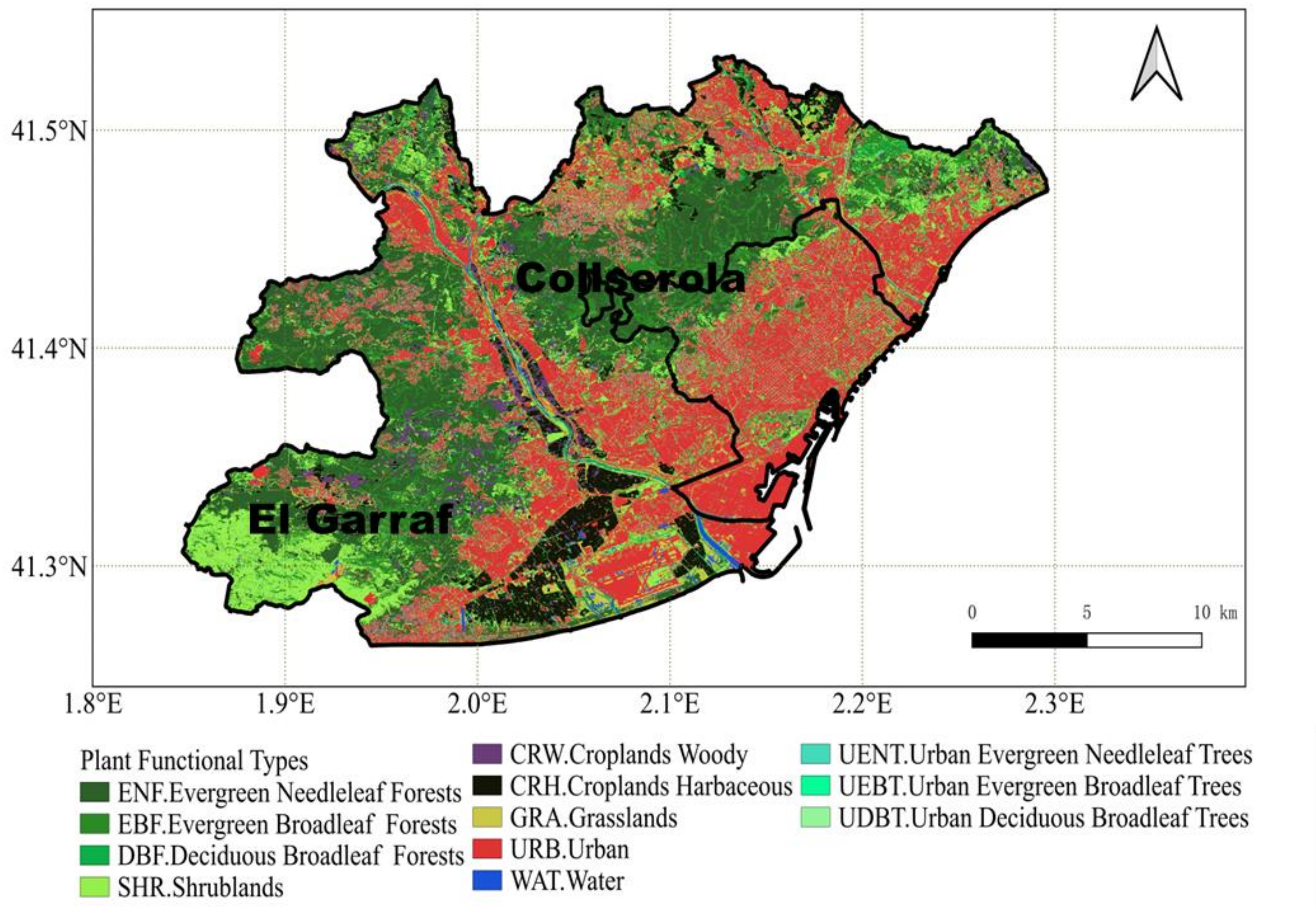
2) **To what extent does the improved resolution and parameterization enhance our ability to identify urban biogenic CO_2 Fluxes?**

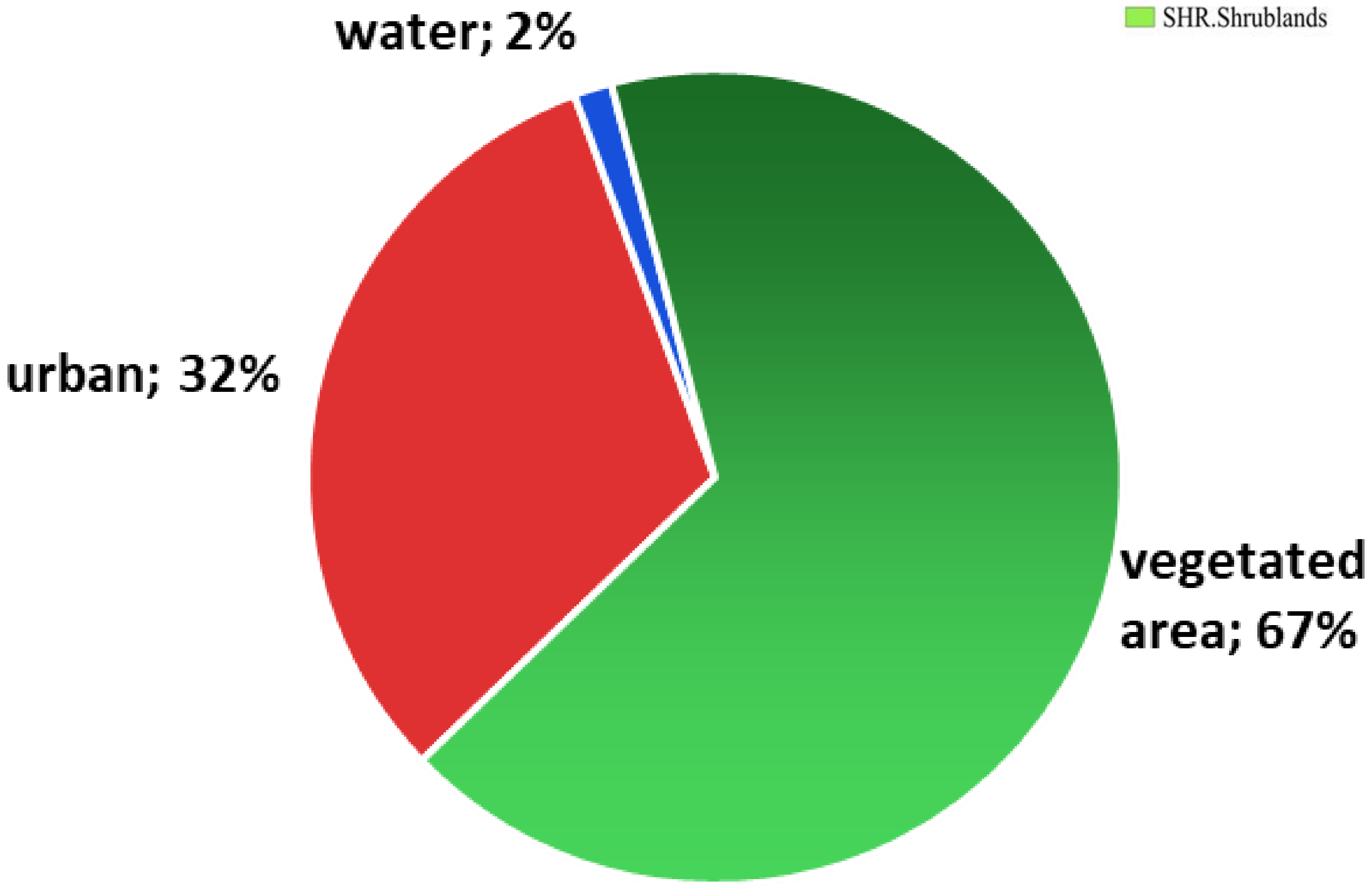
- Different VPRM configurations
- Estimated biogenic fluxes are constrained with atmospheric CO_2 observations using WRF-Chem

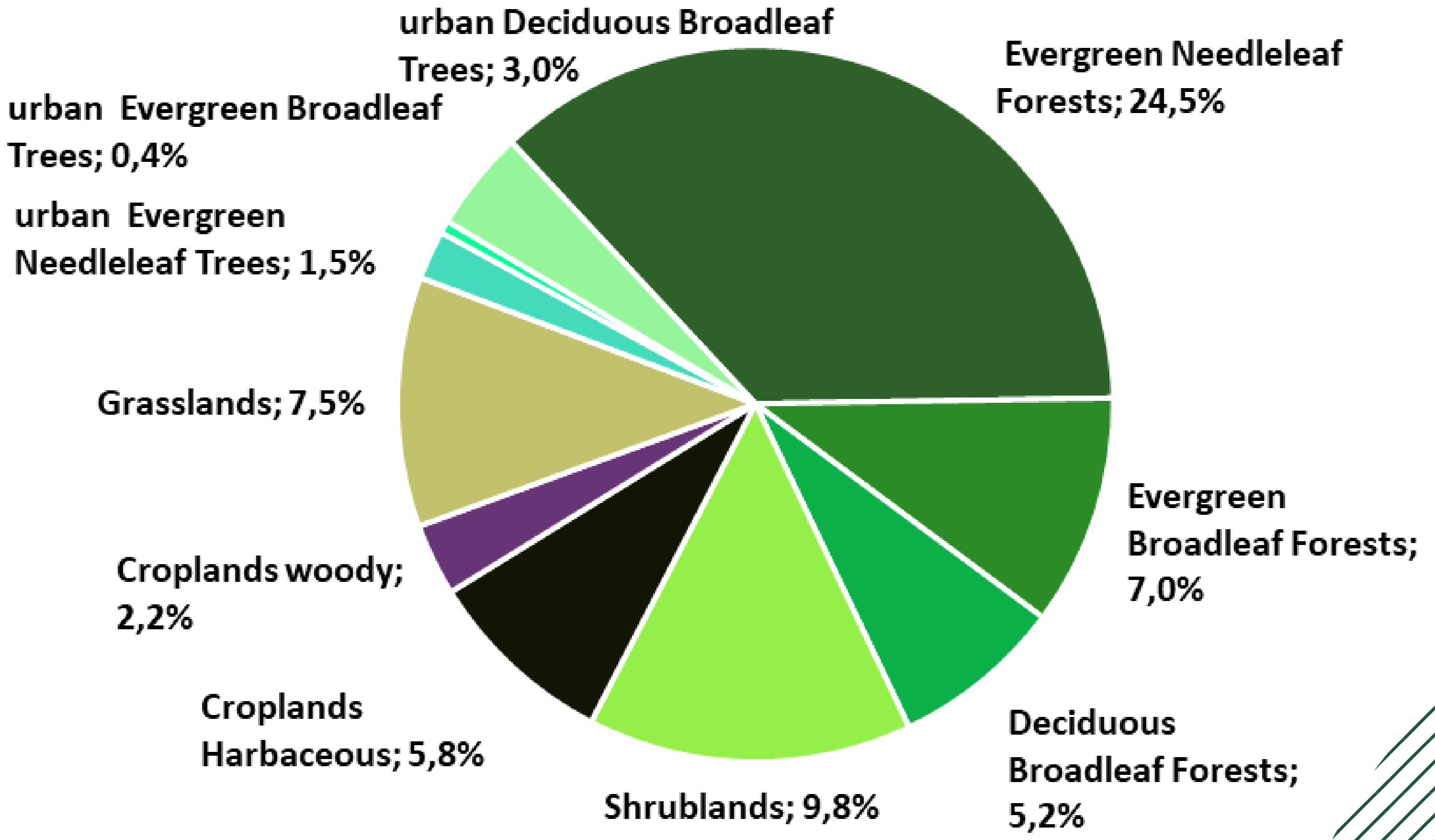
Part 2

Case study

How much green infrastructure does the AMB have?

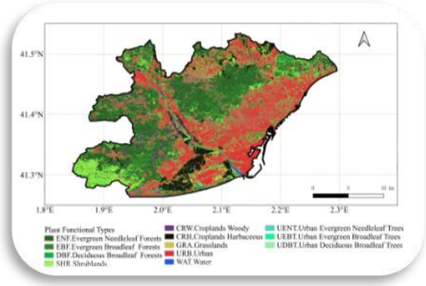






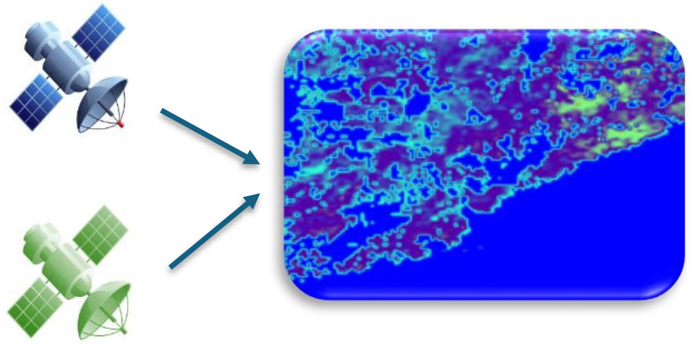
Methodological Framework

INPUT



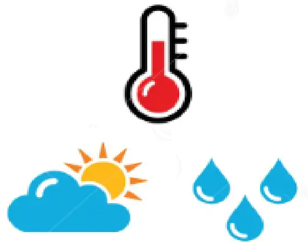
Land Cover

Modis

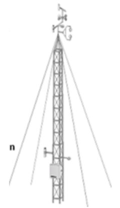


sentinel2(S2)

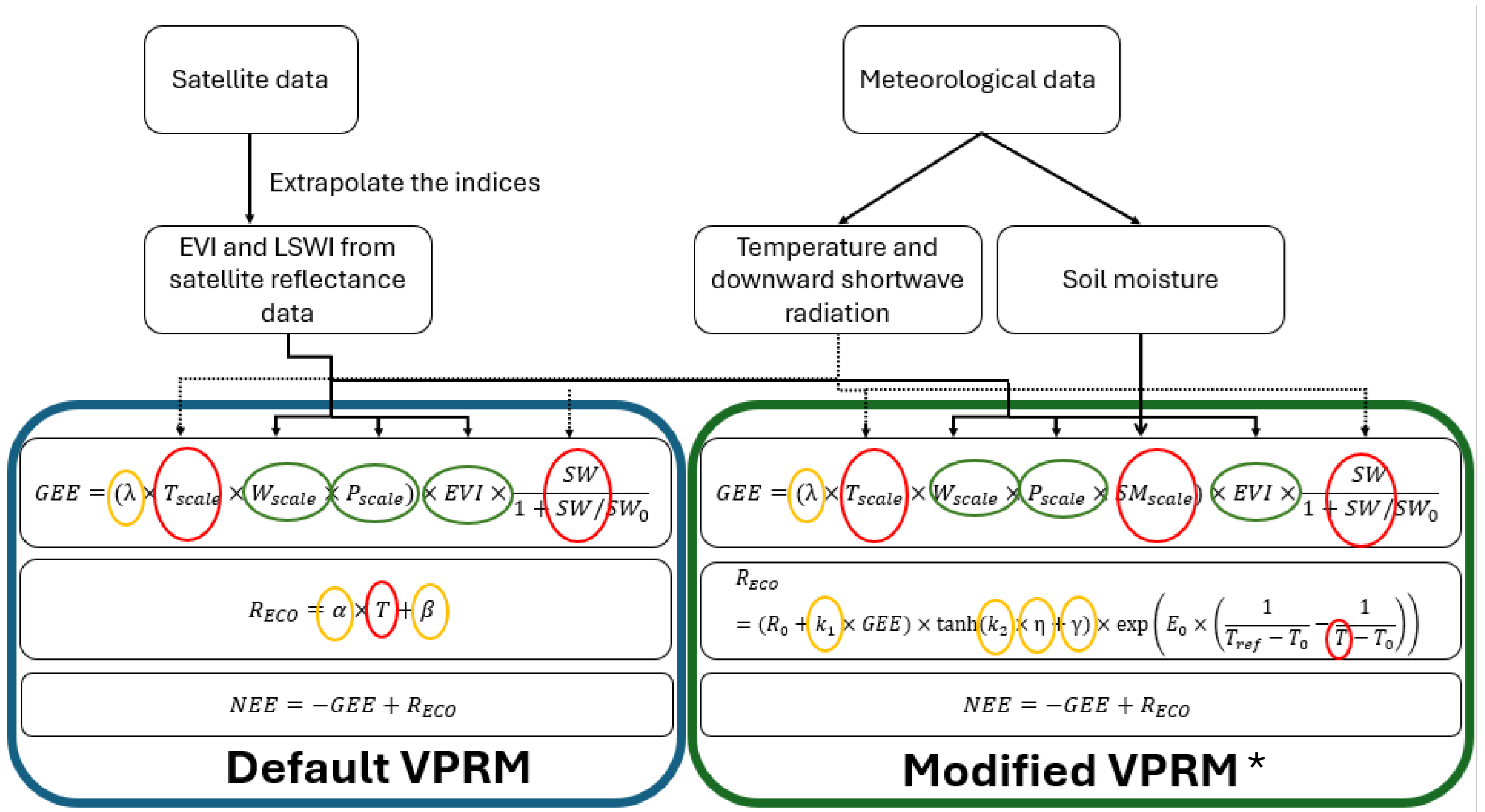
Vegetation indexes (500m;10m)



Meteorological data

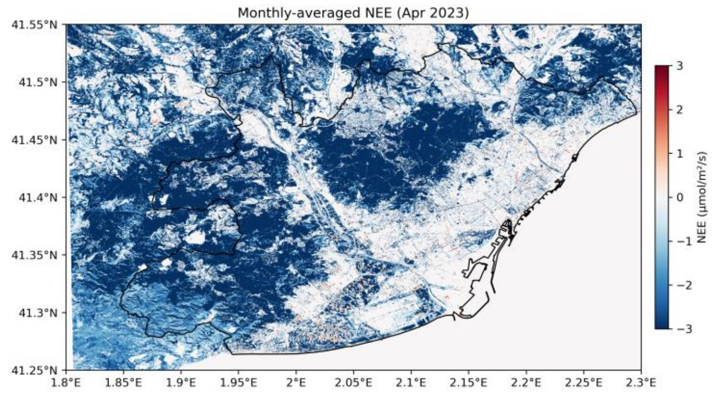


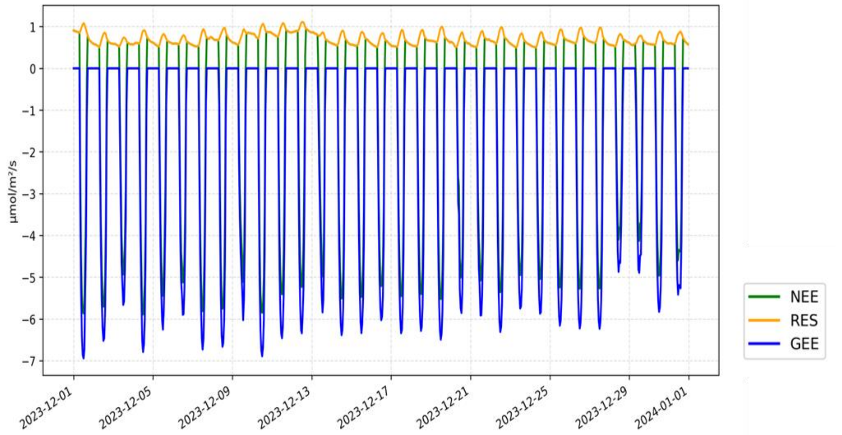
Eddy Covariance Tower*



Output

Biogenic CO_2 Fluxes

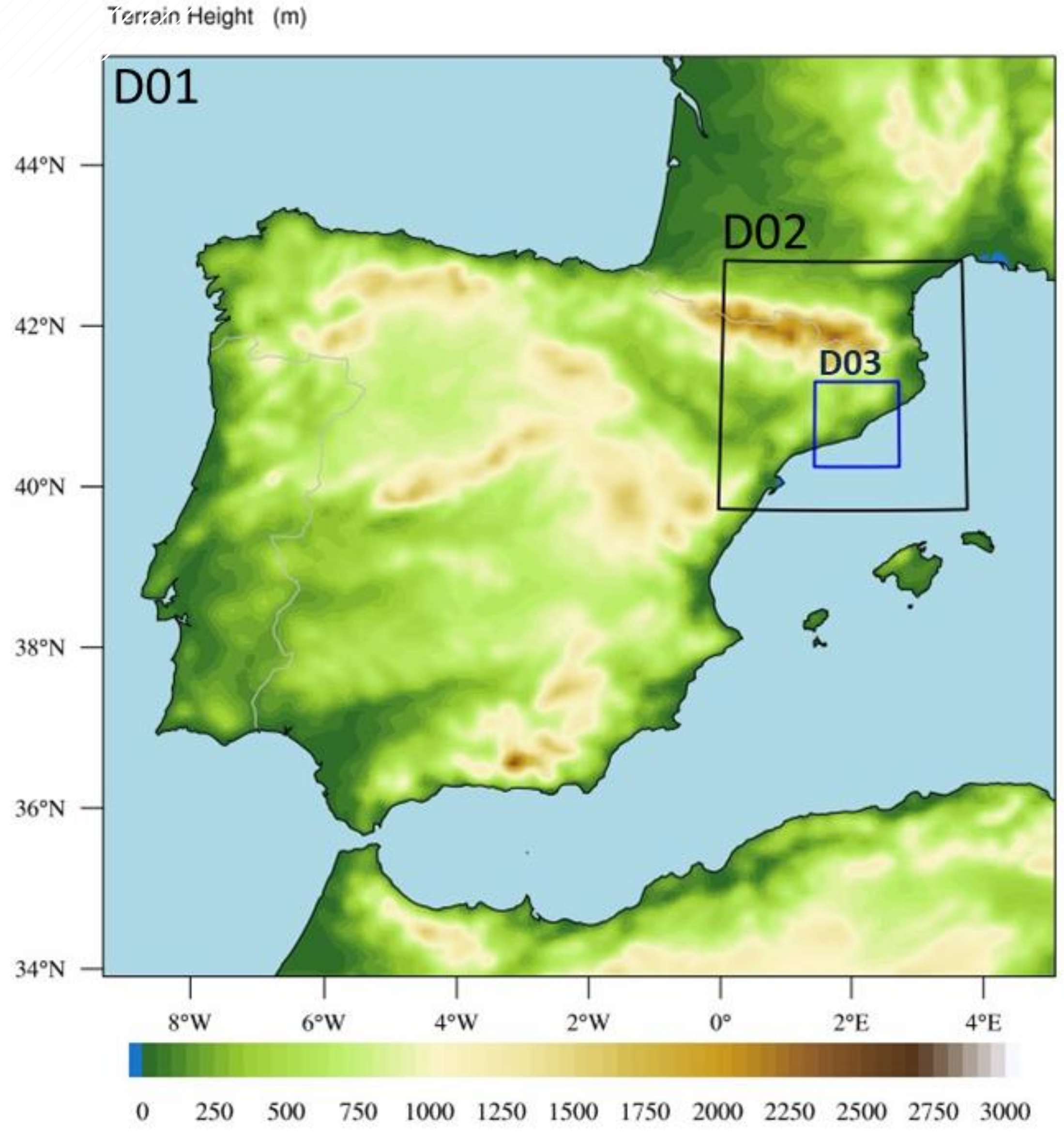




*Segura-Barrero, R., and Coauthors, 2025: Heat and Drought Events Alter Biogenic Capacity to Balance CO2 Budget in South-Western Europe. Glob. Biogeochem. Cycles, 39, e2024GB008163, https://doi.org/10.1029/2024GB008163

Methodological Framework

WRF-Chem V4.3.3



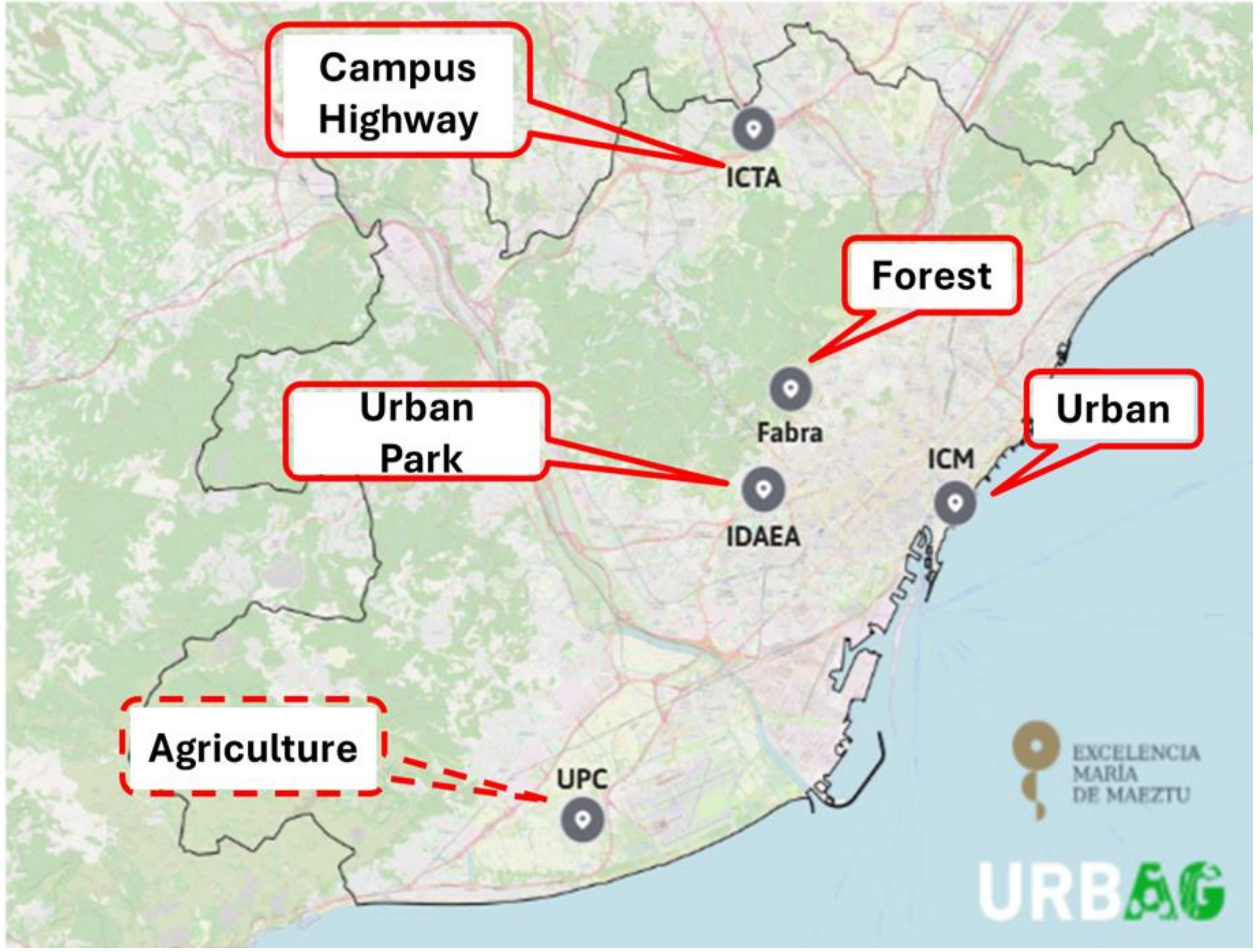
Simulation period: (spin-up time is 2 days)

April and **December, 2023**

Domain	D01(9km)	D02(3km)	D03(1km)
horizontal grid	150 ×145	118 ×118	121 ×121
Vertical layers	45		
Biogenic emission	VPRMDef_modis	VPRMDef_modis	VPRMDef_modis
	VPRMMod_modis	VPRMMod_modis	VPRMMod_modis
	VPRMMod_modis	VPRMMod_modis	VPRMMod_s2
Anthropogenic emission	BSC(2023) (0.1x 0.1º)*		
Human Respiration	/	/	Population density * 280kg/person year
Ocean emission	ICOS		
Chemical boundary	CAMS global inversion dataset		

* https://github.com/BSC-ES/HERMES_Delta

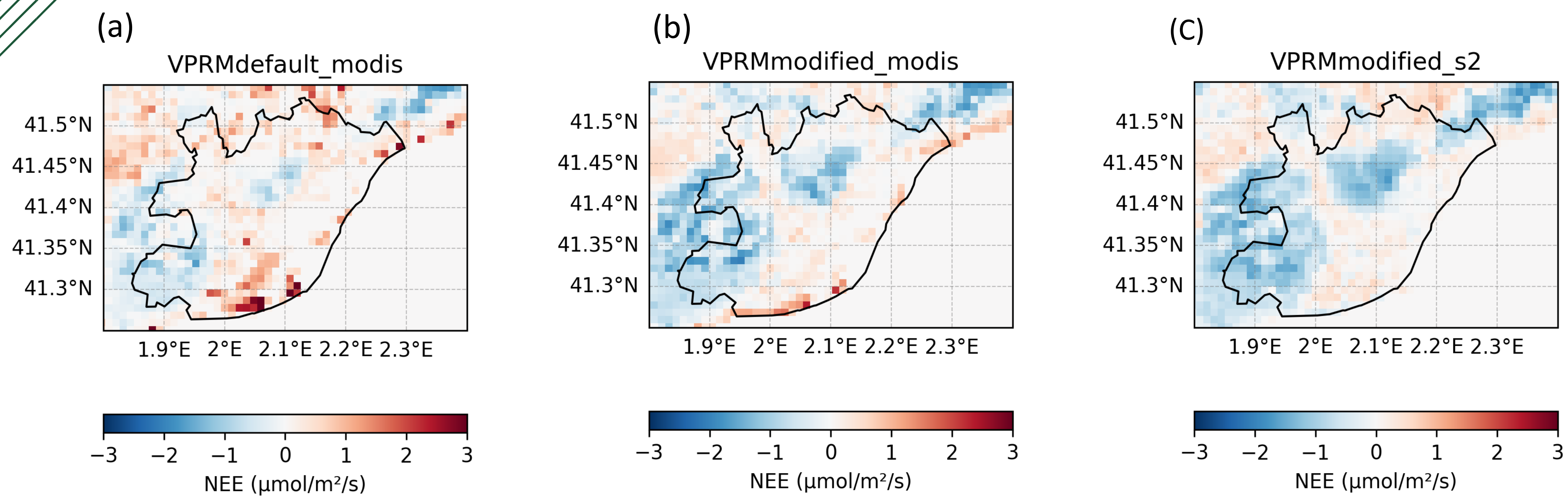
Monitoring Network

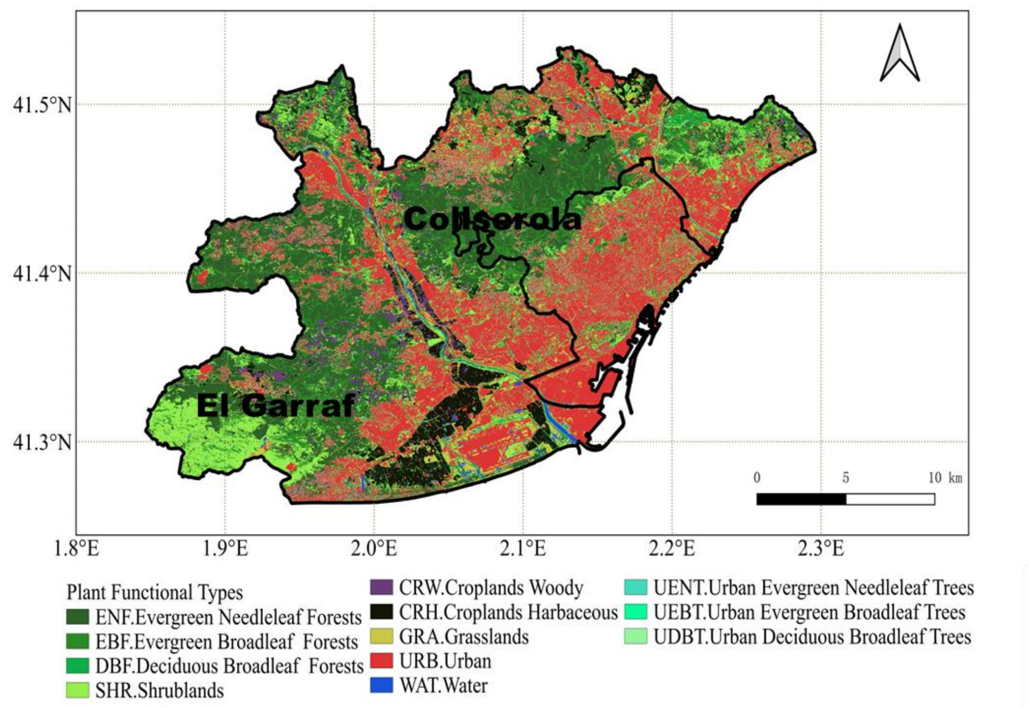


Part 2

Results

Biogenic CO_2 Fluxes





NEE from different configurations (kiloton C/month)

Simulations	Apr	Dec
VPRMdef_modis	-7.1	-0.1
VPRMmod_modis	-13.8	-7.4
VPRMmod_s2	-21.4	-9.1

Methodological Framework

EMISSION(wrfchemi_d0*.nc)

```
E_TRA1 = out.createVariable('E_TRA1', dtype, dim)
E_TRA1[:] = 0
out['E_TRA1'].setncatts(edgar['E_CO2'].__dict__)


E_TRA3 = out.createVariable('E_TRA3', dtype, dim)
E_TRA3[:] = co2_cams
out['E_TRA3'].setncatts(edgar['E_CO2'].__dict__)

E_TRA4 = out.createVariable('E_TRA4', dtype, dim)
E_TRA4[:] = co2_bio1
out['E_TRA4'].setncatts(edgar['E_CO2'].__dict__)
# by qing
E_TRA5 = out.createVariable('E_TRA5', dtype, dim)
E_TRA5[:] = co2_bio2
out['E_TRA5'].setncatts(edgar['E_CO2'].__dict__)
print(np.nanmax(E_TRA5[:]))

E_TRA6 = out.createVariable('E_TRA6', dtype, dim)
E_TRA6[:] = co2_bio3
out['E_TRA6'].setncatts(edgar['E_CO2'].__dict__)

E_TRA7 = out.createVariable('E_TRA7', dtype, dim)
E_TRA7[:] = co2_bio4
out['E_TRA7'].setncatts(edgar['E_CO2'].__dict__)

E_TRA8 = out.createVariable('E_TRA8', dtype, dim)
E_TRA8[:] = co2_hum
```

CONCENTRATIONS(wrfout_d0*.nc)

```
&chem
chem_opt                             = 14,14,14,
chem_in_opt                          = 0,0,0,
have_bcs_chem                        = .true.,.true.,.true.,
have_bcs_tracer                      = .false.,.false.,.false.,
gaschem_onoff                        = 0,0,0,
aerchem_onoff                        = 0,0,0,
vertmix_onoff                        = 1,1,1,
chem_conv_tr                         = 1,1,1,
gas_drydep_opt                       = 0,0,0,
aer_drydep_opt                       = 0,0,0,
diagnostic_chem                      = 0,0,0,
chemdt                               = 2.,2.,2.,
bioemdt                              = 30.,30.,30.,
emiss_inpt_opt                       = 1,1,1,
emiss_opt                            = 12,12,12,
kemit                                = 44,
io_style_emissions                   = 2,
```

Registry/registry.chem

```
# Anthropogenic emissions
#
state   real    -        i+jf   emis_ant   -   -   -    -          "Anthropogenic Emissions"  ""
state   real  e_tra1     i+jf   emis_ant   1   Z   i5   "E_TRA1"   "Emission field for GHG"  "mol km^-2 hr^-1"
state   real  e_tra2     i+jf   emis_ant   1   Z   i5   "E_TRA2"   "Emission field for GHG"  "mol km^-2 hr^-1"
state   real  e_tra3     i+jf   emis_ant   1   Z   i5   "E_TRA3"   "Emission field for GHG"  "mol km^-2 hr^-1"
state   real  e_tra4     i+jf   emis_ant   1   Z   i5   "E_TRA4"   "Emission field for GHG"  "mol km^-2 hr^-1"
state   real  e_tra5     i+jf   emis_ant   1   Z   i5   "E_TRA5"   "Emission field for GHG"  "mol km^-2 hr^-1"
state   real  e_tra6     i+jf   emis_ant   1   Z   i5   "E_TRA6"   "Emission field for GHG"  "mol km^-2 hr^-1"
state   real  e_tra7     i+jf   emis_ant   1   Z   i5   "E_TRA7"   "Emission field for GHG"  "mol km^-2 hr^-1"
state   real  e_tra8     i+jf   emis_ant   1   Z   i5   "E_TRA8"   "Emission field for GHG"  "mol km^-2 hr^-1"
state   real  e_tra9     i+jf   emis_ant   1   Z   i5   "E_TRA9"   "Emission field for GHG"  "mol km^-2 hr^-1"
```

emissions_driver.F

```
chem(i,k,j,p_tracer_1)  = chem(i,k,j,p_tracer_1) &
     +emis_ant(i,k,j,p_e_tra1)*conv
chem(i,k,j,p_tracer_2)  = chem(i,k,j,p_tracer_2) &
     +emis_ant(i,k,j,p_e_tra2)*conv
chem(i,k,j,p_tracer_3)  = chem(i,k,j,p_tracer_3) &
     +emis_ant(i,k,j,p_e_tra3)*conv
chem(i,k,j,p_tracer_4)  = chem(i,k,j,p_tracer_4) &
     +emis_ant(i,k,j,p_e_tra4)*conv
chem(i,k,j,p_tracer_5)  = chem(i,k,j,p_tracer_5) &
     +emis_ant(i,k,j,p_e_tra5)*conv
chem(i,k,j,p_tracer_6)  = chem(i,k,j,p_tracer_6) &
     +emis_ant(i,k,j,p_e_tra6)*conv
chem(i,k,j,p_tracer_7)  = chem(i,k,j,p_tracer_7) &
     +emis_ant(i,k,j,p_e_tra7)*conv
chem(i,k,j,p_tracer_8)  = chem(i,k,j,p_tracer_8) &
     +emis_ant(i,k,j,p_e_tra8)*conv
chem(i,k,j,p_tracer_9)  = chem(i,k,j,p_tracer_9) &
     +emis_ant(i,k,j,p_e_tra9)*conv
```

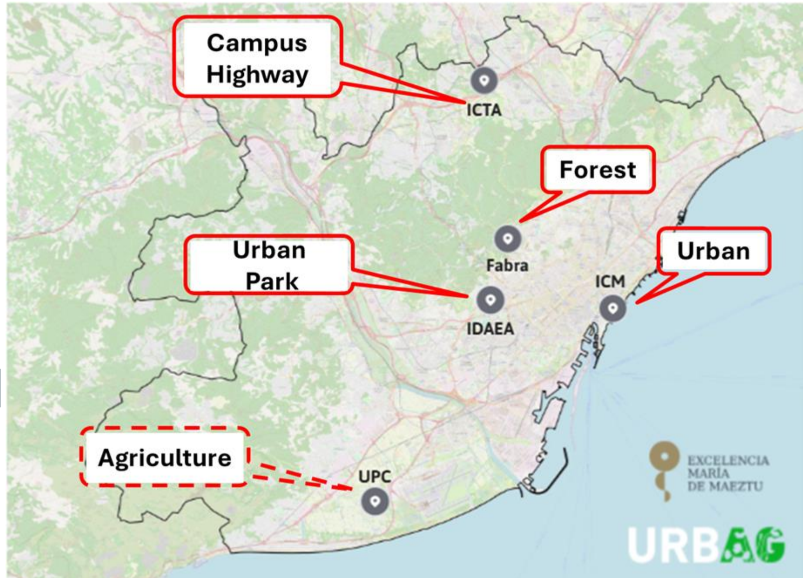
module_input_chem_data.F

```
!      chem = 0.08
    chem = vallbc
  endif
  if( nch .eq. p_tracer_2  ) then
    chem = vallbc
  endif
  if( nch .eq. p_tracer_3  ) then
    chem = vallbc
  endif
  if( nch .eq. p_tracer_4  ) then
    chem = vallbc
  endif
  if( nch .eq. p_tracer_5  ) then
    chem = vallbc
  endif
  if( nch .eq. p_tracer_6  ) then
    chem = vallbc
  endif
  if( nch .eq. p_tracer_7  ) then
    chem = vallbc
 endif
 if( nch .eq. p_tracer_8  ) then
    chem = vallbc
  endif
 if( nch .eq. p_tracer_9  ) then
```

The Weather and Research Forecasting model (WRF) coupled with chemical transport (WRF-Chem)

MONITORING NETWORK

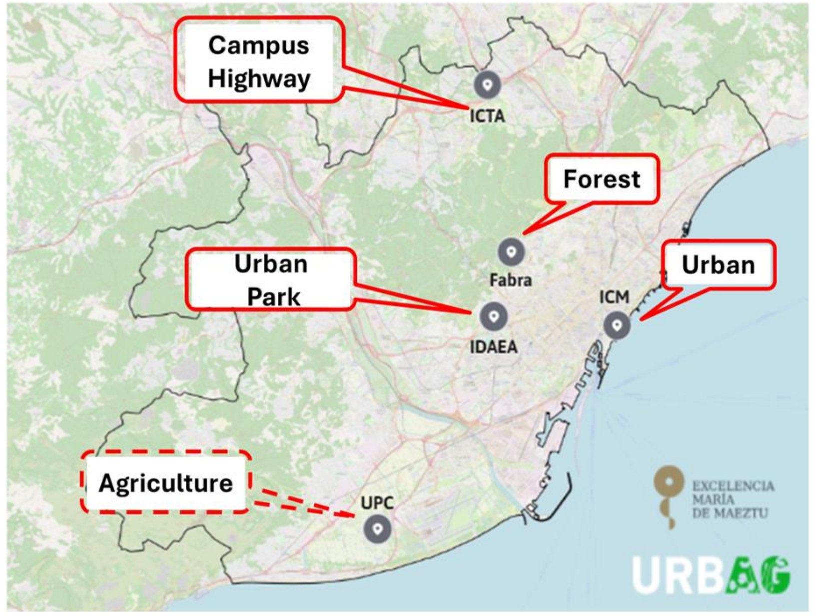
validate

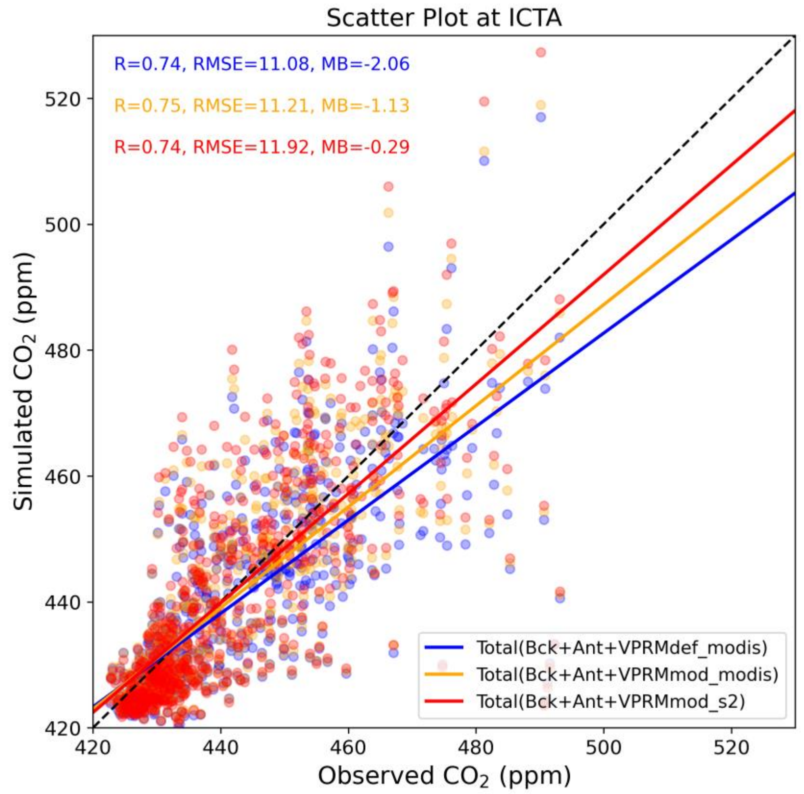


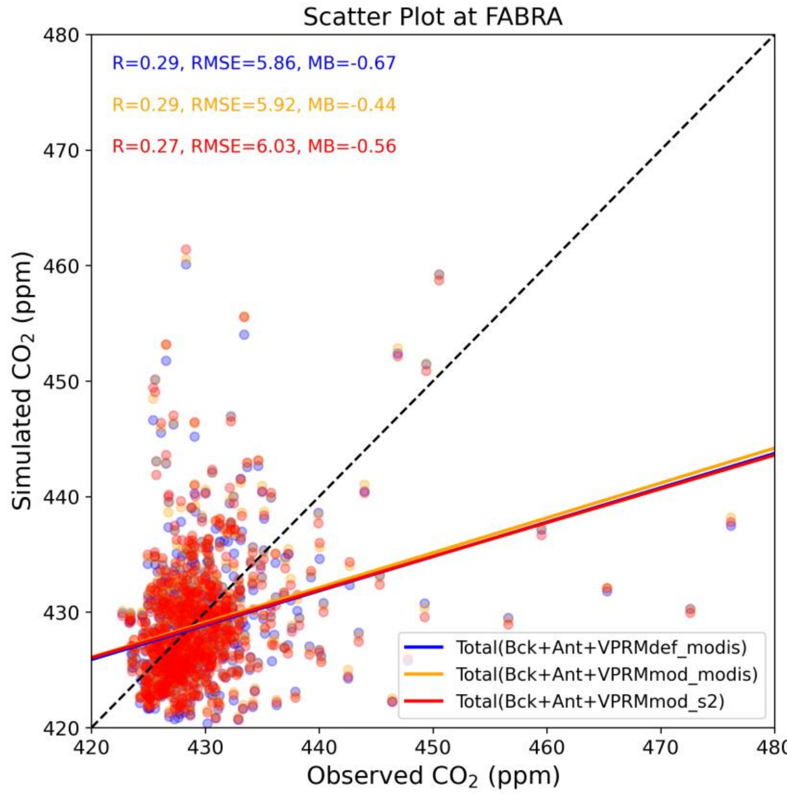
GHG stations
https://urbag.eu/ghg/
ICOS cities portal

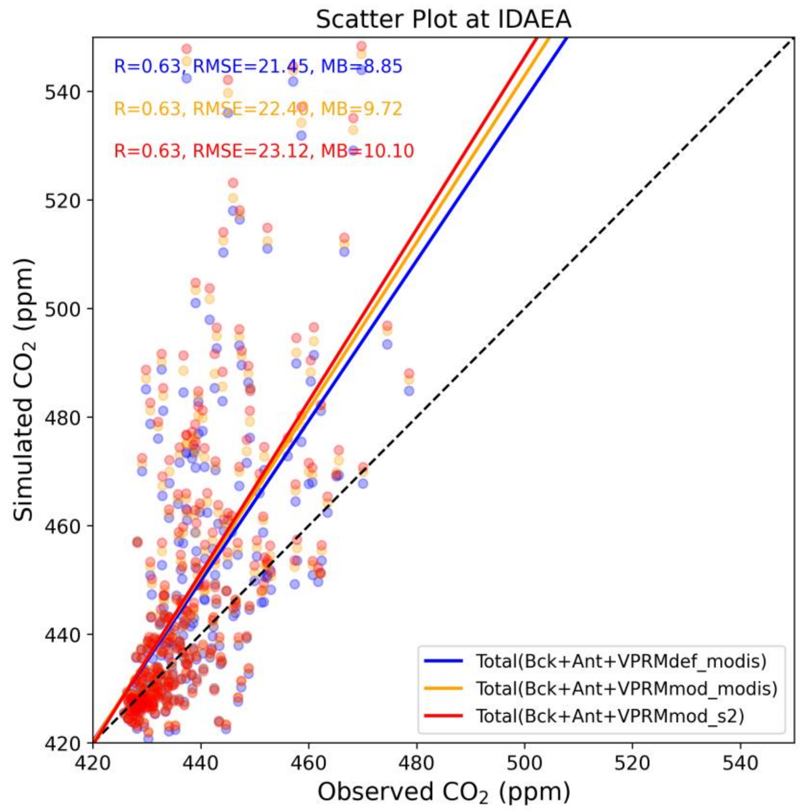
Results

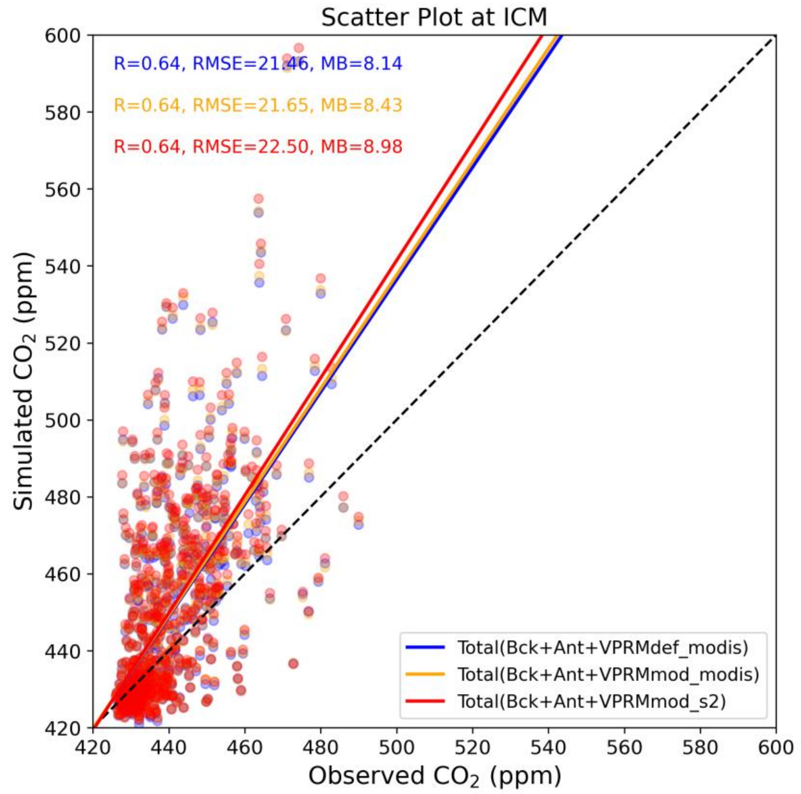
Total Concentrations in April









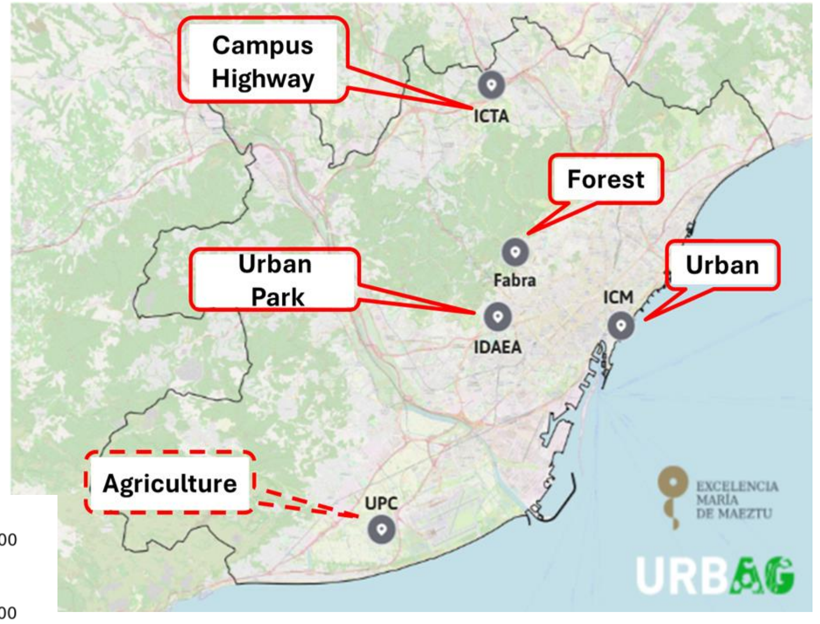


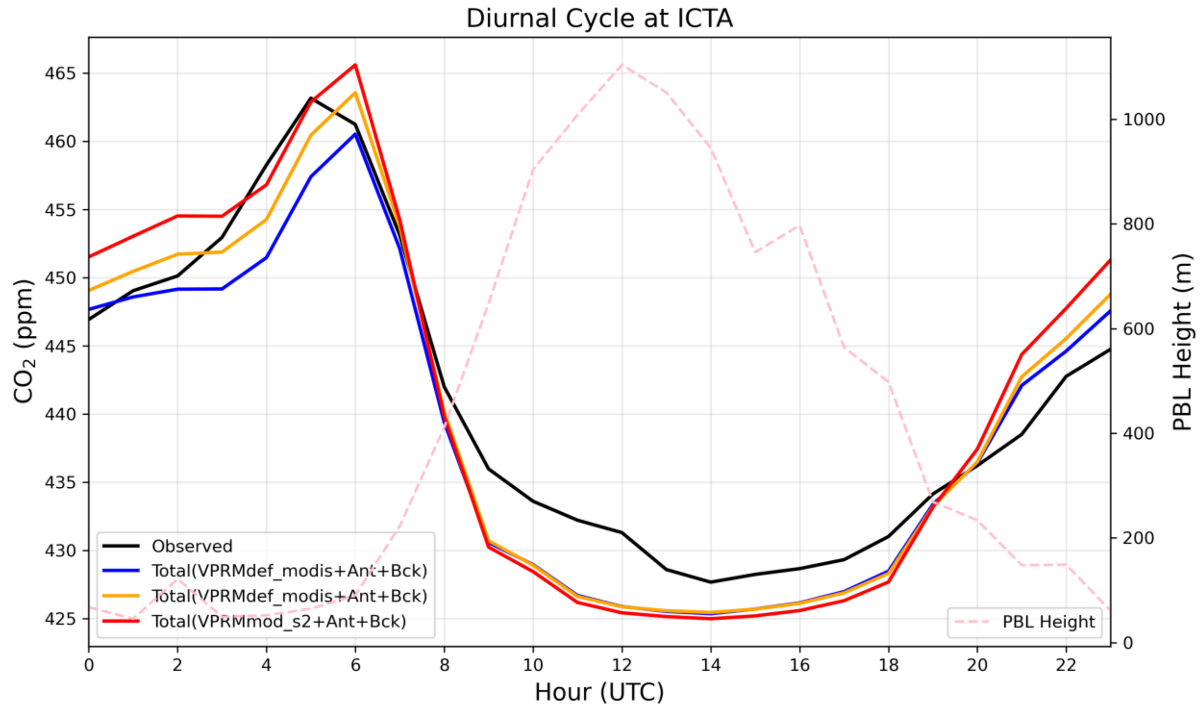
- Differences among VPRM configurations are relatively small.

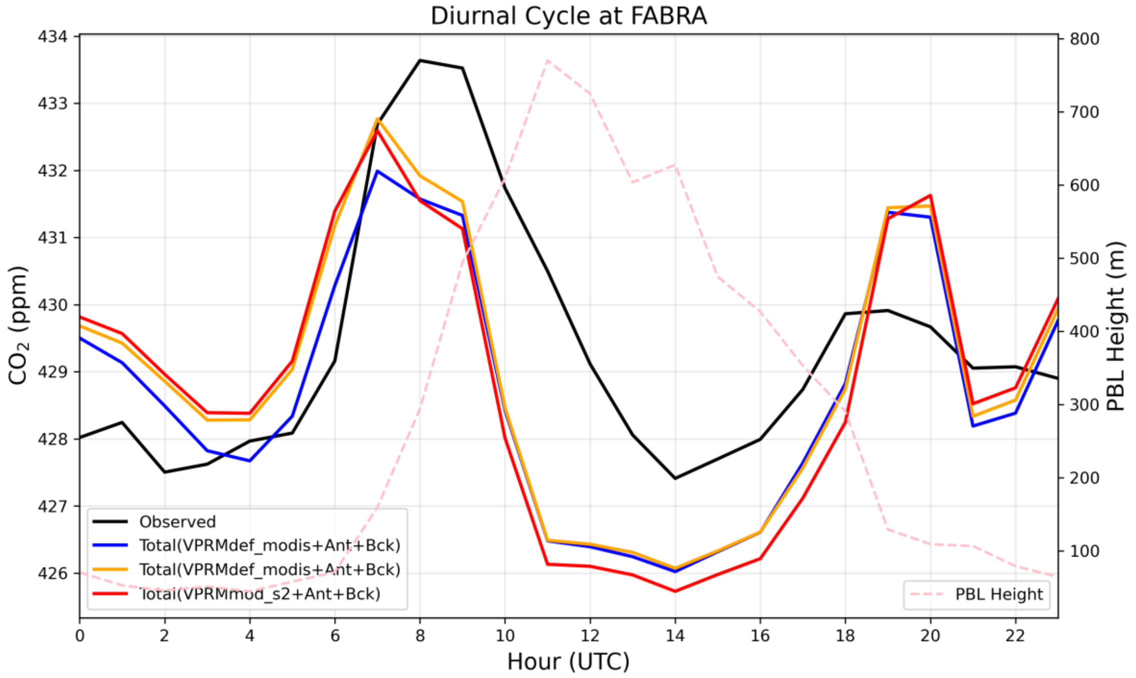
Part 2

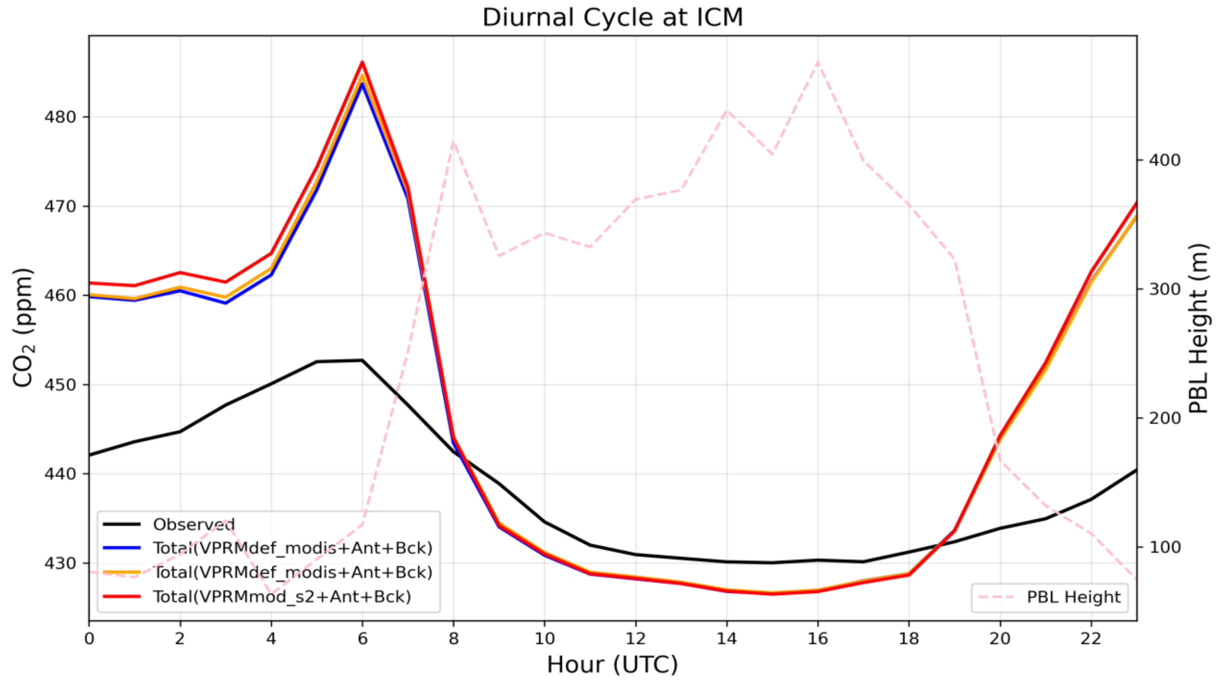
Results

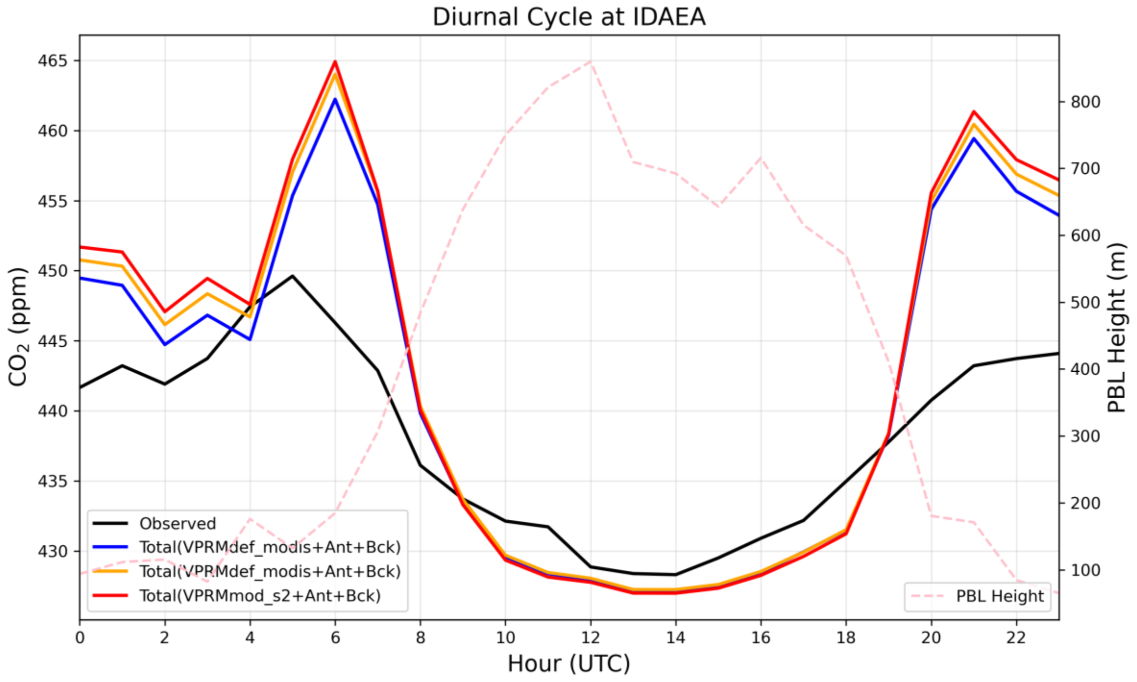
Total Concentrations in April







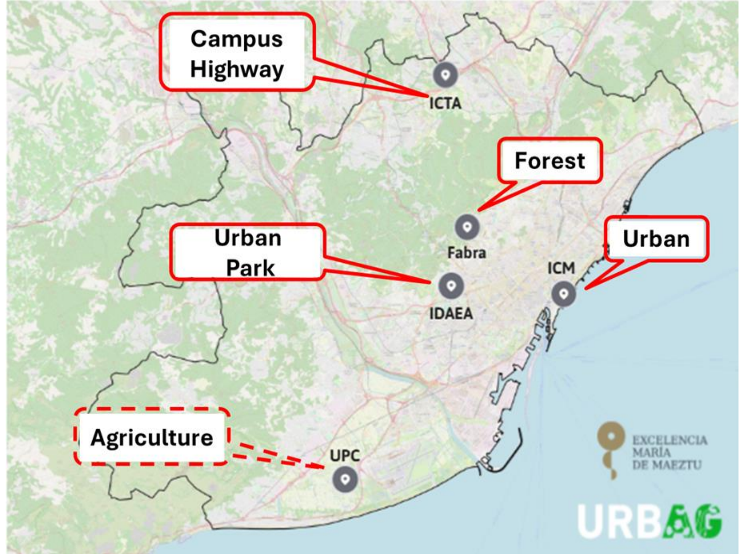




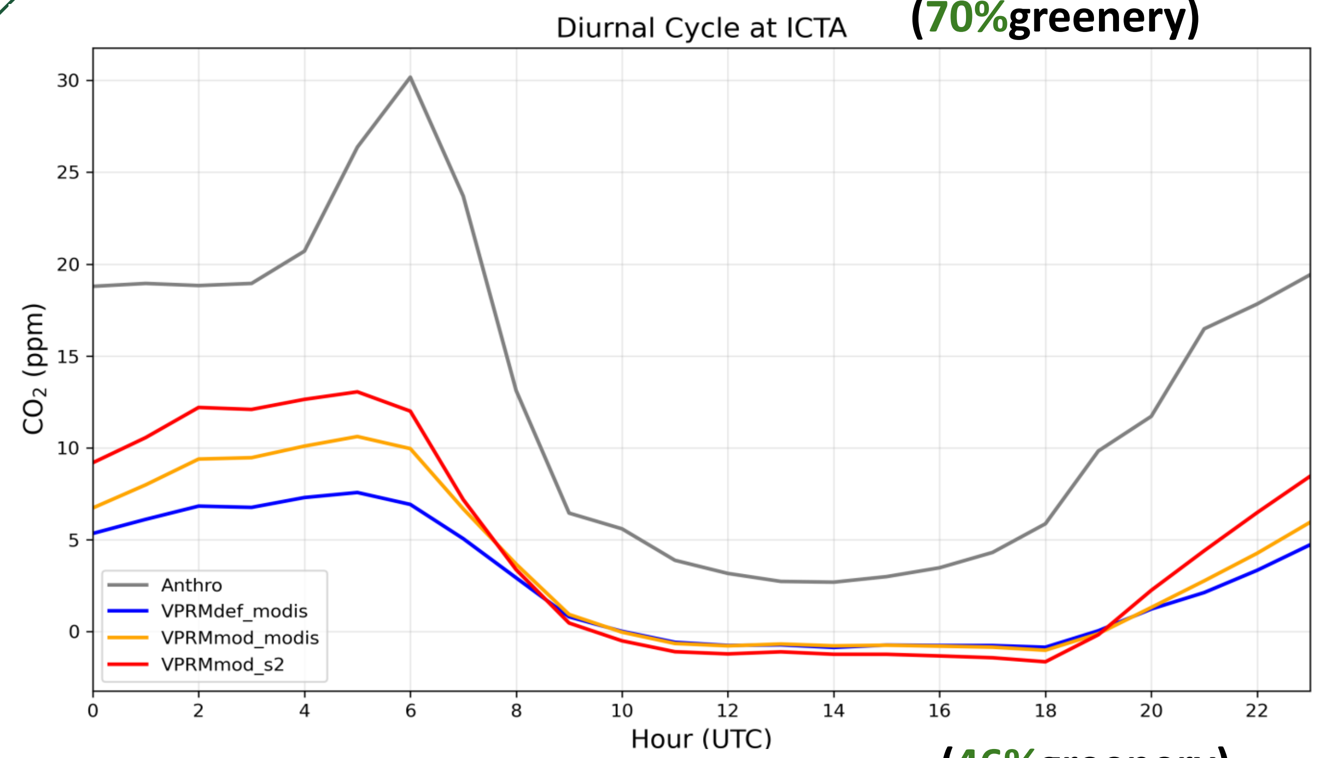
- WRF-Chem well captures the observed diurnal variability of atmospheric CO_2
- Discrepancies occur during nighttime stable conditions and shallow PBL period.
- Differences among VPRM configurations remain relatively small (few ppm)

Results

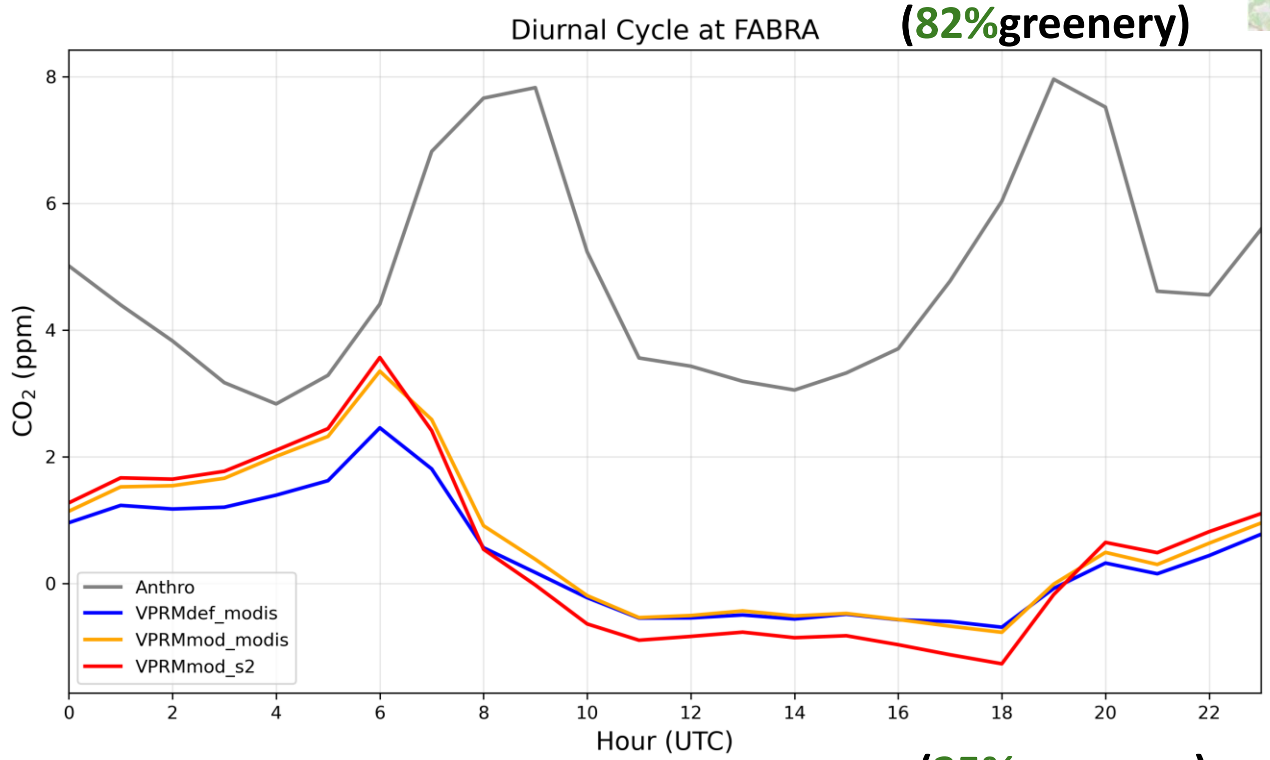
CO2 contributions



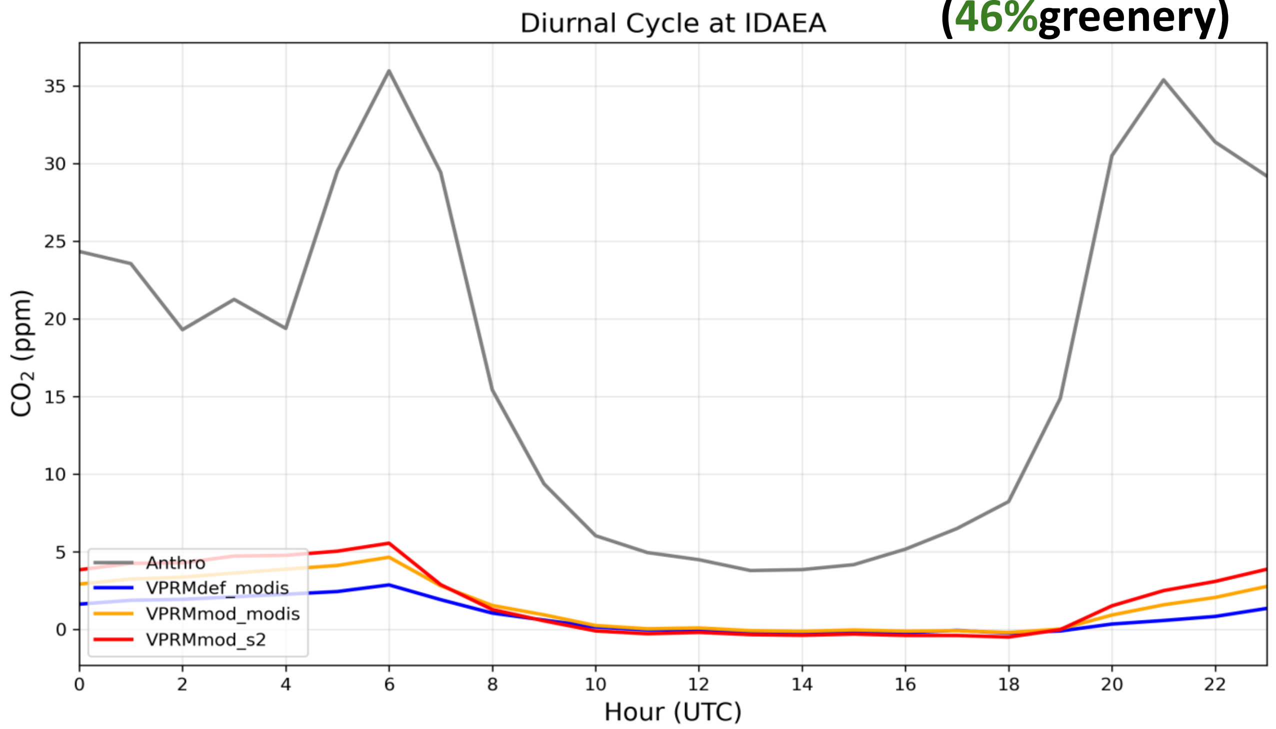
(70%greenery)



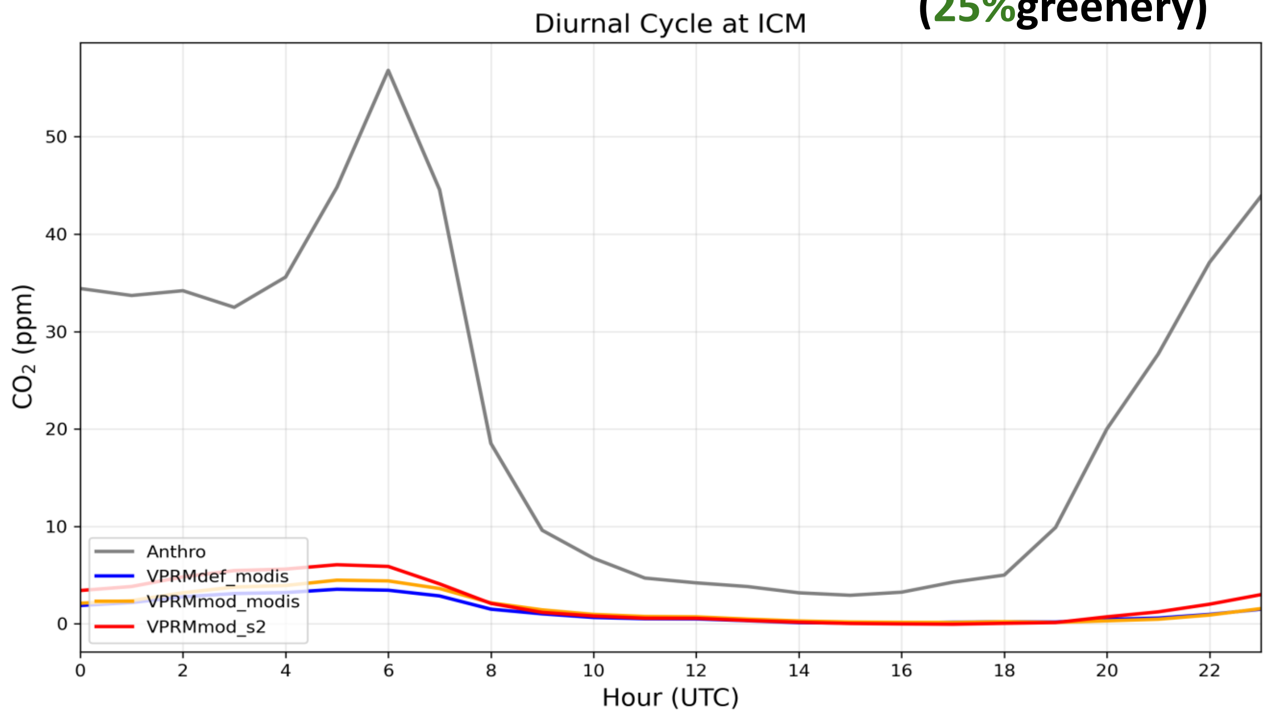
(82%greenery)



(46%greenery)



(25%greenery)



- Anthropogenic emissions dominate urban CO_2 variability at all stations
- Respiration during the night makes positive concentrations
- Differences among VPRM configurations are modest compared to anthropogenic signals.
- Constraining biogenic fluxes using concentration data and WRF-Chem is limited

Part 4

Conclusions

To understand the role of urban green spaces on urban carbon budget(sink or source?), we need a high-resolution estimate of biogenic CO_2 fluxes

1) Can we improve the resolution of biogenic CO_2 fluxes estimation?

- Default VPRM normally combined with MODIS satellite data (500m)
- Incorporate high-resolution satellite data sentinel2 data (10m) to VPRM

->Biogenic CO_2 fluxes estimation at 10m in the Metropolitan Area of Barcelona (AMB)

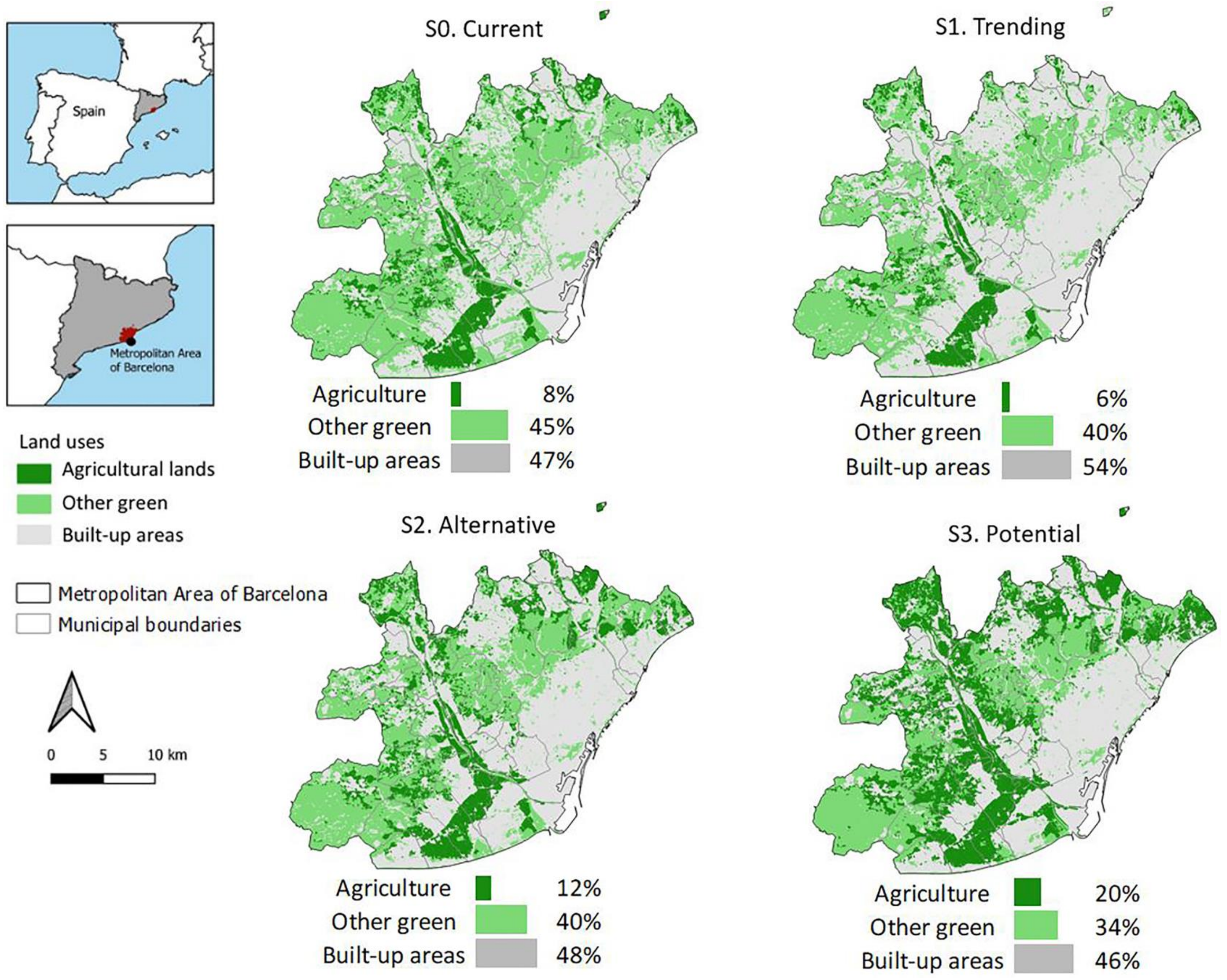
2) To what extent does the improved resolution and parameterization enhance our ability to identify urban biogenic CO_2 Fluxes?

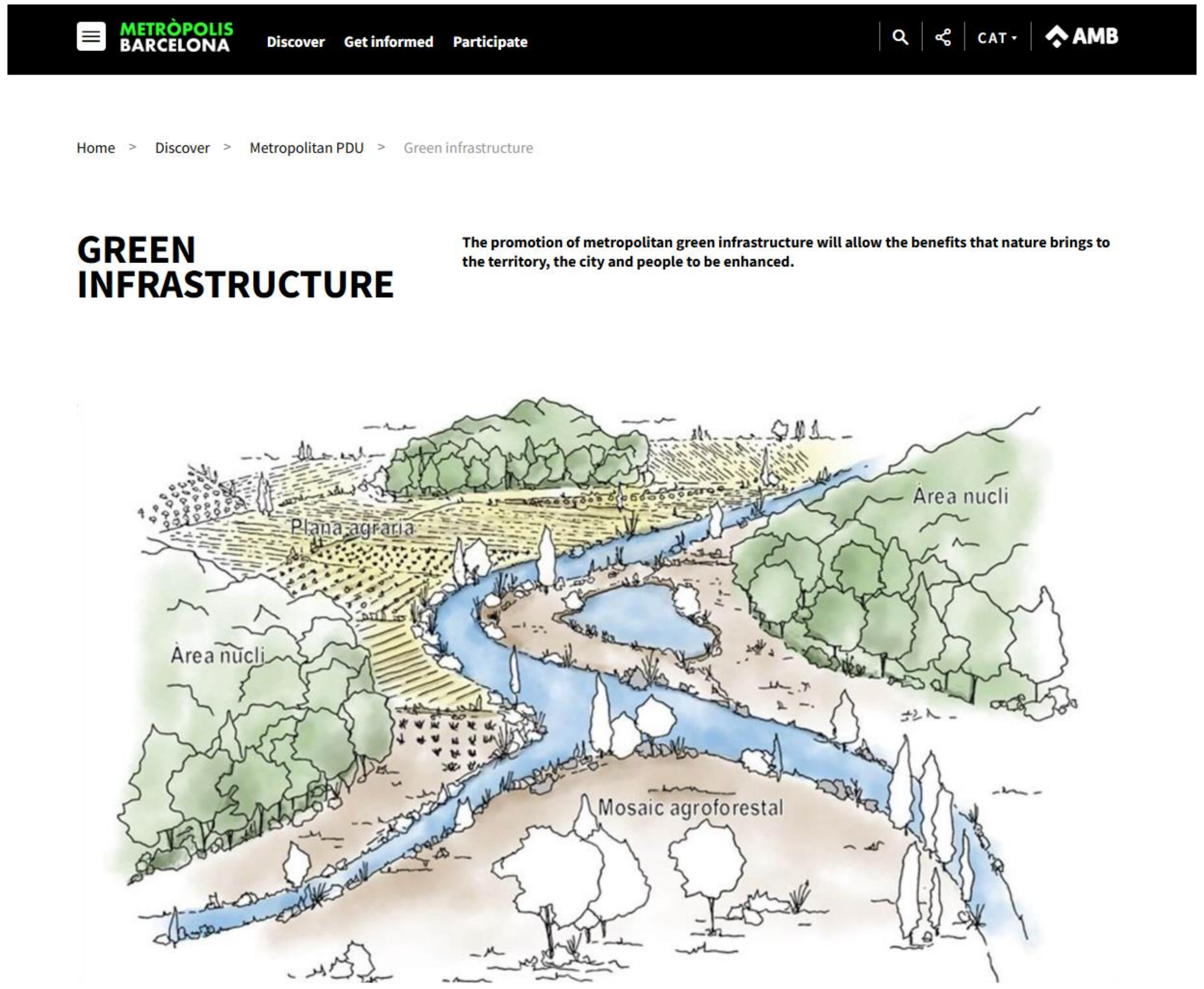
- Different VPRM configurations   2 satellite data input / add soil moisture
- Estimated biogenic fluxes are constrained with atmospheric CO_2 observations using WRF-Chem

WRF-Chem well captures the observed diurnal variability of atmospheric CO_2
Anthropogenic emissions dominate urban CO_2 variability at all stations, Differences among VPRM configurations are modest compared to anthropogenic signals
Emissions measurements should be deployed

Discussion

Effect of land use change on spatial changes in CO_2 levels





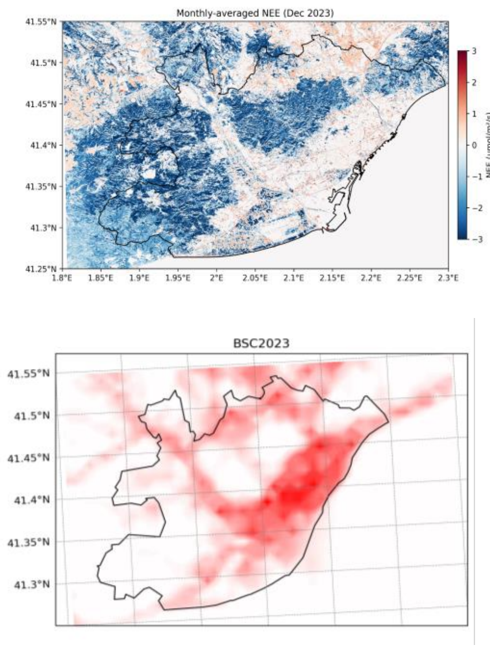
The metropolitan PDU establishes the regulatory framework and guidelines for metropolitan urban planning for 2050 with the aim of enhancing the natural values of the metropolitan territory, improving our cities and promoting active and sustainable mobility.

Discussion

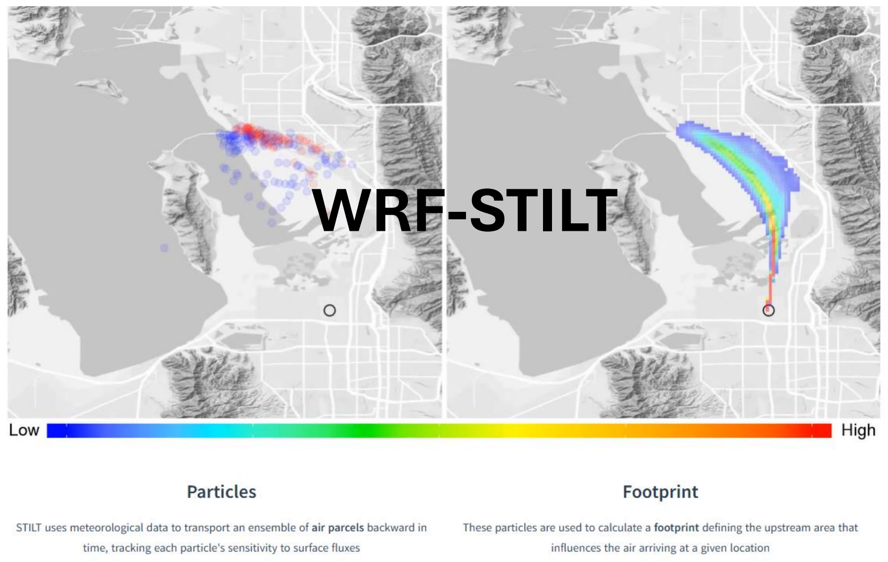
Bayesian Inverse Modeling Framework

The Bayesian inverse modeling framework was developed to derive optimized posterior CO_2 emission estimates over AMB

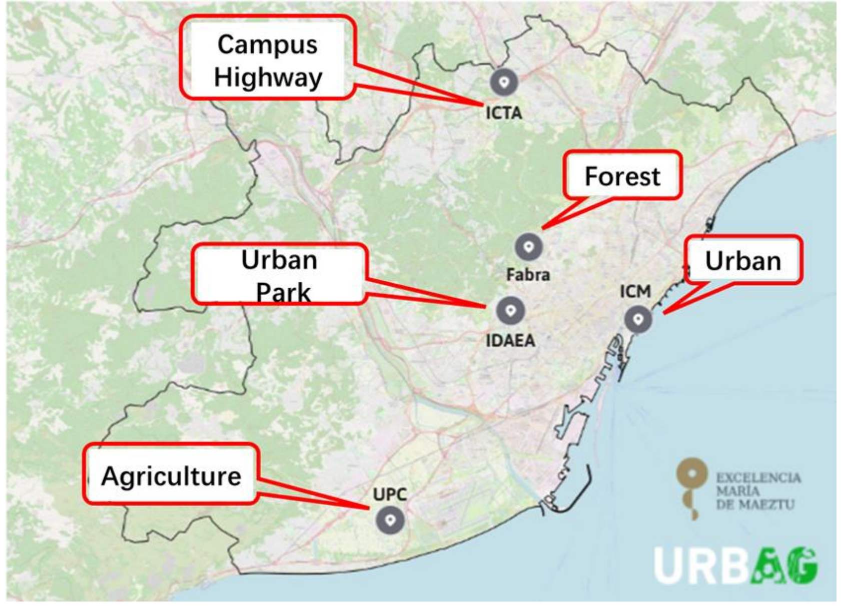
Prior Flux



Footprint



Observations



Posterior Fluxes $\boxed{\hat{s}} = s_p + (HQ)^T (HQH^T + R)^{-1} (z - Hs_p)$

[Prior emission error covariance (Q)]

[Observation error covariance(R)]

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ICTA-UAB Institute of Environmental Science and Technology

EXCELENCIA MARÍA DE MAEZTU

UAB Universitat Autònoma de Barcelona

Thank you!

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