Advancing the representation of land-based mitigation in Earth system models

Anna Harper

NCAR Land Model Working Group annual meeting

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Lots of input and effort from: Arthur Argles, Emma Littleton, Hsi-Kai Chou, Evan Baker, Peter Cox, Andy Wiltshire, Eddy Robertson, Danny Williamson, Deyu Ming, Carolina Duran-Rojas, Ian Bateman, James Morison, Kate Beauchamp

Overview

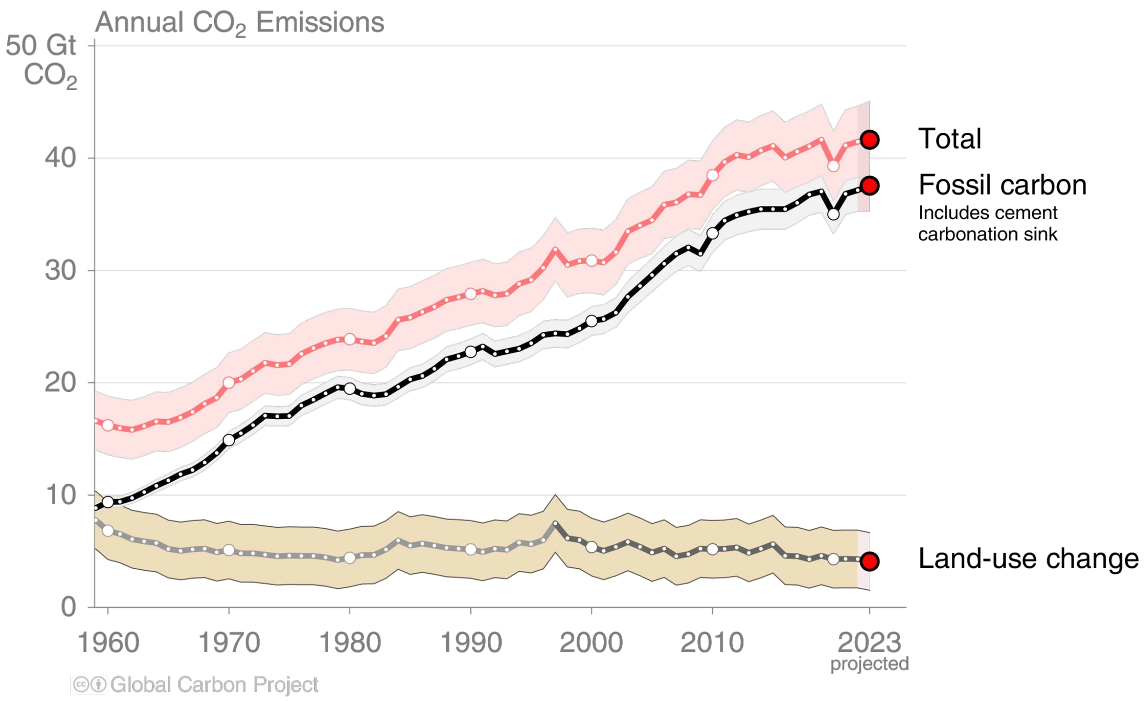
- The case for including land management in Earth System Models
- Wish list of processes and impacts
- What we've done in JULES to represent:
  - Bioenergy crops
  - Managed forests
- Concluding thoughts

Large role of land use change and managed land in global carbon cycle

CO2 Sources (2013-2022)

88%

12%



Source: Friedlingstein et al. 2023; Global Carbon Project 2023

Large role of land use change and managed land in global carbon cycle

CO2 Sources (2013-2022)

88%

12%

CO2 Sinks (2013-2022)

47%

31%

About 2/3 of land is managed!

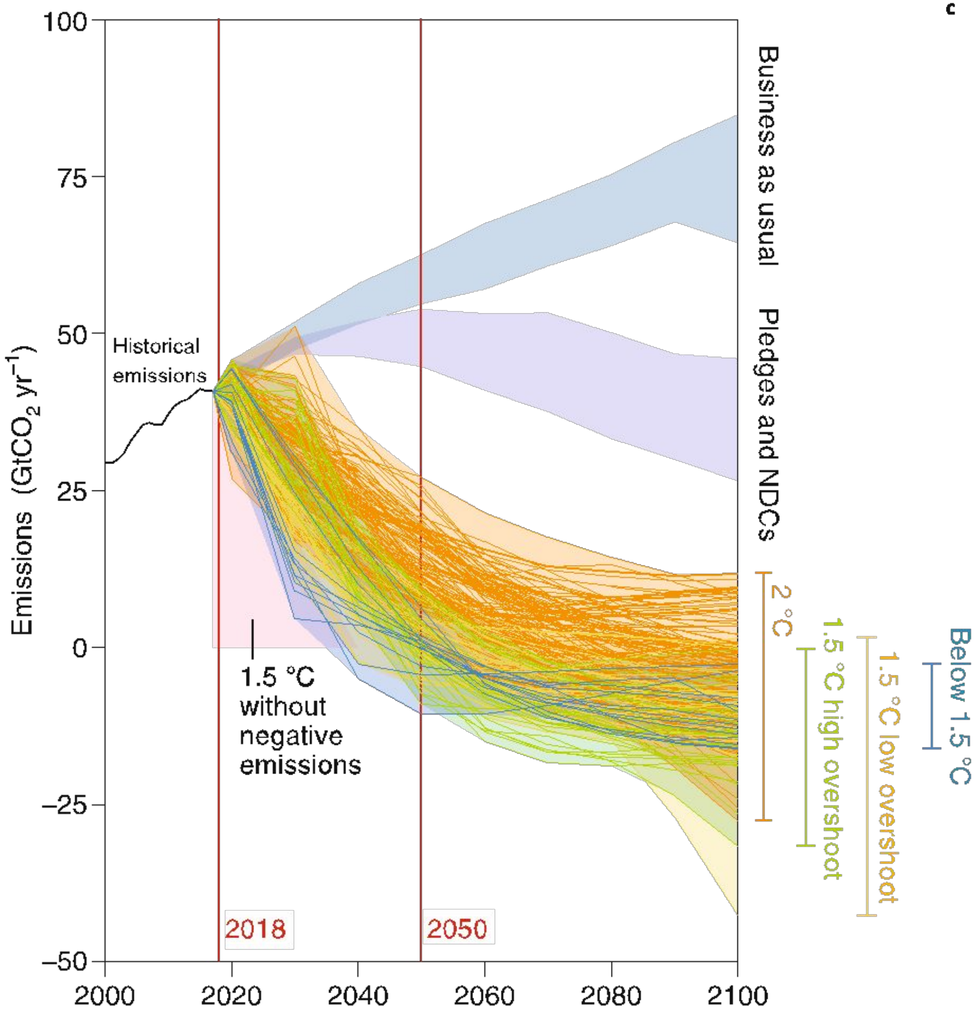
26%

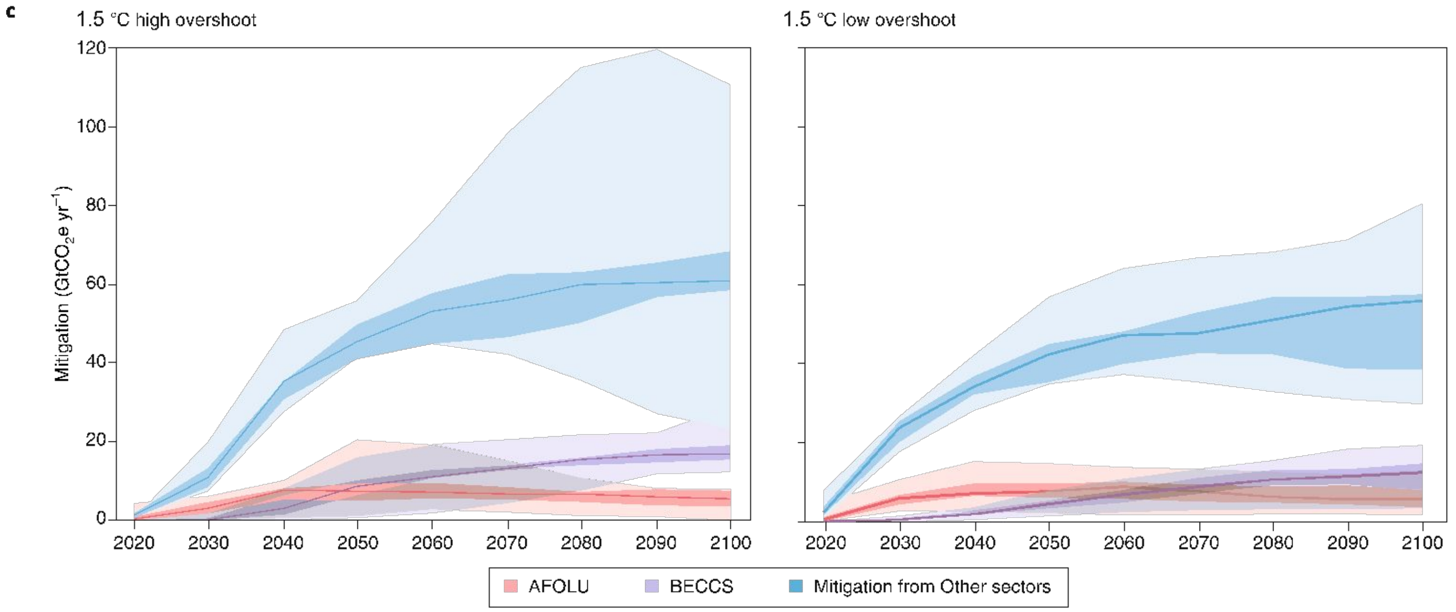
Budget Imbalance: 4%

(the difference between estimated sources & sinks)

Source: Friedlingstein et al. 2023; Global Carbon Project 2023

Large role of land carbon sinks in global climate mitigation pathways

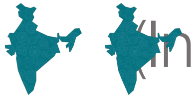




25% of emissions cuts by 2050 come from the land sector

Roe et al. 2019

Large role of land carbon sinks in global climate mitigation pathways

- Negative emissions from land use and BECCS are assumed in majority of CMIP scenarios.
- Median land requirement for bioenergy to remain below 2°C =  (India x 2)
- Afforestation + reforestation minimum land requirement = 

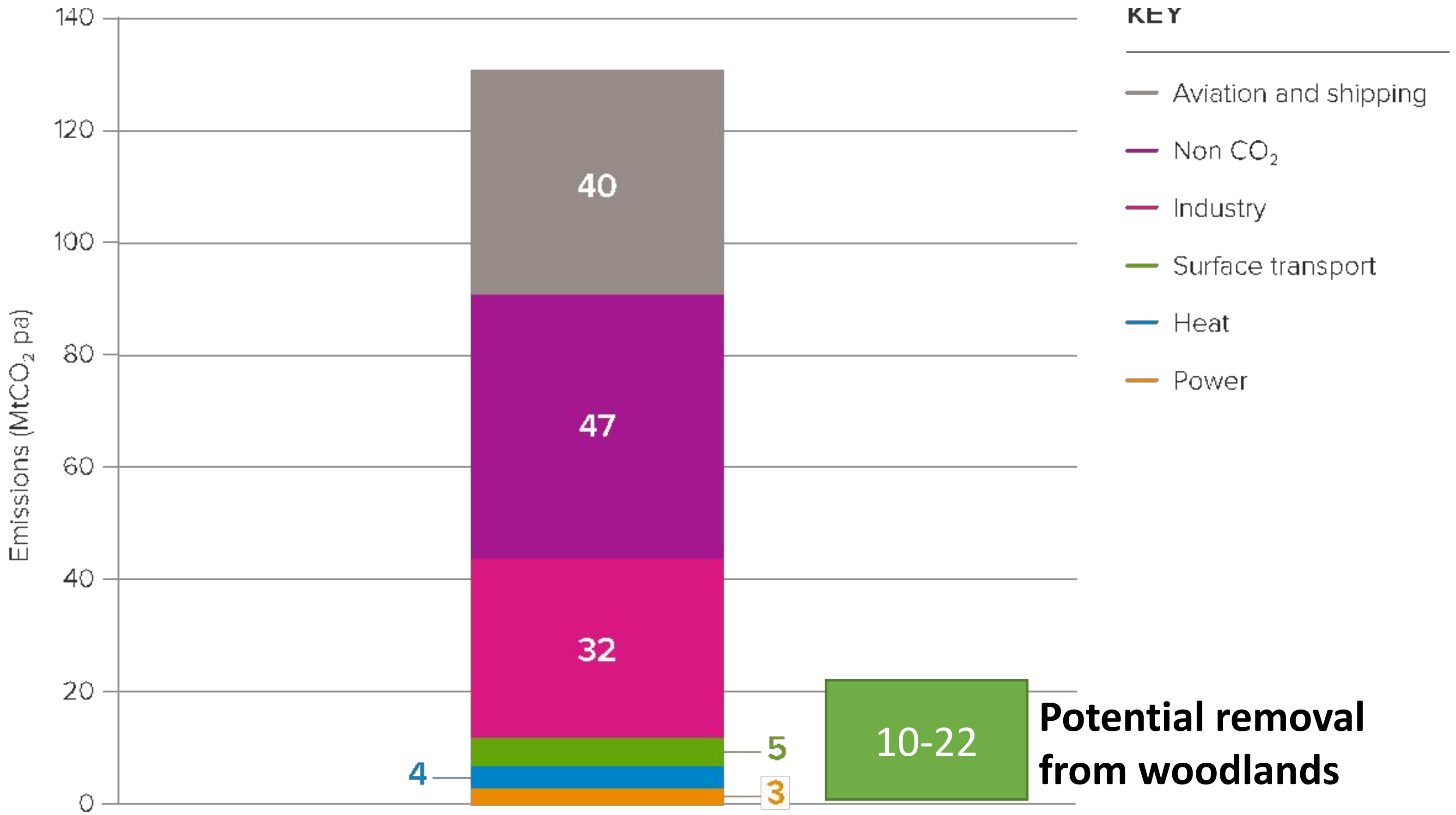
How would these land use changes impact ecosystems and the climate? Would they be effective at removing the CO_2 assumed in the IAM simulations?

Fuss et al. 2014, Smith et al. 2016, Wiltshire and Davies-Barnard, 2015.

Large role of land carbon sinks in **national** climate mitigation pathways

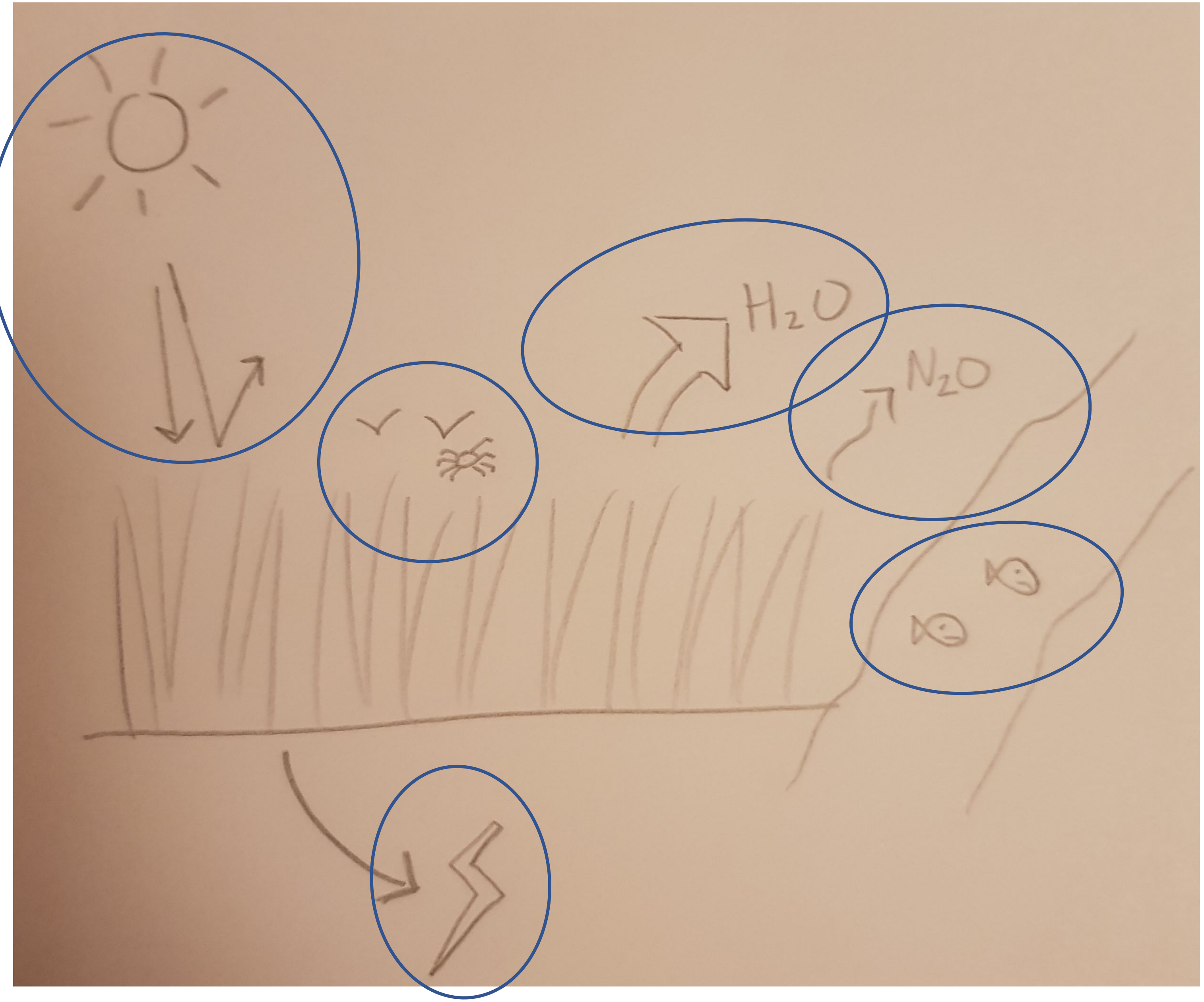
UK climate action following the Paris Agreement

Residual GGR emissions in 2050 with maximum reductions to emissions in all sectors



Royal Soc. and Royal Acad. of Engineering report on GGR, 2018

Earth system impacts of bioenergy crops



- High evapotranspiration and long growing season reduces water resources.
  - Especially if crops are irrigated
- Degrade water quality if fertilizer applied
- Fertilizer also N_2O emissions
- Lower albedo than food crops (warming effect, uncertain)
- Biodiversity effects depend on previous land use
- Can lead to long-term C storage and energy production

Earth system impacts of new forests

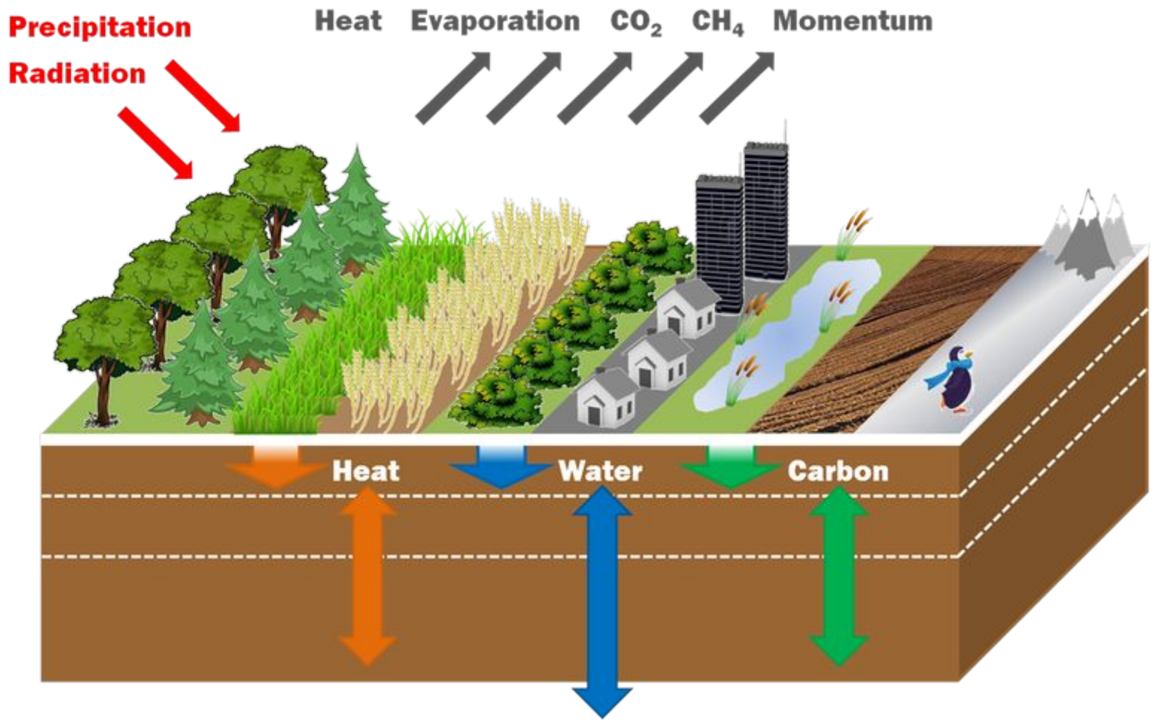
- High ET reduces water resources
- Improve water quality
- Lower albedo than crops (warming effect)
  - Overall cooling in Tropics
  - Overall warming in mid- to high-latitudes
- Mixed forests increase biodiversity and resilience
- Sustainable harvesting can increase C sink

JULES is the land surface in the UK climate model

Seller et al. 2019: JAMES

Given a set of inputs, JULES:

- Simulates the processes that control carbon uptake and storage on land.
- Predicts hydrology and energy exchange with the atmosphere.
- Predicts what kind of vegetation grows where.
- Represents all Earth's plants in 9 "plant functional types" (PFTs)



Cox et al. 2002; Harper et al. 2018b, Geosci Mod Dev

Earth system impacts: A wish list

Our models need to include:

- Carbon sequestration in ecosystems (plant and soil C)
- Surface ener
- Bioenergy cr
- Forest growt
- Managemen harvesting)
- Growing season of crops
- Albedo differences between land cover types
- Impacts of irrigation and fertilizer inputs on water and nutrient cycles
- Biodiversity measures

Input requested from ESMs!

E-mail a.harper@uga.edu to be involved

Progress in JULES:

-

ization

del)

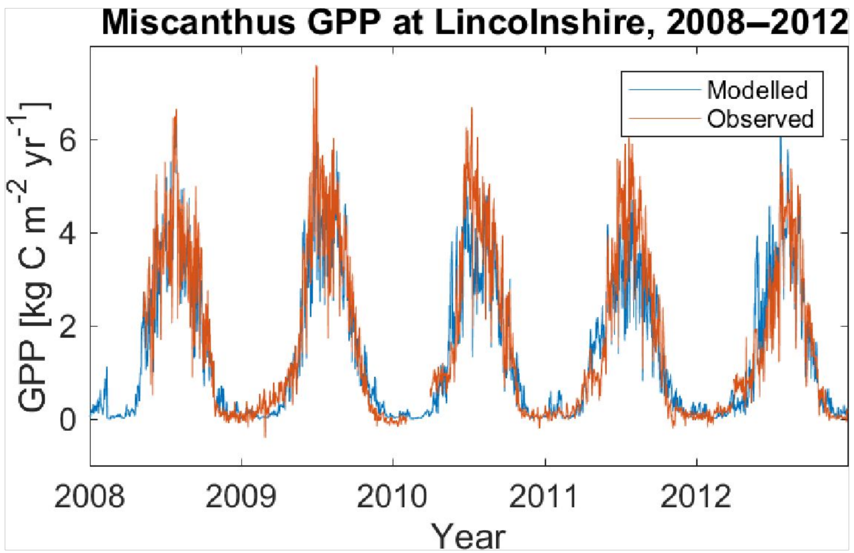
eme

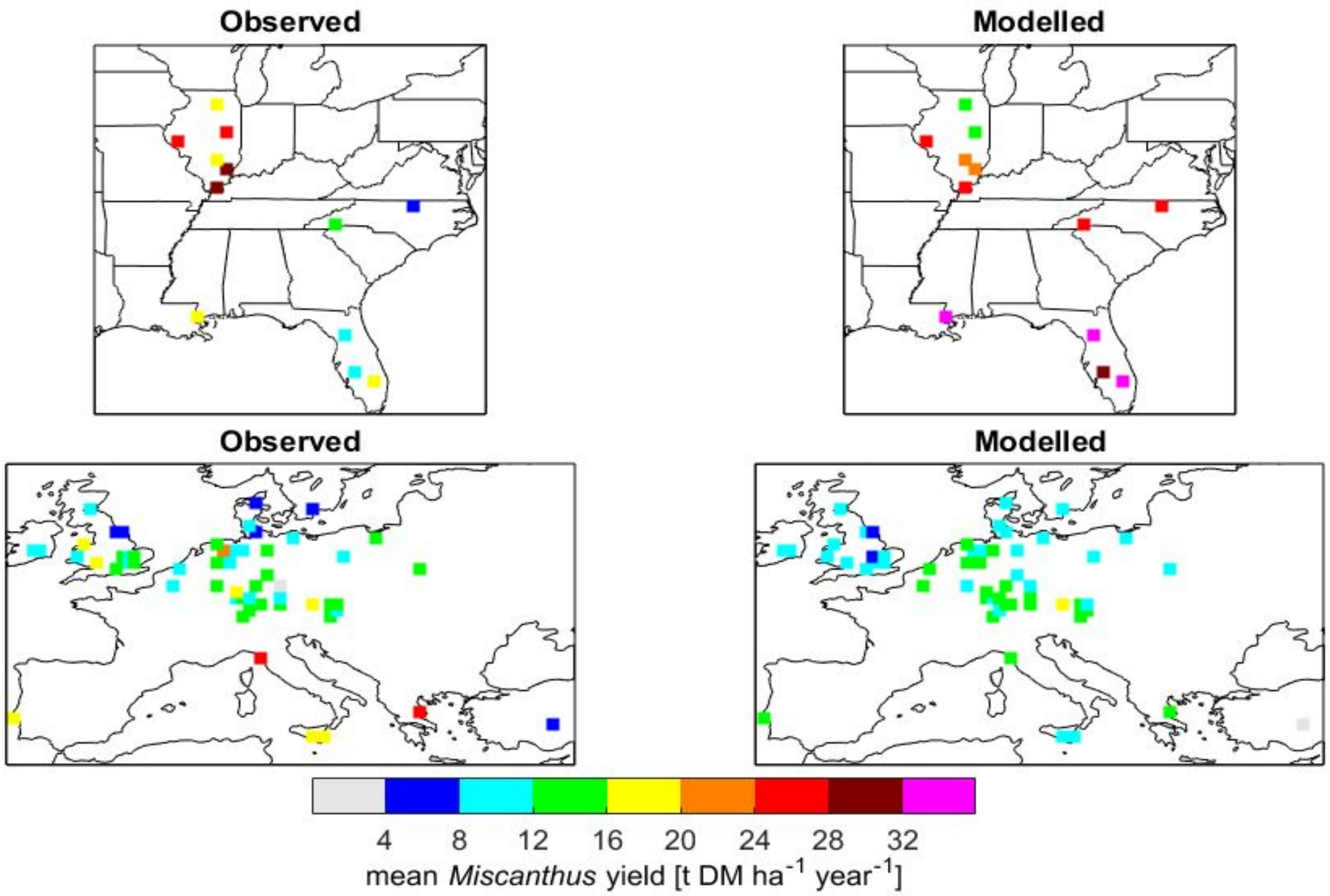
- Relevant tree species
- ?
- ?

Bioenergy crops

JULES-BE

with post-doc Emma Littleton

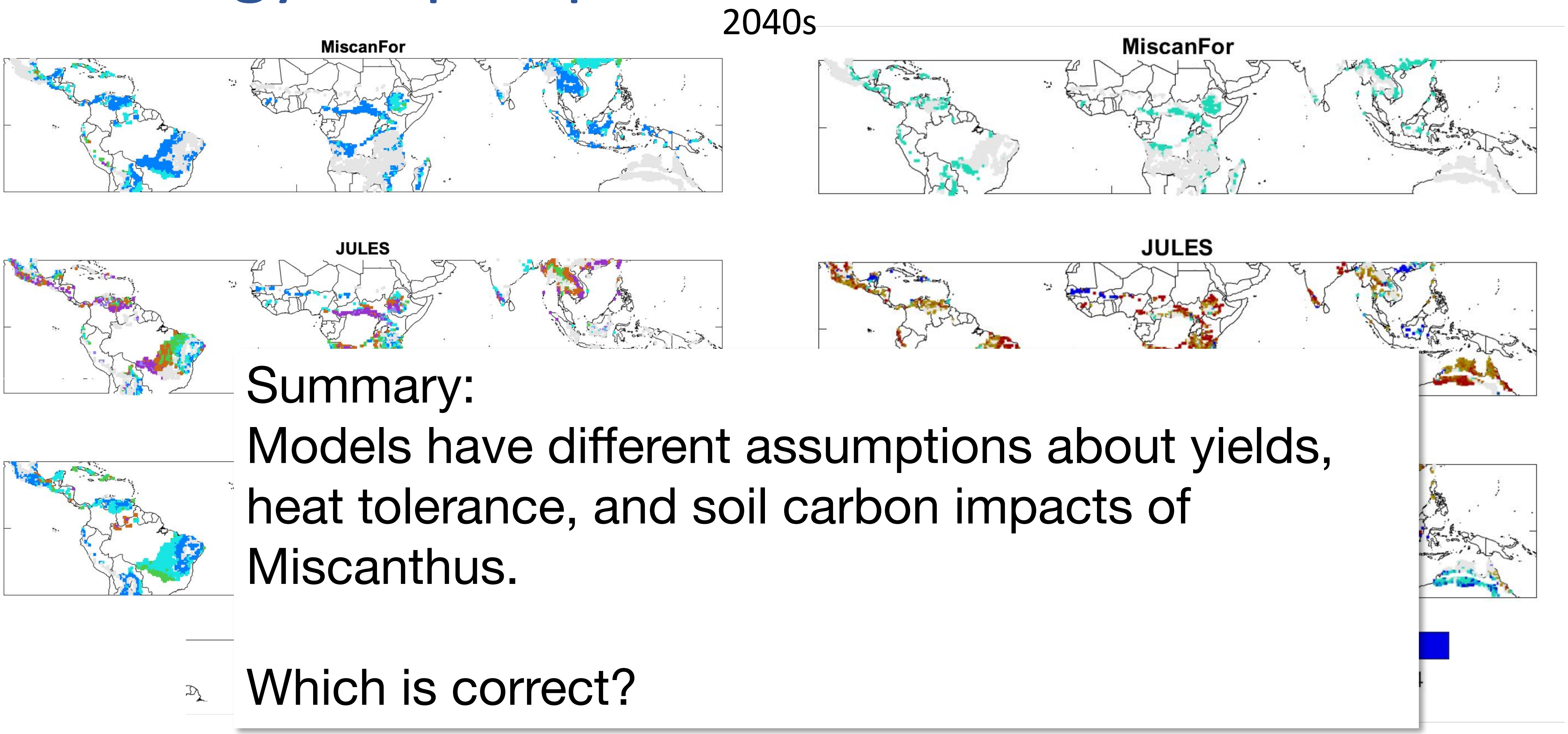




Good fit in Europe but over-estimates yields in southern USA

Littleton et al. 2020, *Geosci. Mod. Dev.*

Bioenergy crop impacts

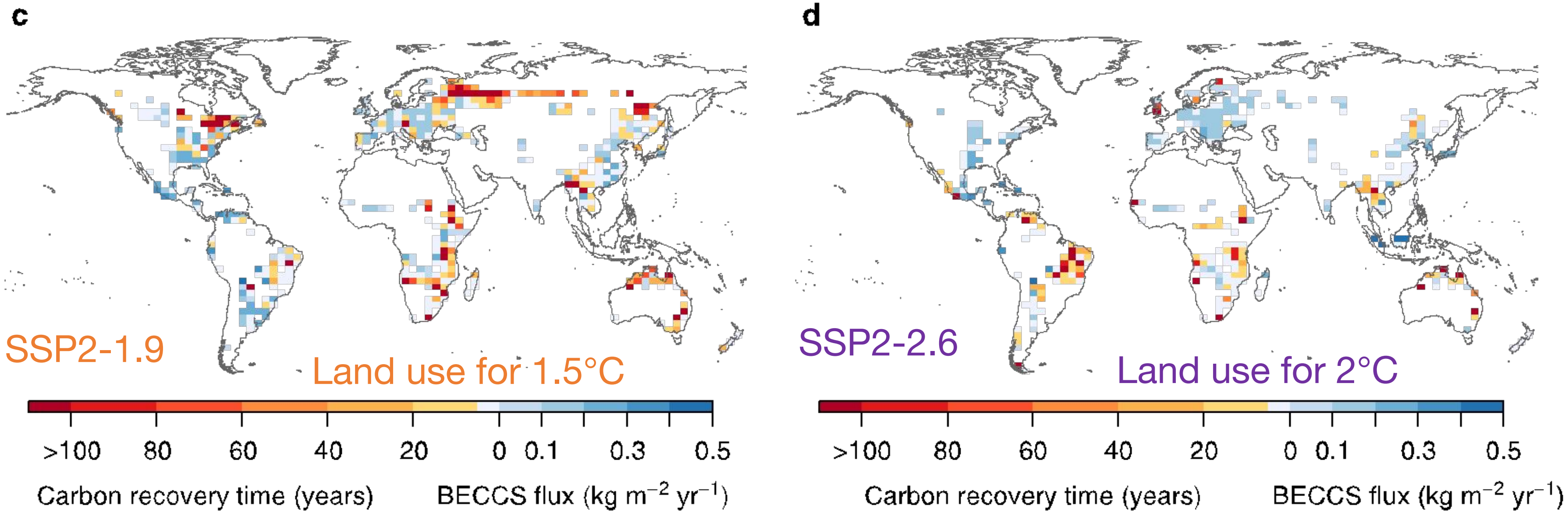


Summary:
Models have different assumptions about yields, heat tolerance, and soil carbon impacts of Miscanthus.

Which is correct?

Littleton et al., 2022 (GCB-Bioenergy)

Bioenergy crop impacts



Red: Places where yields do not make up for soil carbon losses by 2100

Blue: Places where BECCS pays off by 2100

Harper et al. 2018 *Nature Communications*

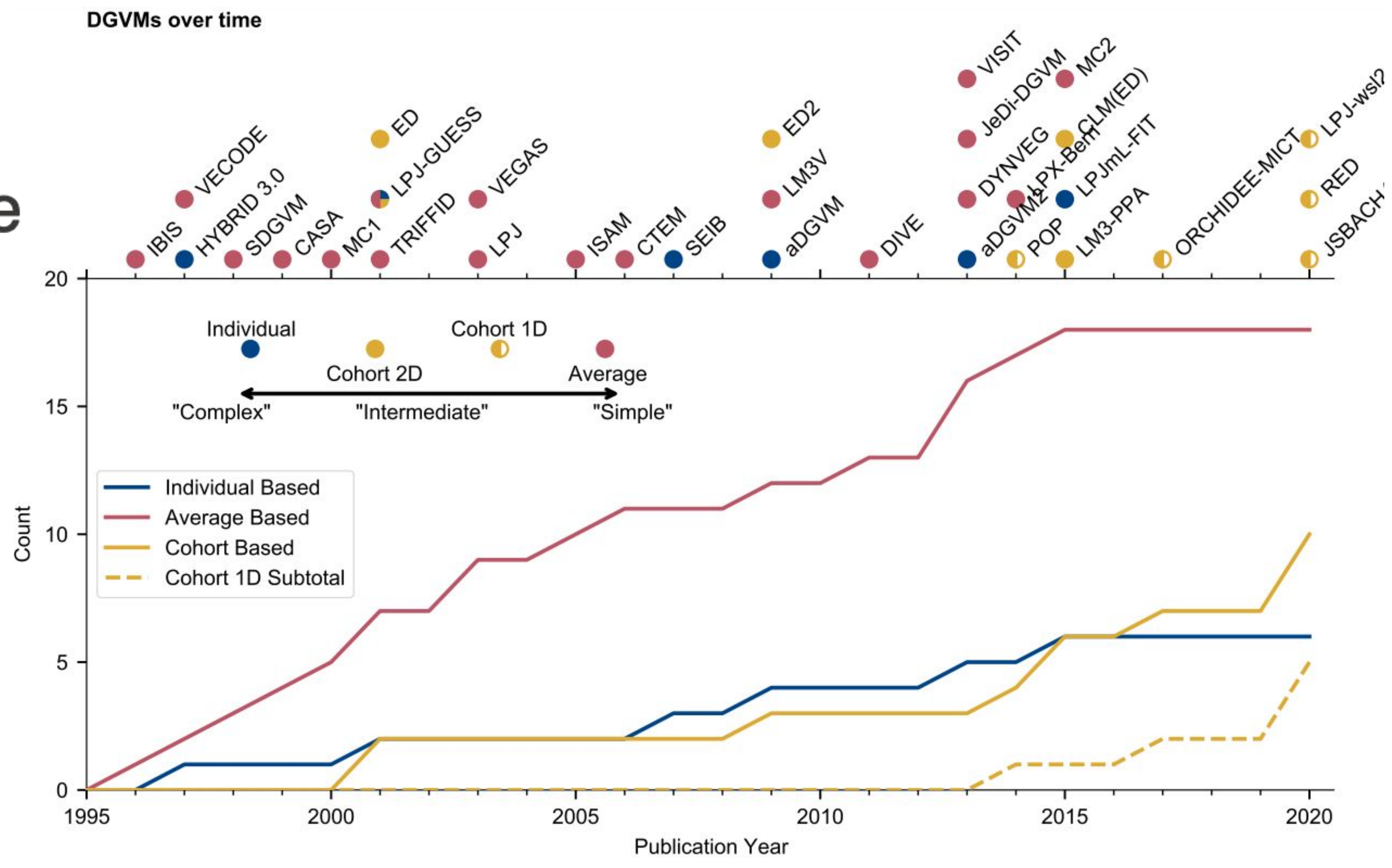

Forests

JULES-RED: cohort-based dynamic global vegetation model

- Simulates one demographic dimension, number density (*n*), across plant mass (*m*) using the Von Foerster equation:

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial m}[ng] = -\gamma n$$

g = plant growth and γ = plant mortality



Lit Review Paper: (Argles et al., 2022). Model description: Argles et al. 2020; DET: (Moore et al 2019 & 2020)

JULES-RED

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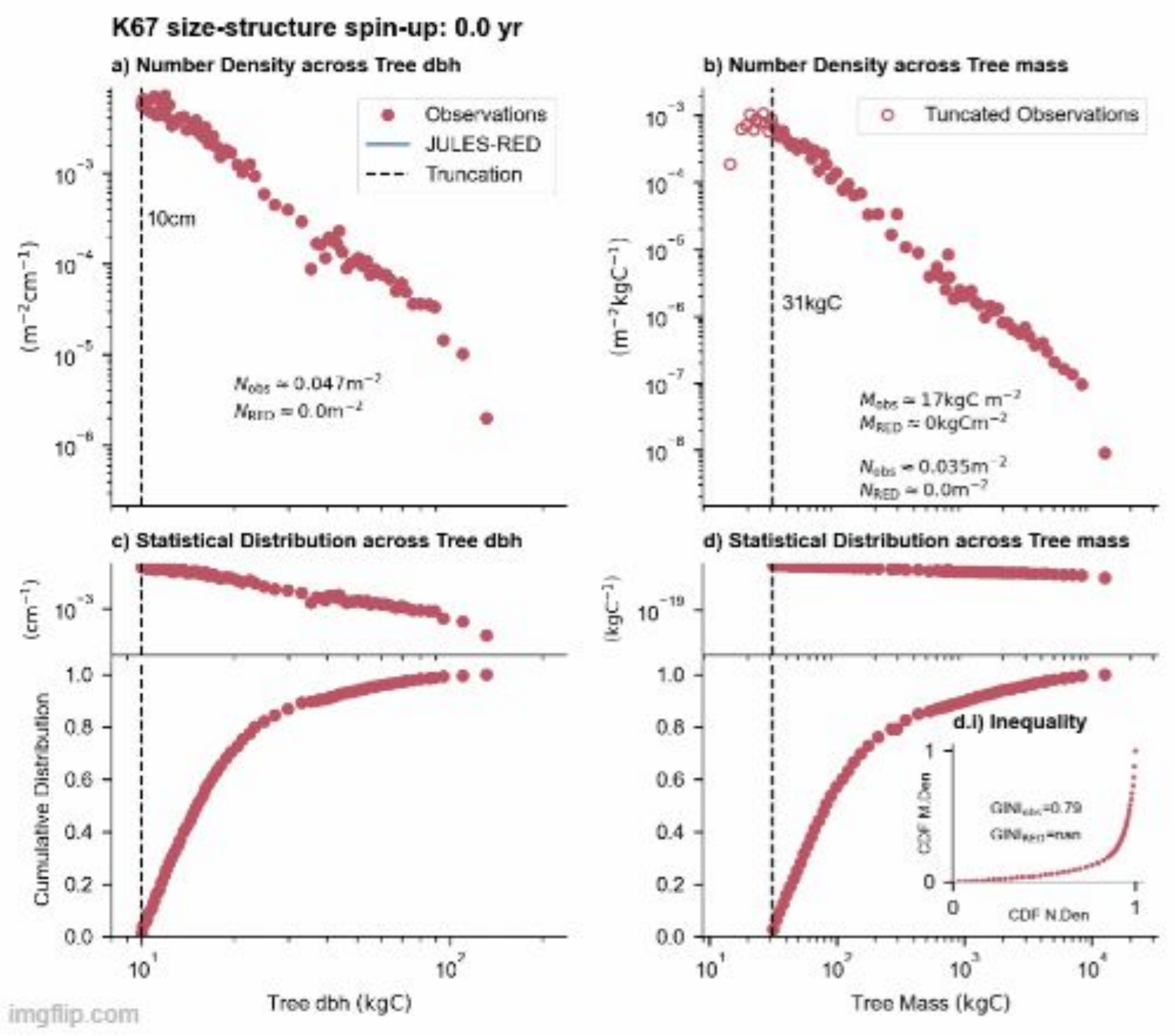
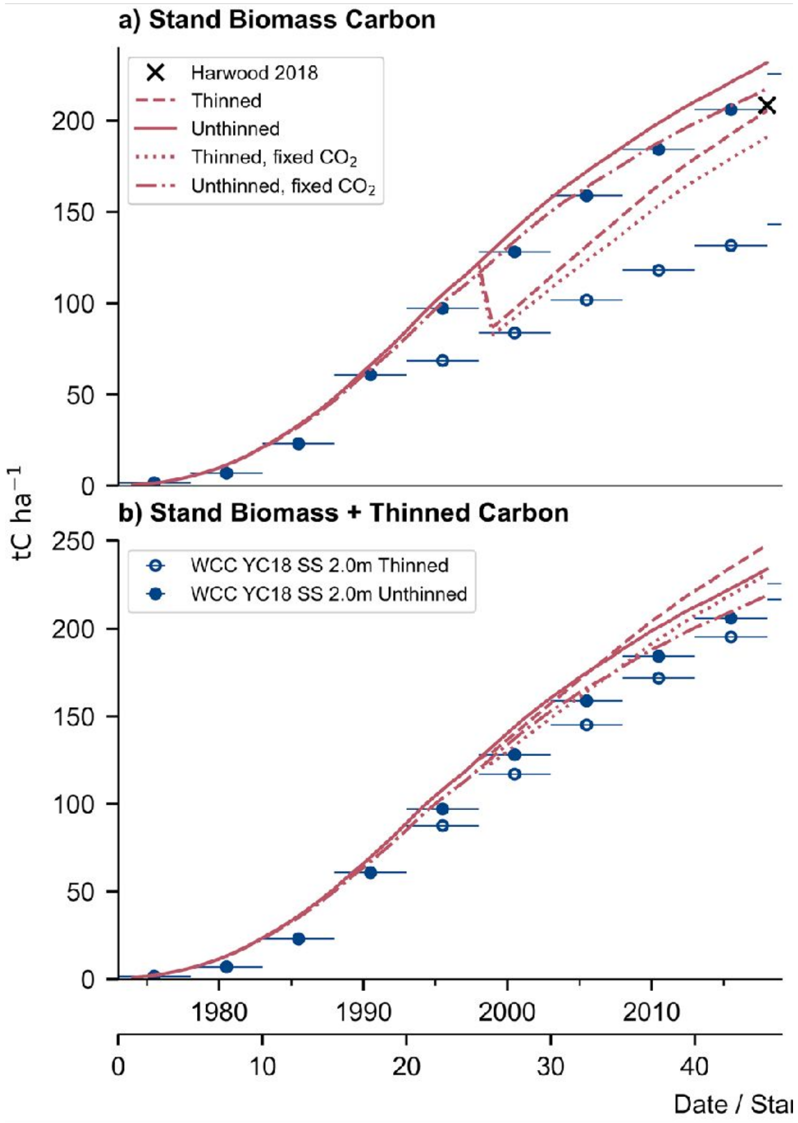


A. Harper

University of Georgia

JULES-RED

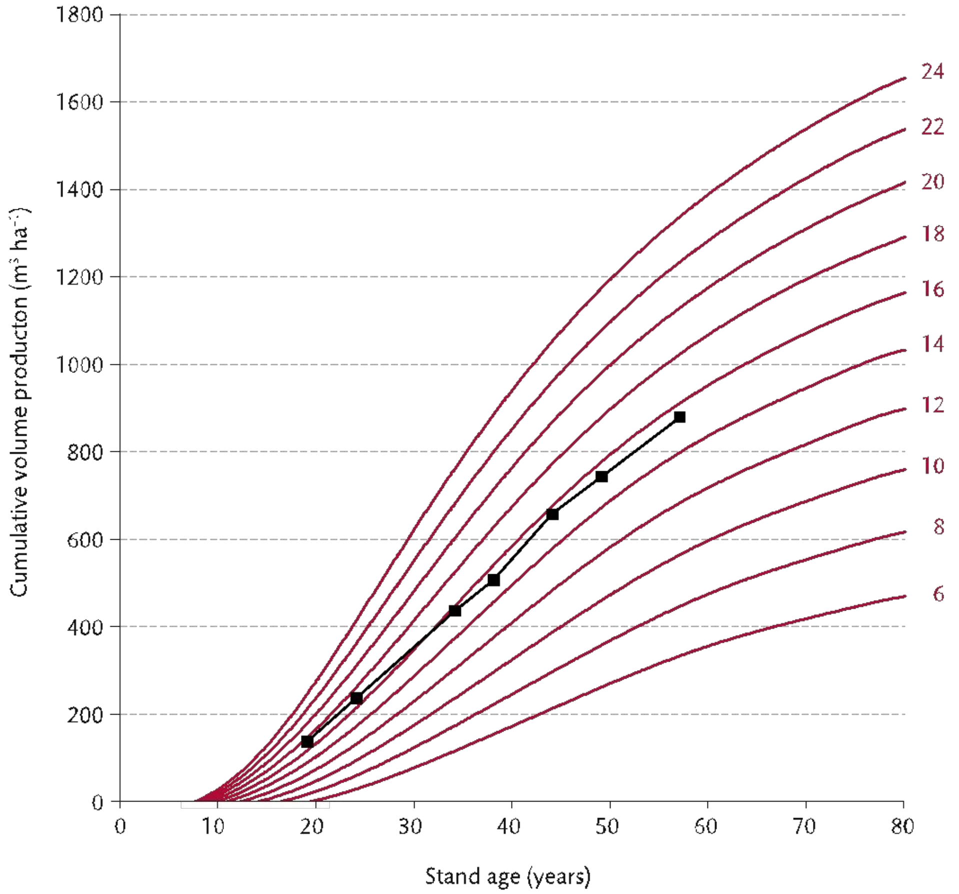


Thinning + CO_2 effects best captures current carbon content of Harwood forest

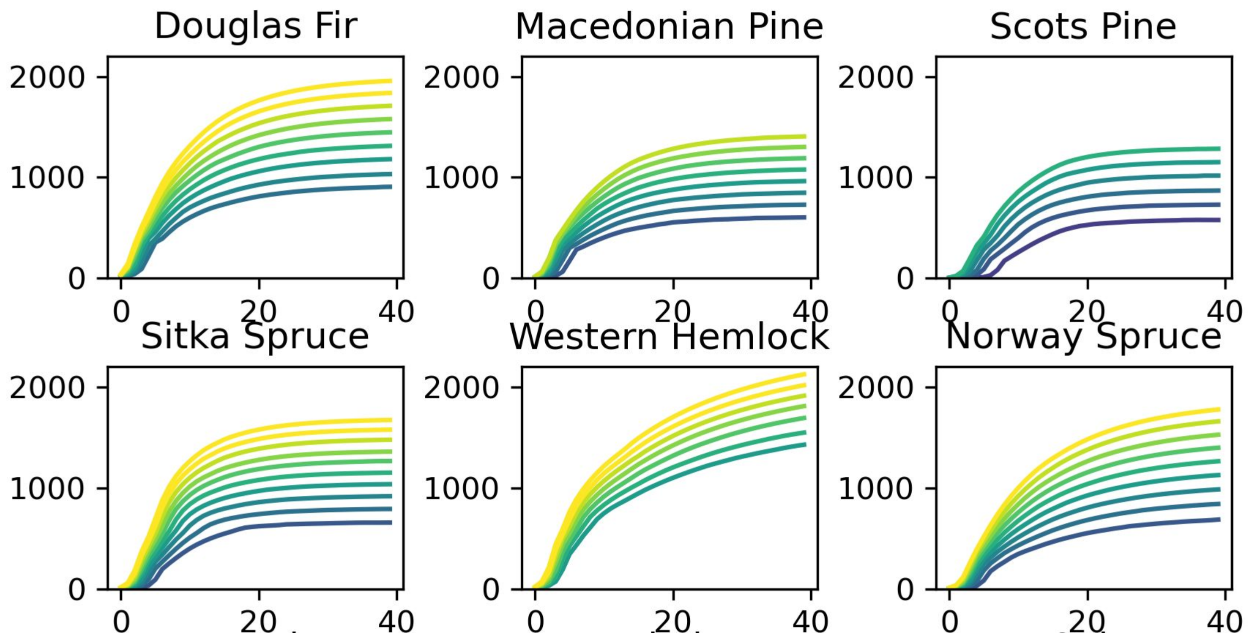
Range of outputs due to climate impacts and CO_2 fertilization, previously not included in estimates of future woodland growth

Argles et al. 2023, *Scientific Reports*

Representing UK species



Data source: UK Forest Research Woodland Carbon Code



Next steps: Calibrating growth in JULES-RED with automated GP emulator (Baker et al. 2022).

Summary

- Land-based climate mitigation has many impacts on carbon cycle, hydrological cycle, local biophysics, and biodiversity.
- Earth system models are catching up to include these impacts.
- In JULES, we've added a bioenergy crop, an improved representation of forests, and management.

- Model uncertainty is considerable □ ESM2025 common experiments to evaluate carbon and biophysical impacts of idealized afforestation/reforestation and bioenergy crops.
- JULES, CLM-FATES, JSBACH, ORCHIDEE

Concluding thoughts

- Impacts of land use decisions is a new area for ESMs, with focus on end-users.
- The goal of making ESMs more relevant and useable by society requires fast models and uncertainty quantification.

Resources

- Argles, A.P.K., Robertson, E., **Harper, A.B.**, Morison, J.I.L., Xenakis, G., Hastings, A., McCalmont, J., Moore, J.R., Bateman, I.J., Gannon, K., Betts, R.A., Bathgate, S., Thomas, J., Heard, M., Cox, P.M.: Modelling the impact of forest management and CO2-fertilisation on growth and demography in a Sitka spruce plantation, *Scientific Reports*, https://doi.org/10.1038/s41598-023-39810-2, 2023.
- Argles, A.P.K., Moore, J.R., Huntingford, C., Wiltshire, A.J., **Harper, A.B.,** Jones, C.D., and Cox, P.M.: Robust Ecosystem Demography (RED version 1.0): a parsimonious approach to modelling vegetation dynamics in Earth system models, *Geosci. Model Dev.,* https://doi.org/10.5194/gmd-13-4067-2020, 2020.
- Baker, E., **Harper, A.B.**, Williamson, D., and Challenor, P.: Emulation of high-resolution land surface models using sparse Gaussian processes with application to JULES, *Geosci. Model Dev*, https://doi.org/10.5194/gmd-2021-205, 2022.
- **Harper A.B.**, Wiltshire, A.J., Cox, P.M, Friedlingstein, P., Jones, C.D., Mercado, L.M., Sitch, S., Williams, K., Duran-Rojas, C.: Vegetation distribution and terrestrial carbon cycle in a carbon cycle configuration of JULES4.6 with new plant functional types, *Geosci. Model Dev.*, doi:10.5194/gmd-11-2857-2018, 2018.
- **Harper A.B.**, Powell, T., Cox, P.M., House, J., Huntingford, C., Lenton, T.M., Sitch, S., Burke, E., Chadburn, S.E., Collins, W.C., Comyn-Platt, E., Daioglou, V., Doelman, J.C., Hayman, G., Robertson, E., van Vuuren, D., Wiltshire, A., Webber, C.P., Bastos, A., Boysen, L., Ciais, P., Devaraju, N., Jain, A.K., Krause, A., Poulter, B., Shu, S.: Land-use emissions play a critical role in land-based mitigation for Paris climate targets, *Nature Communications*, doi:10.1038/s41467-018-05340-z, 2018.
- **Harper, A.B.,** Cox, P. M., Friedlingstein, P., Wiltshire, A. J., Jones, C. D., Sitch, S., Mercado, L. M., Groenendijk, M., Robertson, E., Kattge, J., Bönisch, G., Atkin, O. K., Bahn, M., Cornelissen, J., Niinemets, Ü., Onipchenko, V., Peñuelas, J., Poorter, L., Reich, P. B., Soudzilovskaia, N. A., and Bodegom, P. V.: Improved representation of plant functional types and physiology in the Joint UK Land Environment Simulator (JULES v4.2) using plant trait information, *Geosci. Model Dev*., doi:10.5194/gmd-9-2415-2016, 2016.
- Littleton, E.W., Shepherd, A., **Harper, A.B.**, Hastings, A.F.S., Vaughan, N.E., Doelman, J., van Vuuren, D.P., and Lenton, T.M.: Uncertain effectiveness of bioenergy expansion for climate change mitigation explored using land surface, agronomic, and integrated assessment models, *Global Change Biology- Bioenergy,* https://doi.org/10.1111/gcbb.12982, 2022.
- Littleton, E.W., Dooley, K., Webb, G., **Harper, A.B.,** Powell, T., Nicholls, Z., et al.: Dynamic modelling shows substantial contribution of ecosystem restoration to climate change mitigation, *Environ. Res. Lett.*, https://doi.org/10.1088/1748-9326/ac3c6c, 2021.
- Littleton, E.W., **Harper, A.B.,** Vaughan, N.E., Oliver, R.J., Duran-Rojas, M.C., Lenton, T.M.: JULES-BE: representation of bioenergy crops and harvesting in the Joint UK Land Environment Simulator vn5.1, *Geoscientific Model Development*, 10.5194/gmd-13-1123-2020, 2020.

Extra slides below here

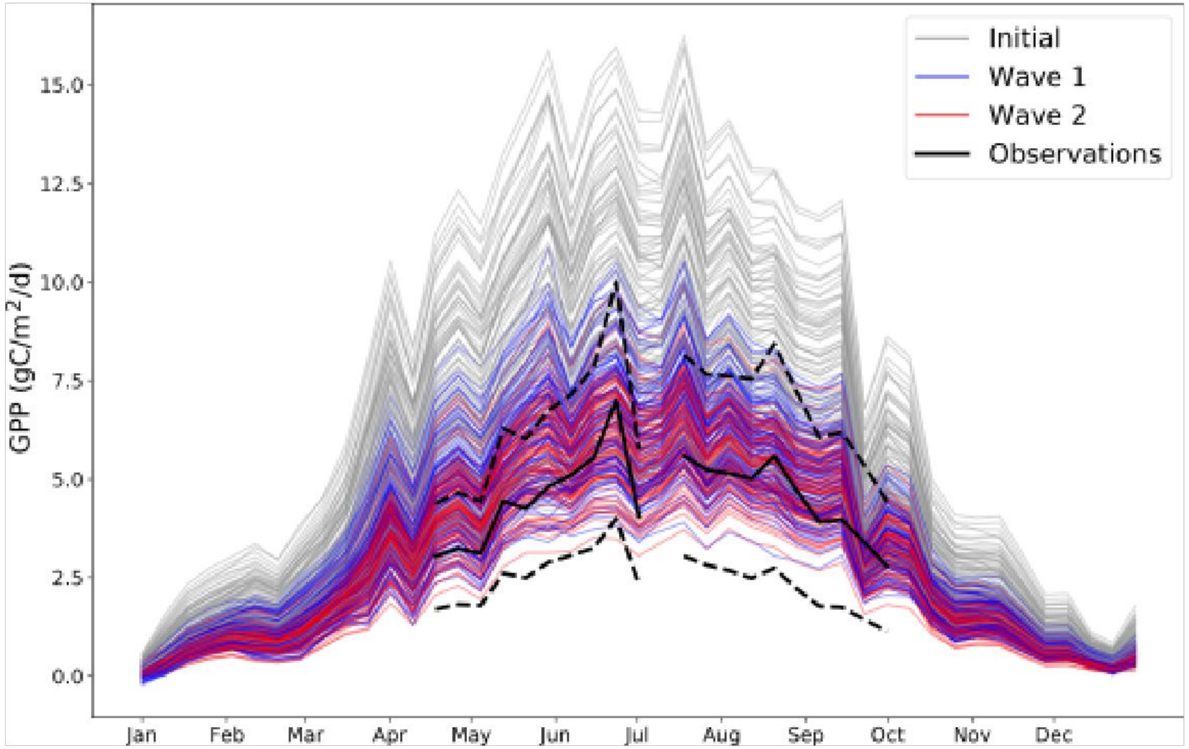
Why do we need emulators?

1. Save time when you need to run the model lots of times:
   - Global century-scale simulation takes around 10 hours on 64 processors (not too bad): 7473 grid cells, ~100 km resolution
   - 10 years of UK-scale simulation takes around 24 hours on 144 processors (eek!): 77980 grid cells, 1.5 km resolution
2. Uncertainty quantification: Our models are uncertain, as is the spatial and temporal patterns of climate change: Shouldn't we account for this in our climate impact projections?
3. Ease of use: If a decision-maker wants to use this model to know impacts of tree planting, it is nearly impossible.

Model calibration

- History matching rules out “implausible” parameter combinations.
- Considers observational error and a certain tolerance of model error.
- Iteratively rule out some parameter settings, rerun the model, fit a new emulator.
- After 2 waves we ruled out 95.6% of parameter settings

Photosynthesis over 2002 from 100 randomly chosen parameter settings per wave, for a randomly chosen grid cell in the UK

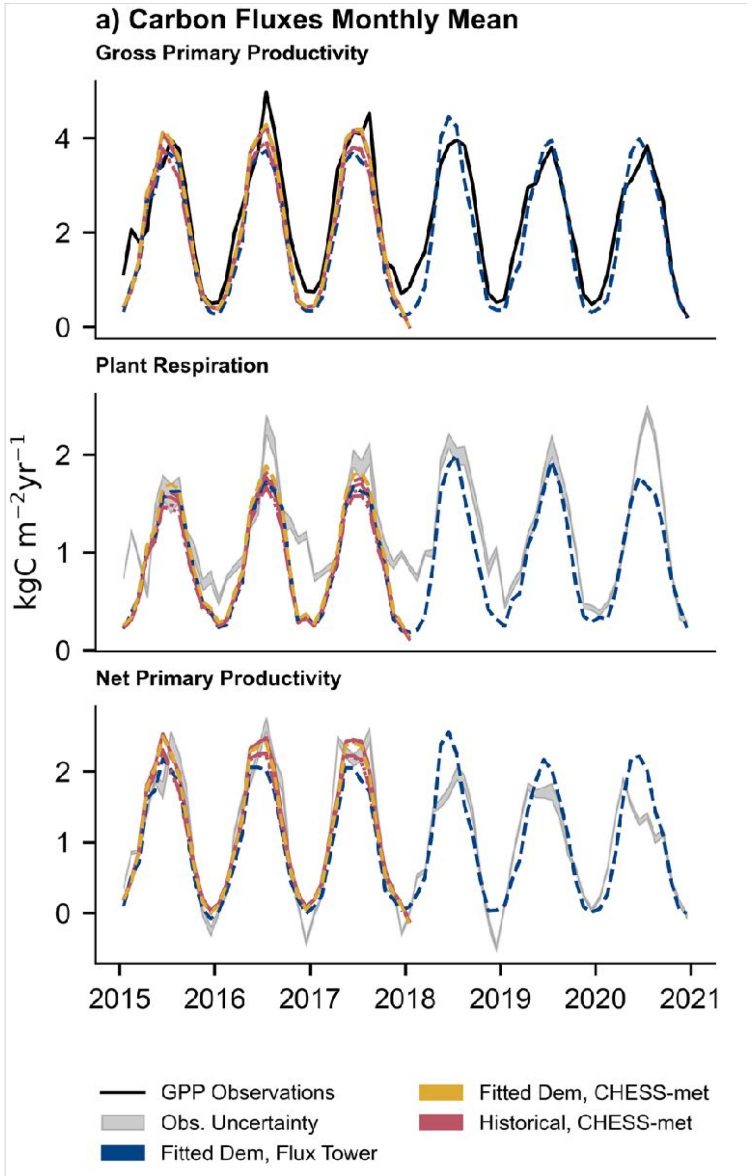


Baker et al. 2022

JULES-RED

Harwood: even-aged conifer stand in northern England

Argles et al. 2023, *Scientific Reports*



Model calibration

Set up input parameters

Select points in UK grid

Run JULES with different parameters at each point

Check outputs

Is parameter space adequately covered?

No

Yes

Build emulator

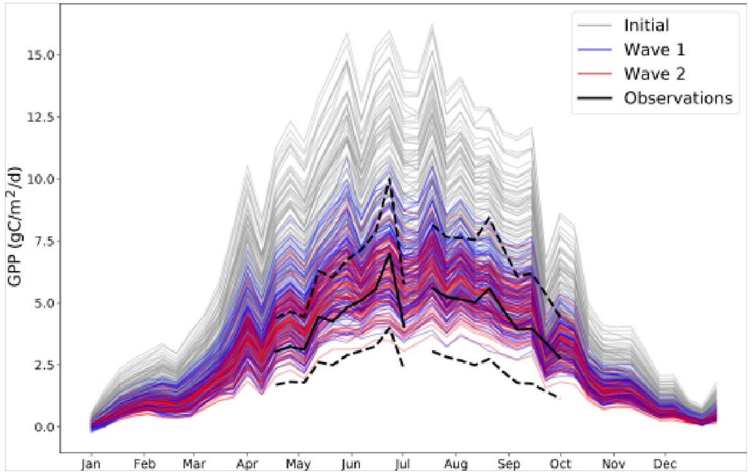
Rule out parameter combinations that don't fit observations

Could we further improve fit with more parameter values?

Yes

No

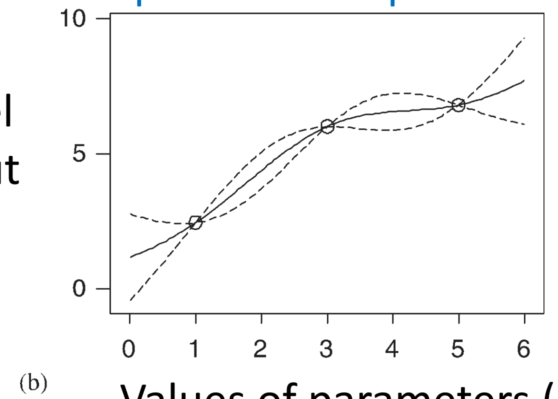
STOP



Baker et al. 2022

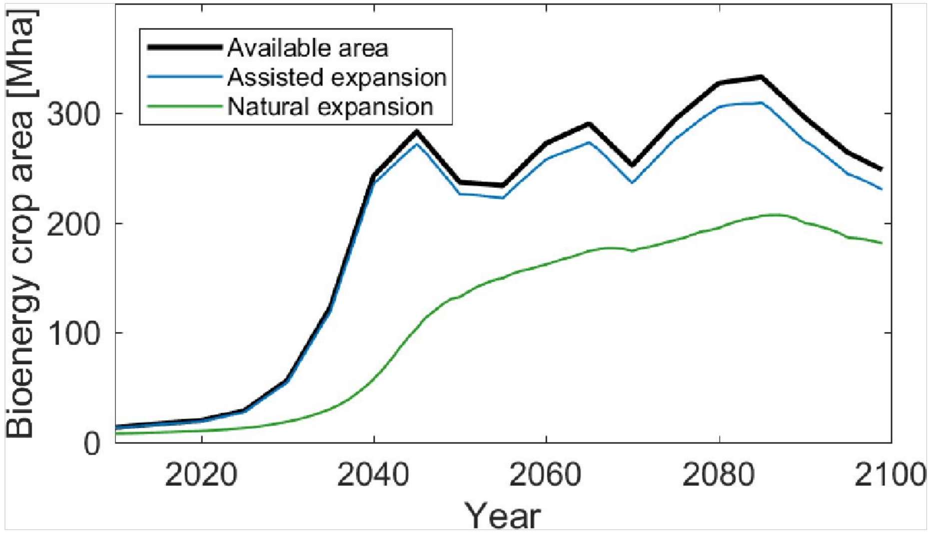
Example with one parameter

Model output y(θ)



Values of parameters (θ)

Bioenergy crop impacts



Summary:
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Which is correct?

2090s