A *Carbon Data Model framework* to generate probabilistic estimates of ecosystem traits and processes

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Digital Twins for the Terrestrial Carbon Cycle
ESA Carbon from Space Workshop

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

What is a digital twin and why is it useful?

A computer program

that takes as inputs

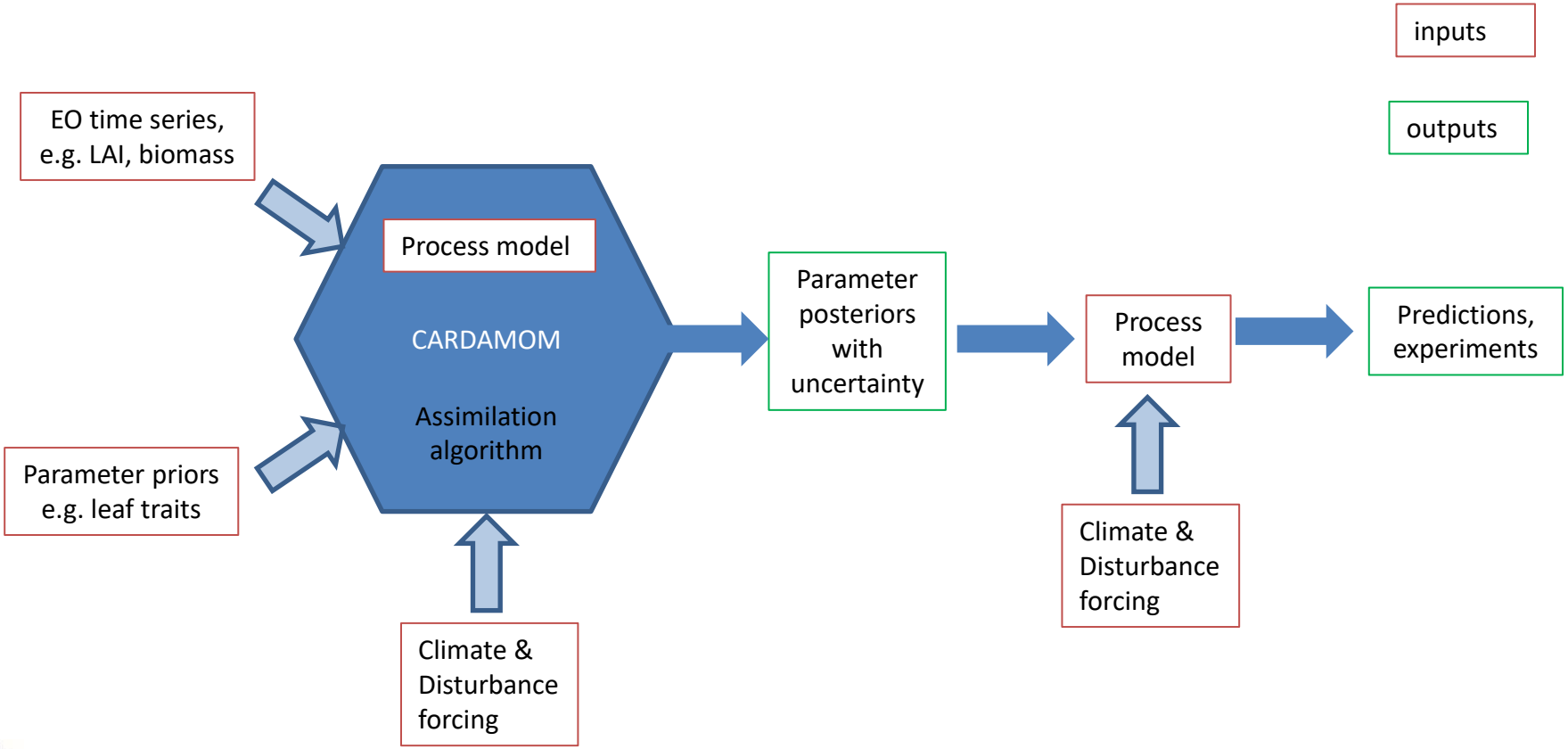
->real-world data about a physical system

and produces as outputs

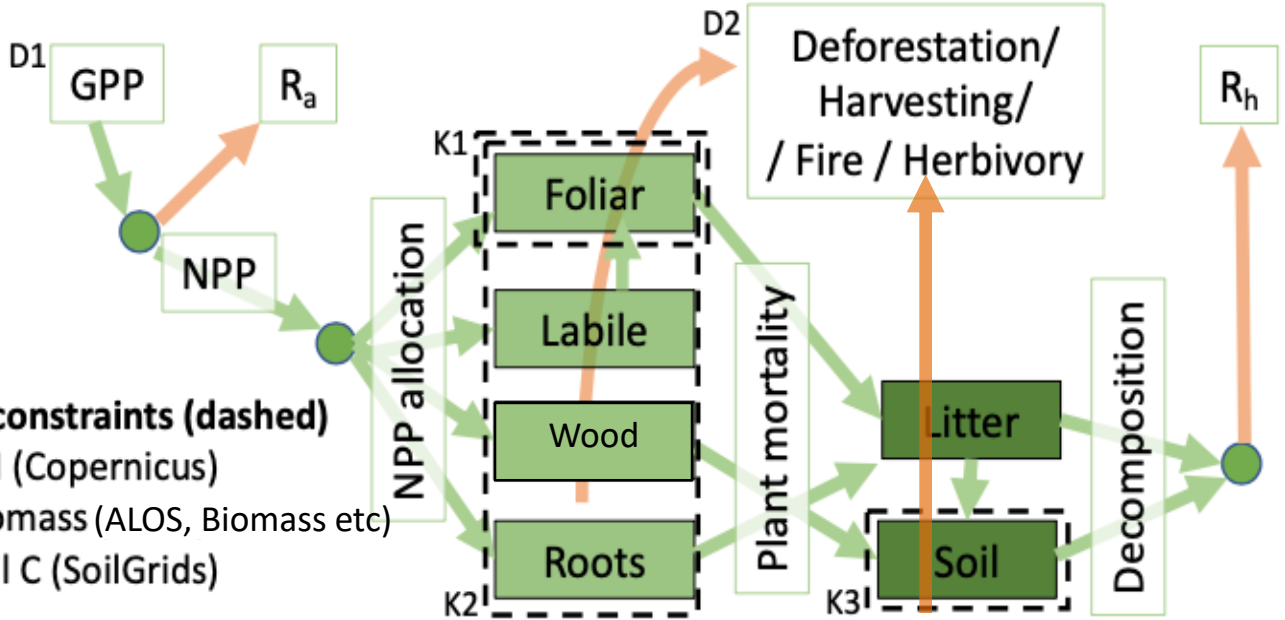
->predictions or simulations of how that physical system will be affected by those inputs

DT can inform global C models, identify sources of forecast error, quantify the information content of EO data, & directly link land use data to C assessments

A C Digital Twin Approach



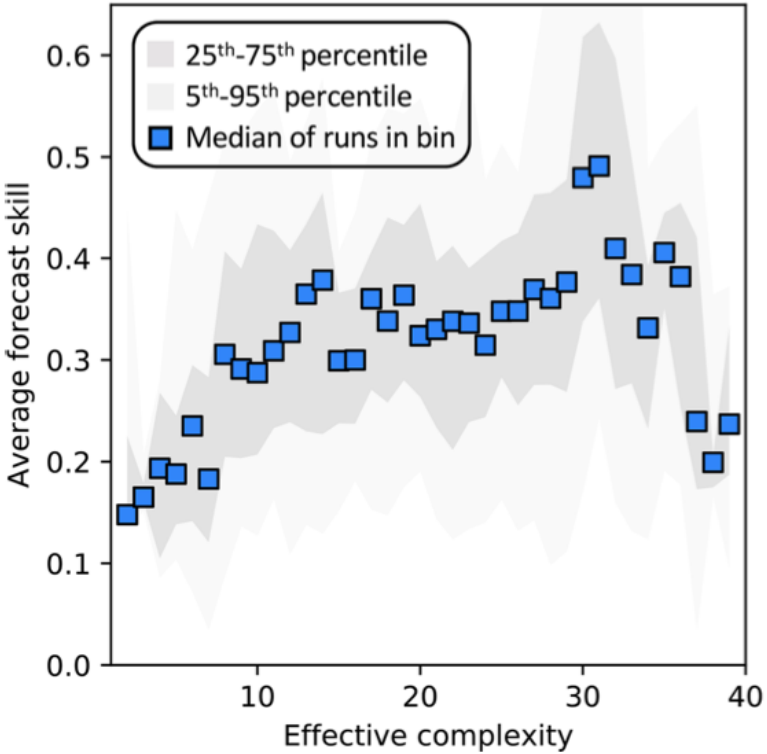
Global calibration via EO data links

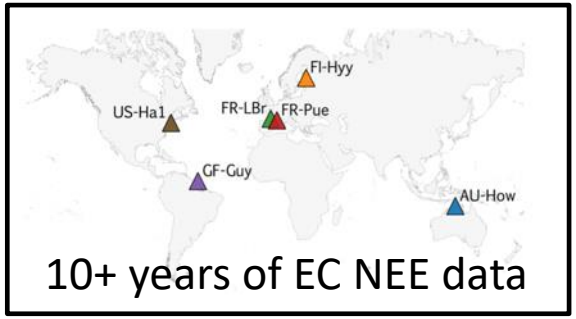


Data constraints (dashed)
K1 LAI (Copernicus)
K2 Biomass (ALOS, Biomass etc)
K3 Soil C (SoilGrids)

Model drivers
D1 Meteorology (various)
D2 Deforestation, tree harvesting (GFW) Fire (MODIS), Herbivory (FAO/Hempson et al)

Complexity ≠ forecasting skill





10+ years of EC NEE data

Famiglietti et al 2021

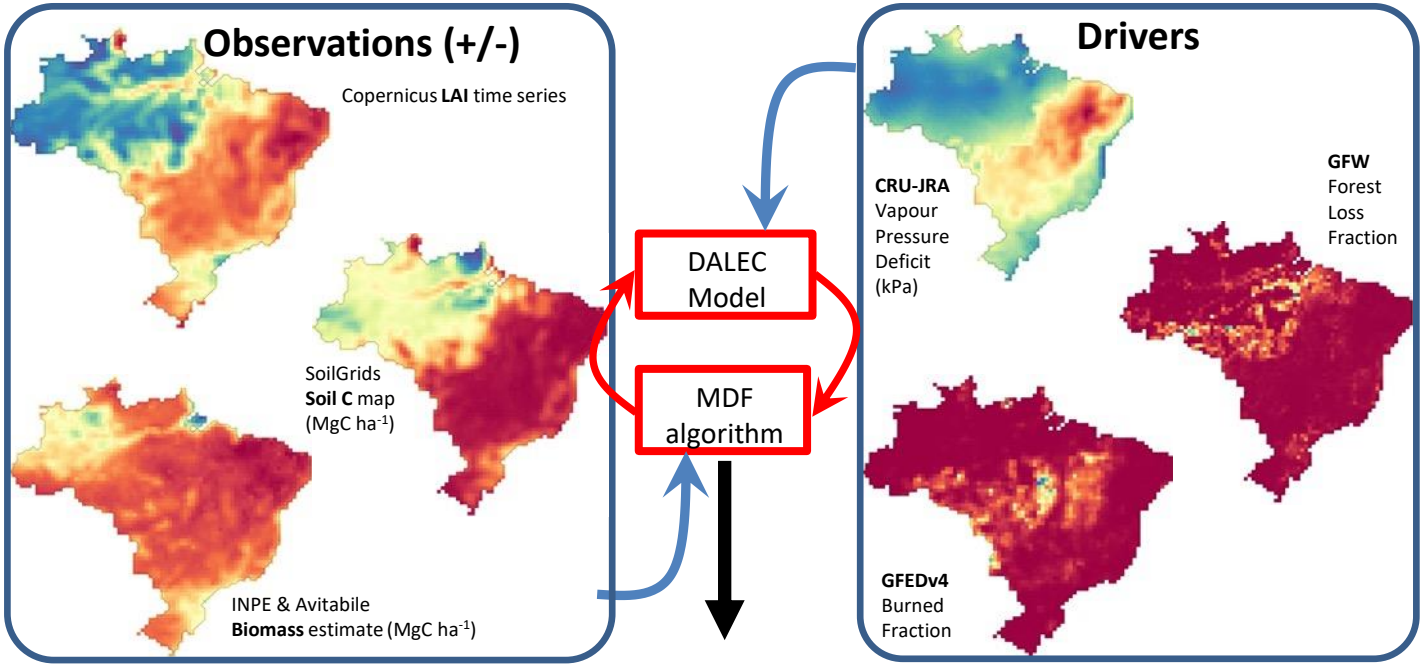
50% of EC NEE data retained for forecast validation

DT: importance of model structure, parameter constraint, forcing effects on forecasts

Model	Photosynthesis	Water cycle	Plant respiration	Wood litter	No. of parameters
M1	ACM1	No	R_a : GPP	No	23
M2	ACM2	No	R_a : GPP	No	23
M3	ACM2	Yes	R_a : GPP	No	23
M4	ACM2	Yes	R_m : GPP + R_g : NPP	No	27
M5	ACM2	Yes	R_m : GPP + R_g : NPP	Yes	29

Smallman et al. 2021

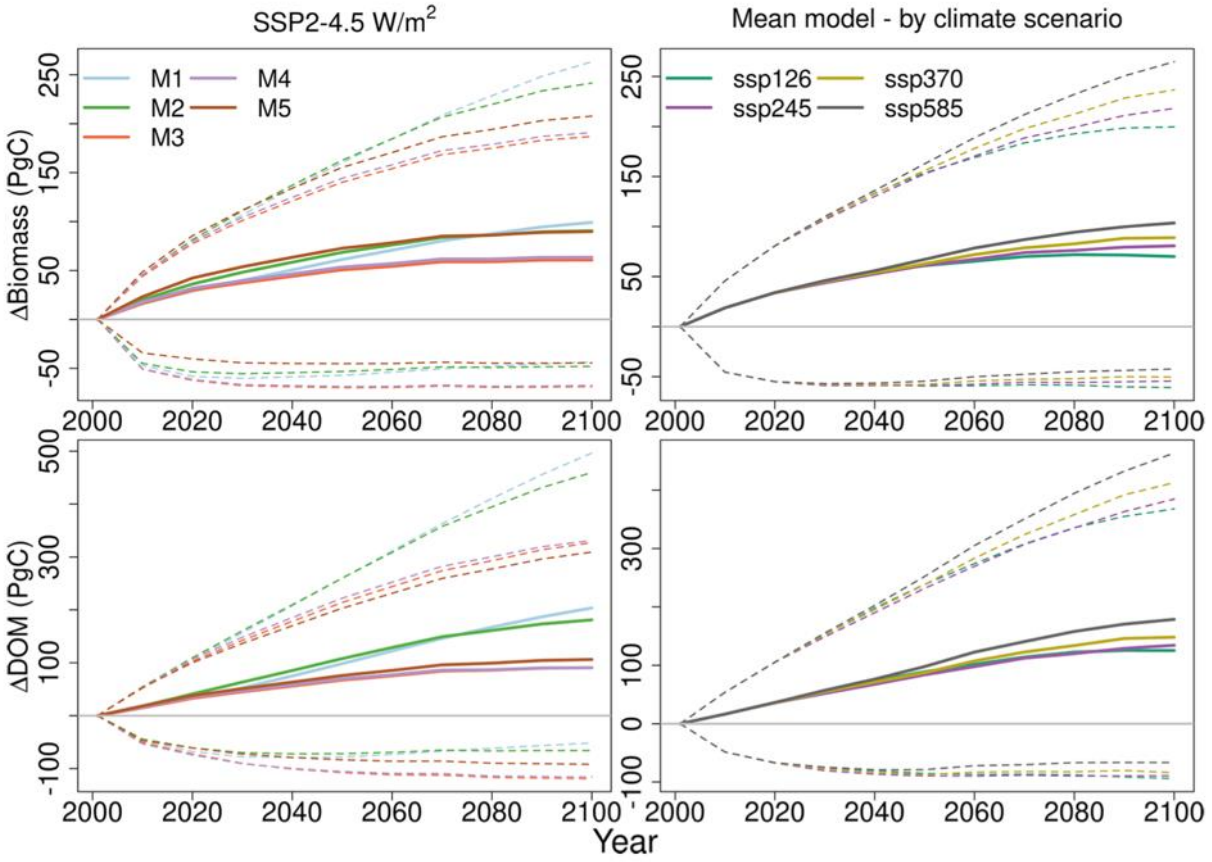
CARDAMOM Assimilation Scheme



Output: Probabilistic estimates of parameters, C pools and fluxes for each pixel

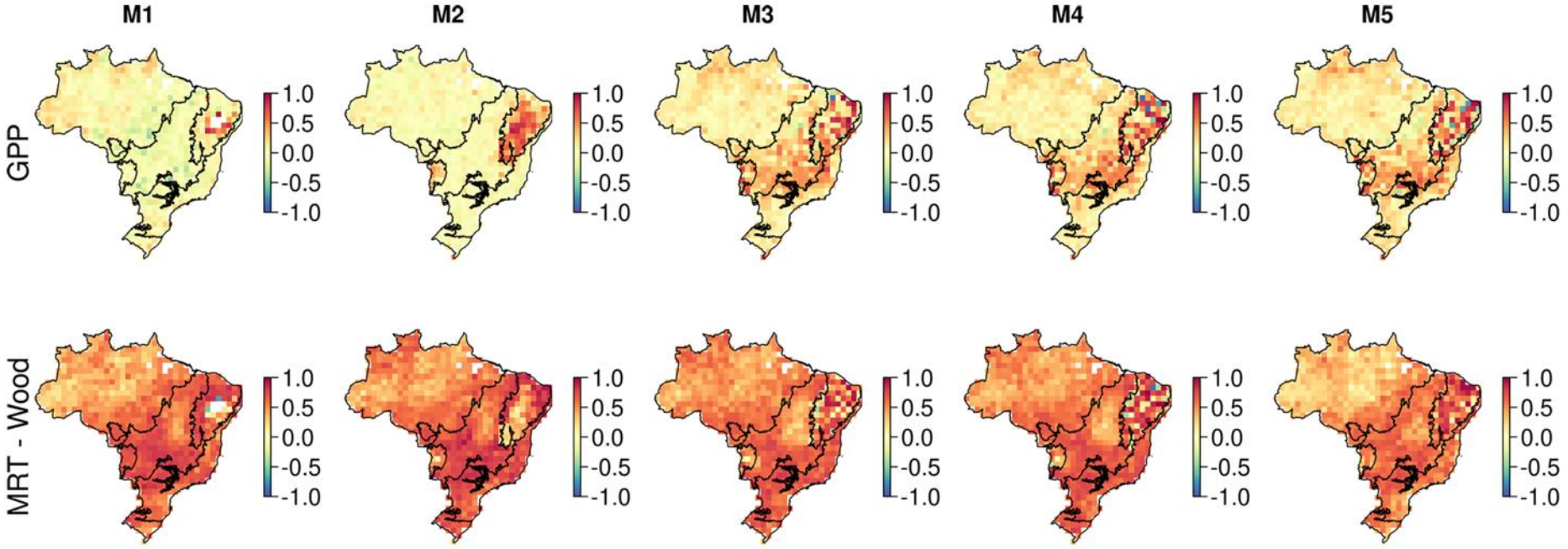
Forecast: C pools & fluxes to 2100 under varied scenarios

Parameter uncertainty dominates forecast spread

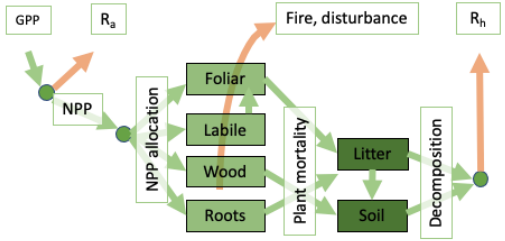


Smallman et al. 2021

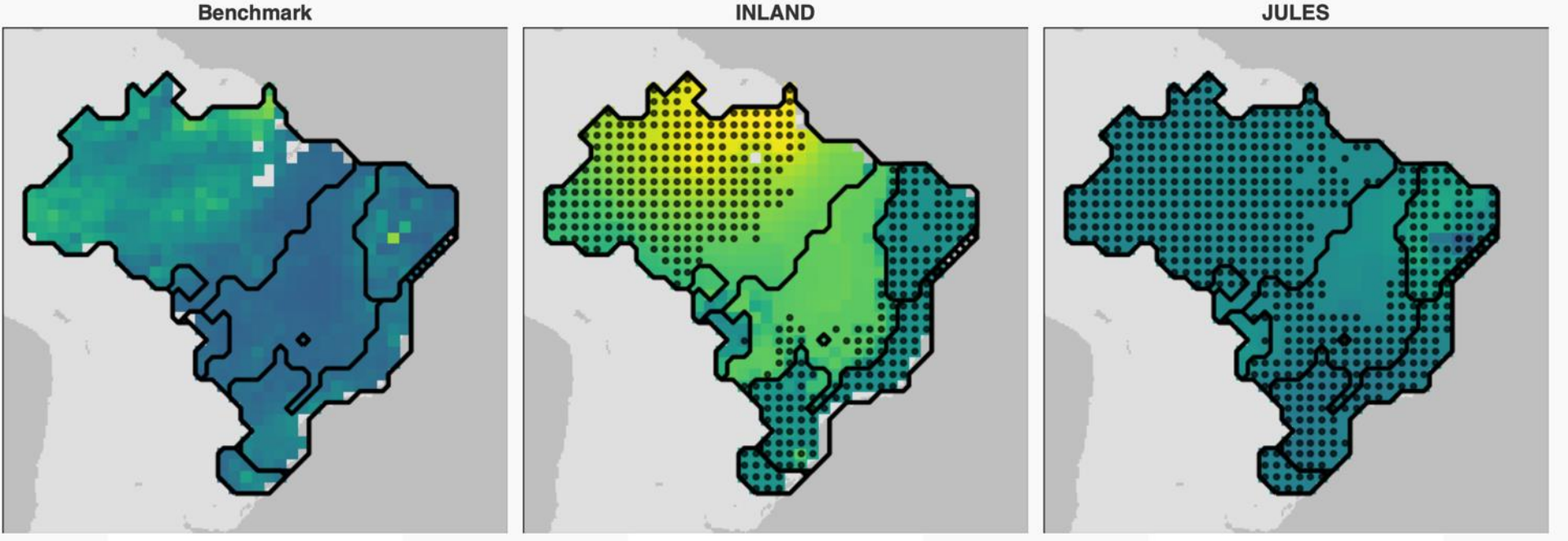
Correlation maps between the simulated change in biomass stocks (2001–2100) and ecosystem variables



(1) MRT_{wood} and (2) NPP_{wood} are the parameters most tightly coupled to the response of biomass C stocks to climate change



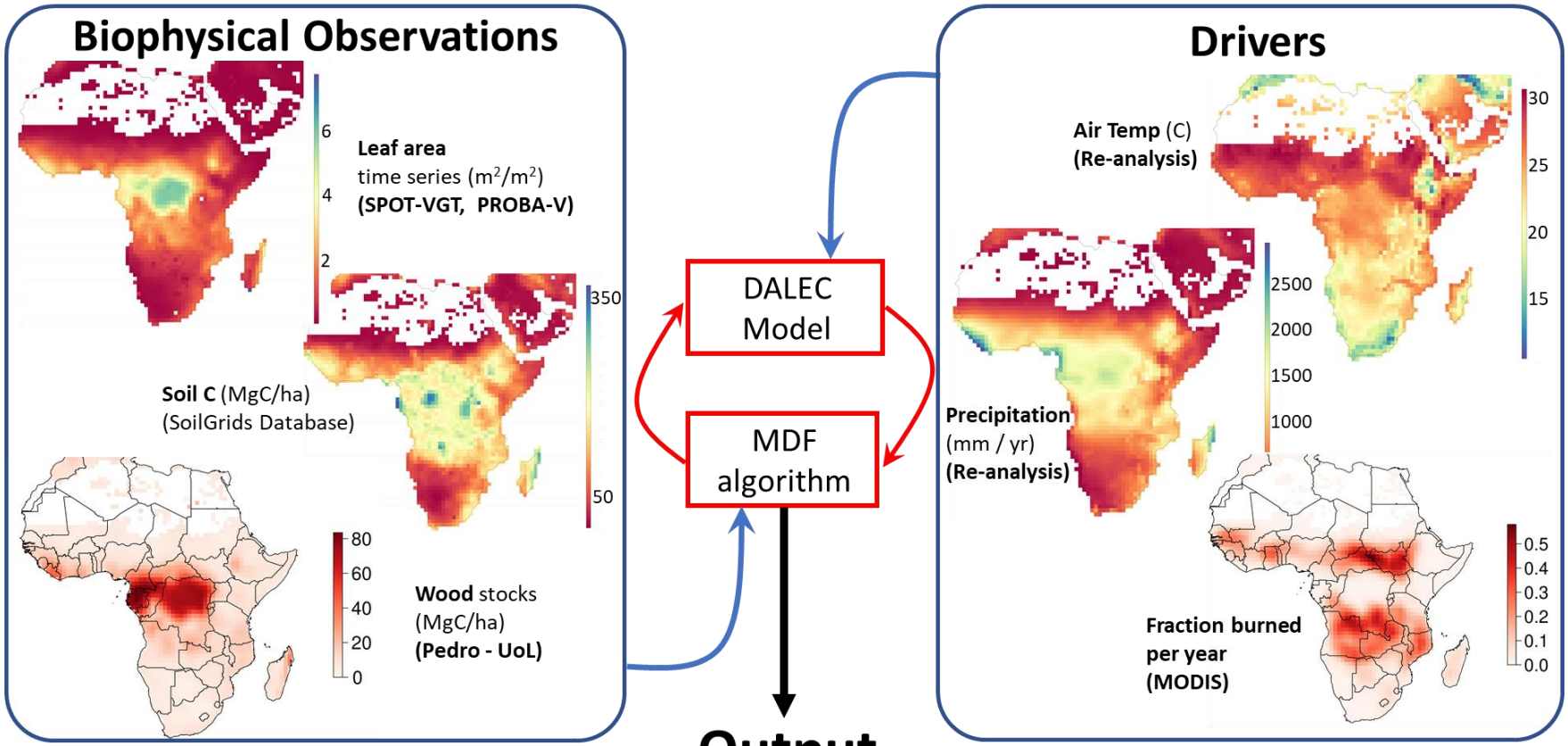
Contemporary wood residence time: CARDAMOM vs two Forecast Models



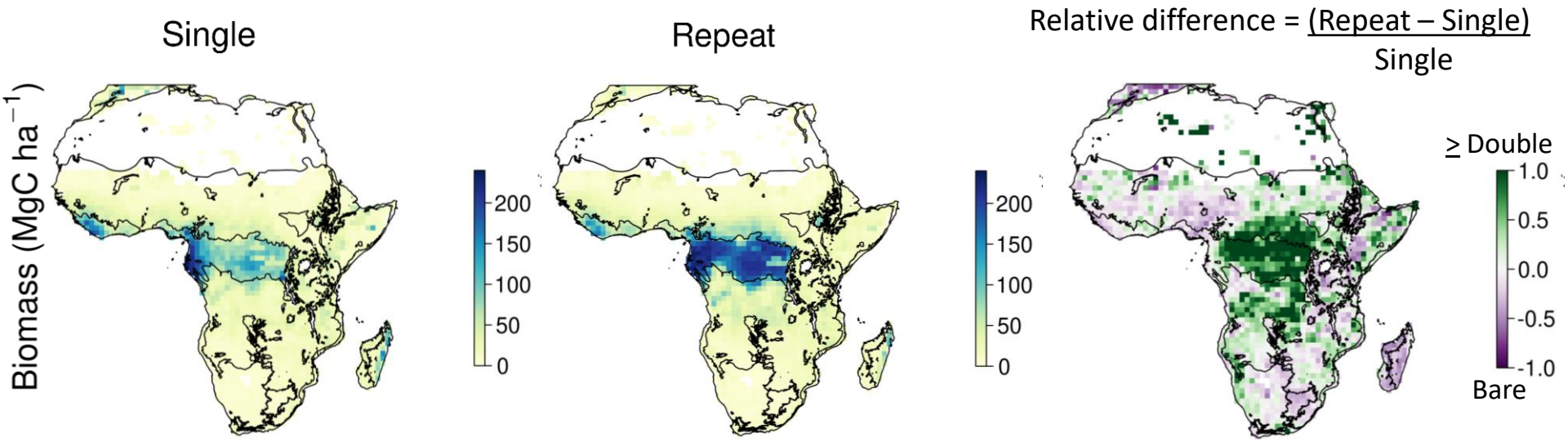
Caen et al. 2021

Stipples show LSM is within 90% CI

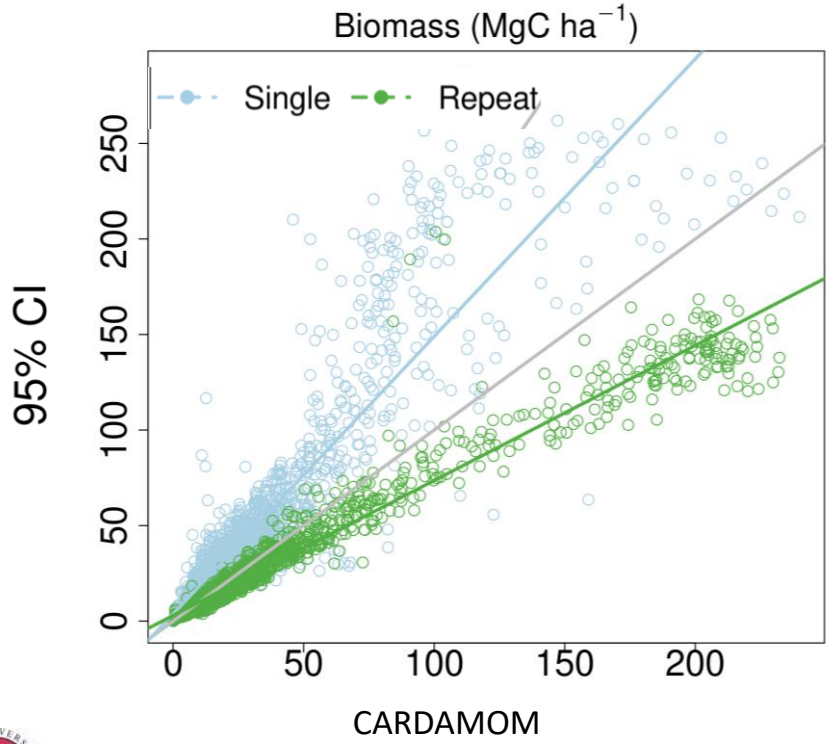
DT to evaluate information content of EO



Estimated biomass is strongly impacted

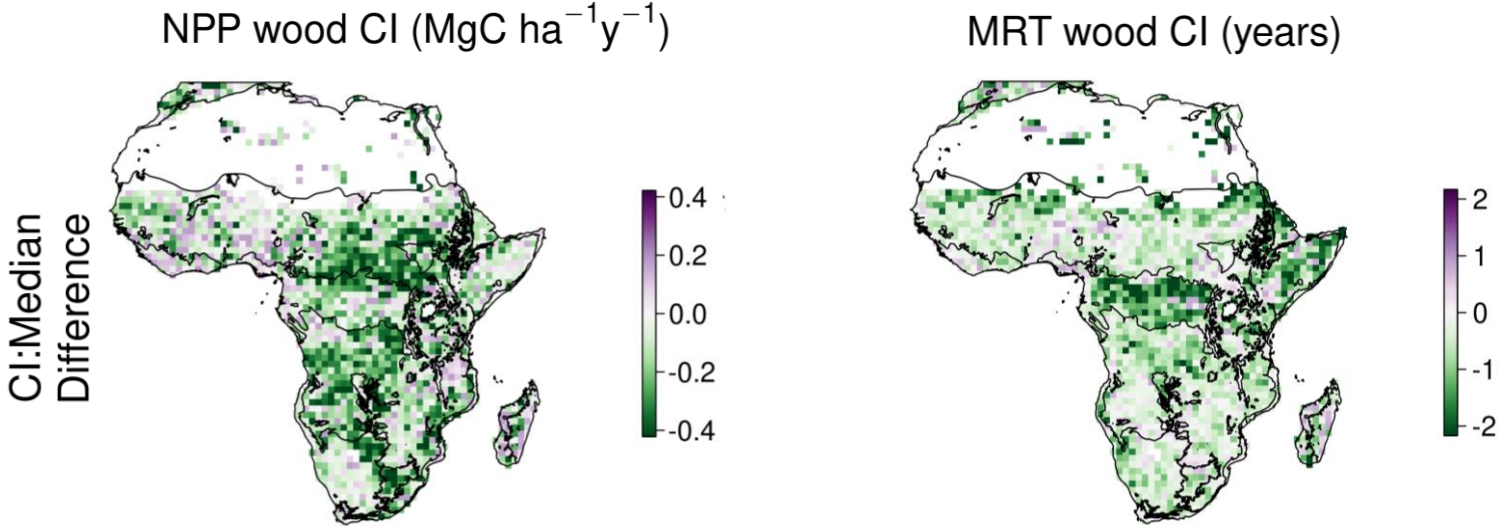


Biomass uncertainty reduced



$$\text{CI:Median} = \frac{\text{CI}}{\text{Median}}$$

Process constraint:
Residence time and NPP uncertainty reduced



$$\text{CI:Median} = \frac{\text{CI}}{\text{Median}}$$

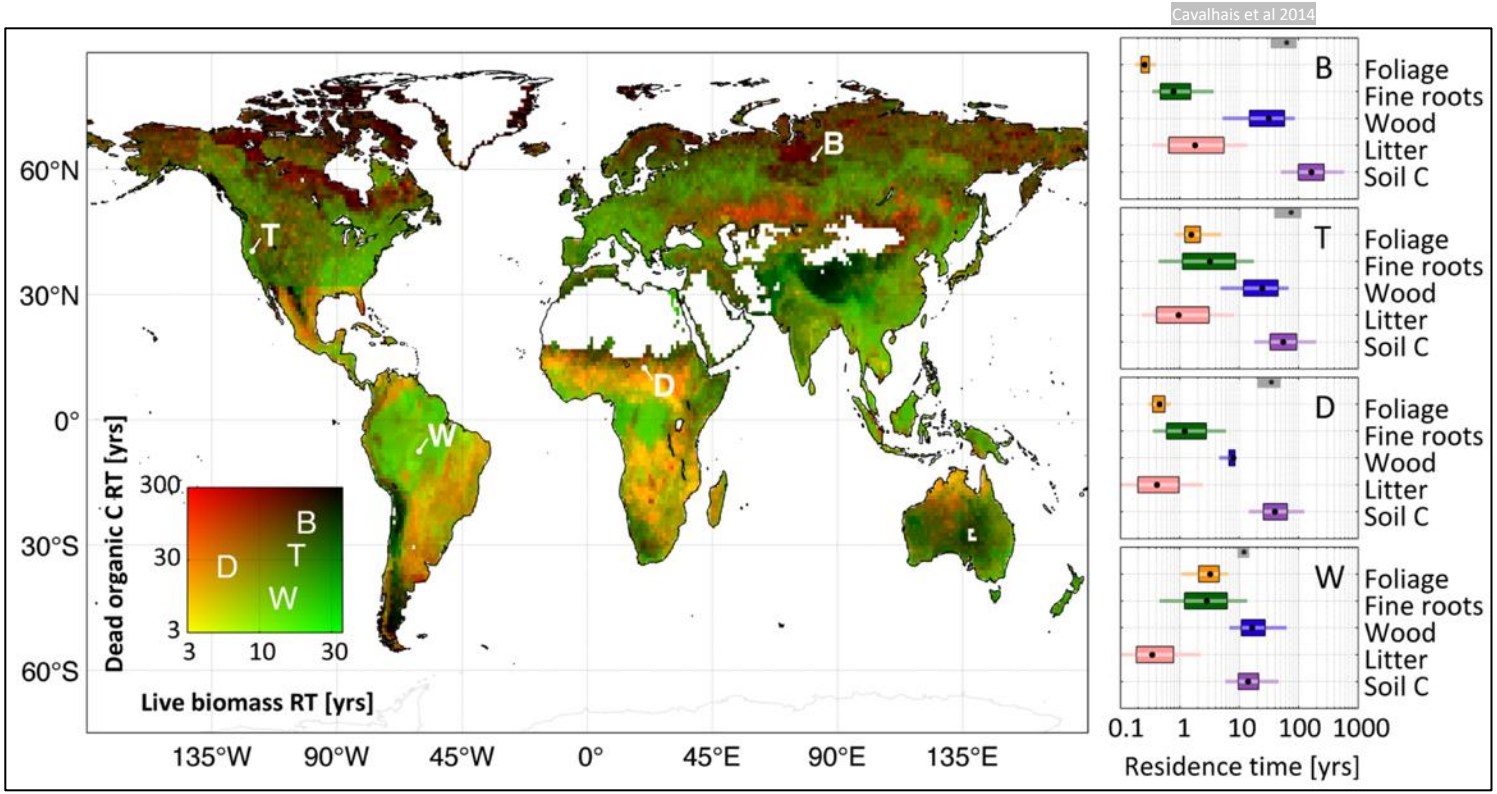
Summary – Digital Twins can

- Identify sources of forecast error, *e.g. from drivers, parameters, structures to focus next steps*
- Inform global C models, *e.g. evaluate process representation, like mean residence times*
- Quantify the information content of EO data, *e.g. determine the value of repeat observations for process constraint*
- Support net zero counter-factuals via probabilistic model experiments; e.g. alternate land use, management (ref: land use talk from Wednesday)

Acknowledgements:
Luke Smallman, Jeff Exbrayat, Anthony Bloom, David Milodowski, Pedro Rodriguez Viega, Caroline Famiglietta, Alex Konings
CARDAMOM Club, INPE, GEDI, ALOS
JULES and INLAND team

Funding: NERC, NCEO, Newton Fund, UKSA

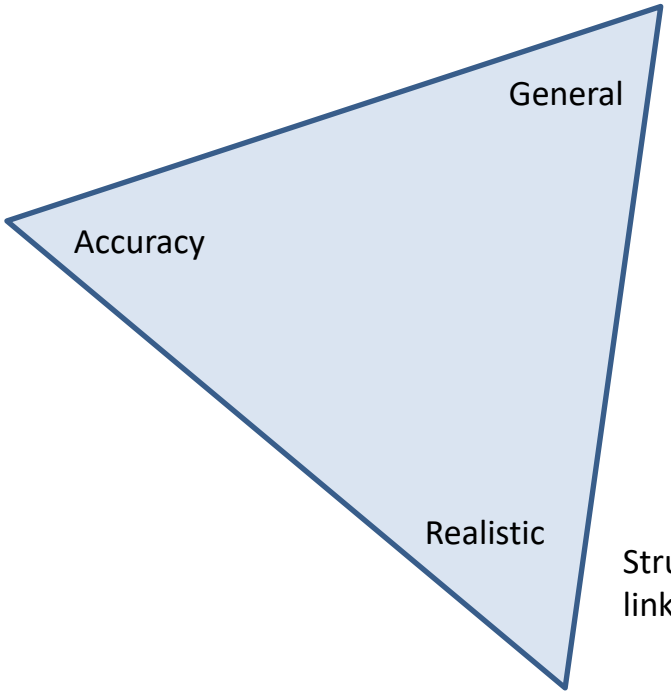
Global retrievals of carbon residence times



Residence time ~ Pool lifespan

Bloom et al., PNAS 2016

Model Trade-offs



Lean requirements
for local-global application

Calibrated
Avoid over-fitting
Validated
Uncertainties

Structure represents key processes,
linked to model complexity

Accurate and general models suffice