National CO_2 budgets (2015-2020) inferred from atmospheric CO_2 observations in support of the Global Stocktake

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Goals

- **Contribute to Global Stocktake (GST) Activities of the Paris Agreement**
  - GST to monitor Paris agreement implementation (e.g., emissions and removals of CO_2)
  - GST to evaluate the collective progress made in achieving goals.

- **Goal of the pilot dataset**: Start a conversation.
  - Provide a pilot product of emissions and removals of CO_2
  - Illustrate the type of dataset we can provide.
  - Identify current limits of our approach and where research is needed.
  - Inform development of Monitoring and Verification System

- **Long term goal**:
  - Provide countries with precise and accurate carbon budgets to track AFOLU (Agriculture, Forestry and Other Land Use) and unmanaged lands. Complement bottom-up datasets.

What is in our dataset?

- **Quantities provided:**
  - Net carbon exchange (net surface-atmosphere CO_2 flux)
  - Change in terrestrial carbon stocks (ΔC_{loss}).
  - Fossil fuel emissions and lateral C fluxes
  - And their uncertainties!

- **Spatiotemporal scale:**
  - Annual net fluxes over (2015-2020)
  - Country totals and as 1^o x 1^o degree.

Methods - CO_2 flux inversions

v10 OCO-2 Model Intercomparison Project (MIP)

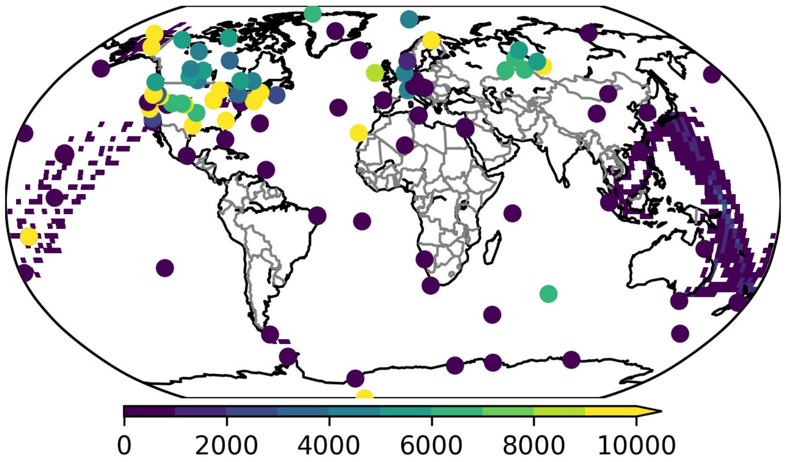
- 12 flux inversion models follow protocol with common data assimilated and fossil fuel emission inventory. Each group free to choose prior NBE and ocean fluxes

Includes four MIP experiments that use different datasets:

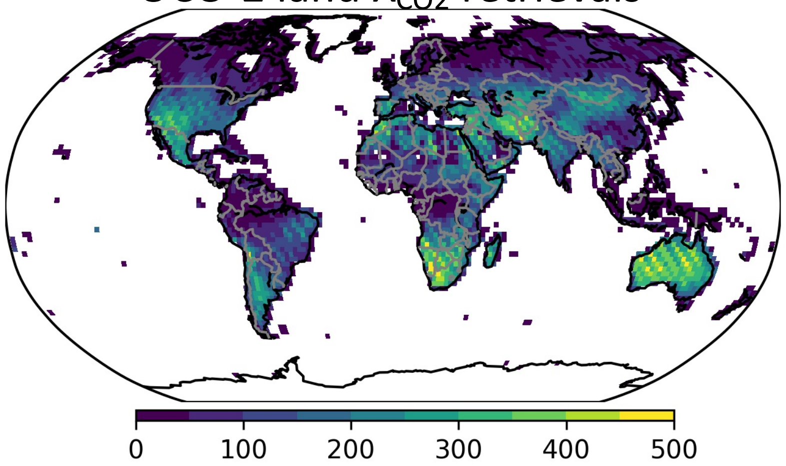
- In situ (IS)
- Land nadir + land glint (LNLG)
- Land nadir + land glint + in situ (LNLGIS)
- Land nadir + land glint + ocean glint + in situ (LNLGOGIS)

Data coverage over 2015-2020

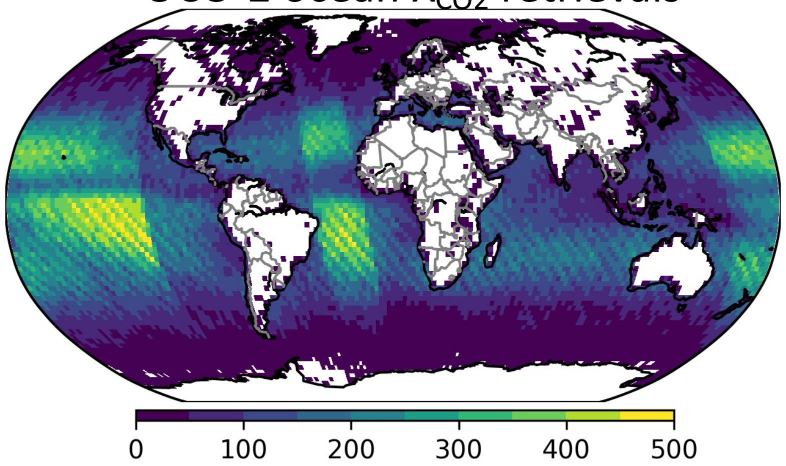
In situ CO2 measurements



OCO-2 land X_{CO2} retrievals



OCO-2 ocean X_{CO2} retrievals



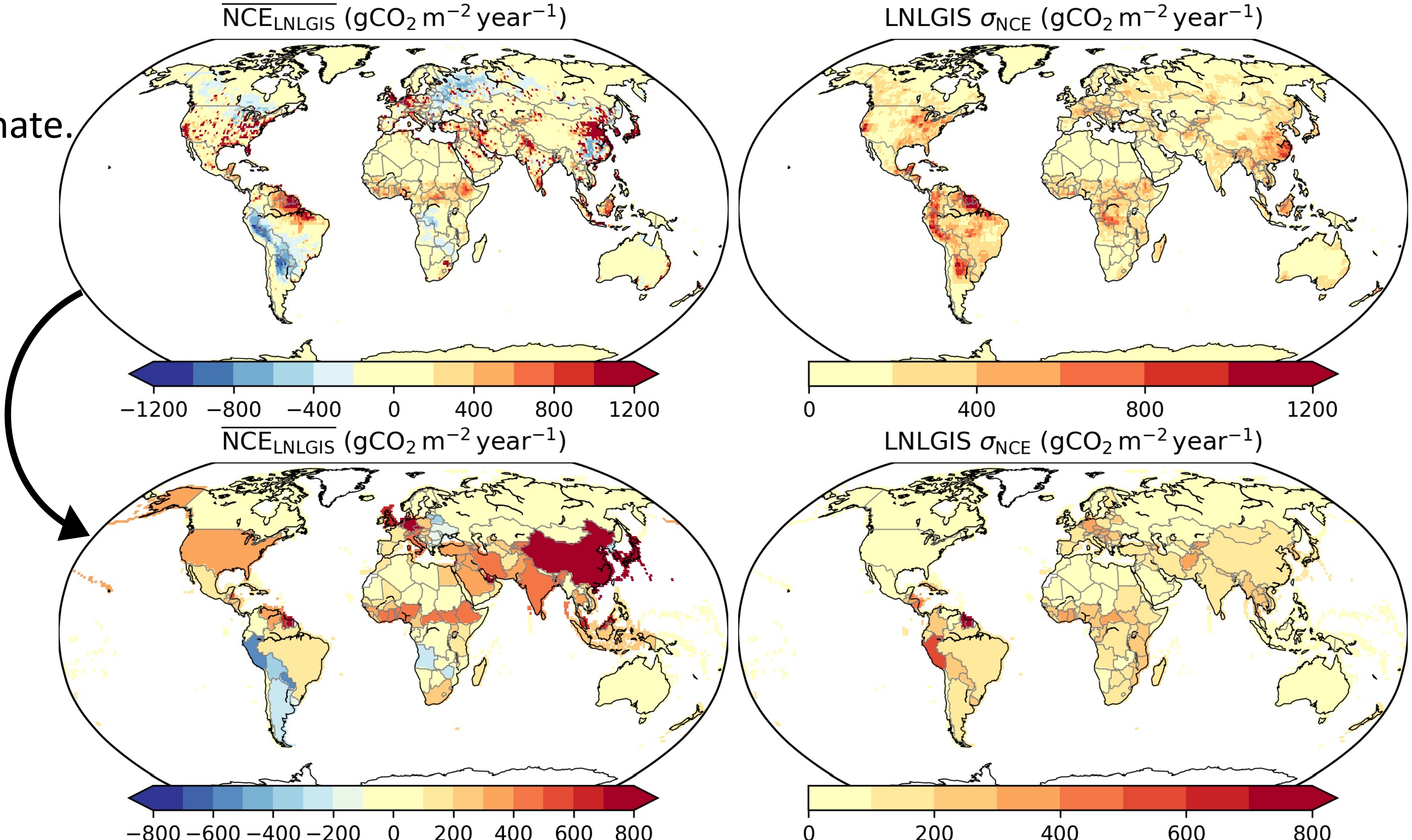
Methods - CO_2 flux inversions

Each modeling group estimates the **Net Carbon Exchange (NCE) = Fossil Fuel + Net Biosphere Exchange**

- Estimates provided on a 1º x 1º grid.
- We aggregate to country totals.
- Take model median as best estimate.
- Uncertainty is estimated as the standard deviation across model estimates.

Net Carbon Exchange (NCE) for 2015–2020

NCE fluxes Aggregated to Country Totals



Methods – carbon stock loss (ΔC_{loss})

- **Land carbon stock loss (ΔC_{loss})** estimated by combining top-down NCE with other carbon flux datasets.
- Calculate:

$$\Delta C_{loss} = NCE - FF - F_{crop\ trade} - F_{wood\ trade} - F_{rivers\ export}$$

FF: CO_2 emissions from fossil fuels and cement production.
(ODIAC w/ fractional uncertainties of Andres et al. (2014))

$F_{crop\ trade}$: lateral flux of carbon due to farming
(Deng et al. 2022, assume std = 30%).

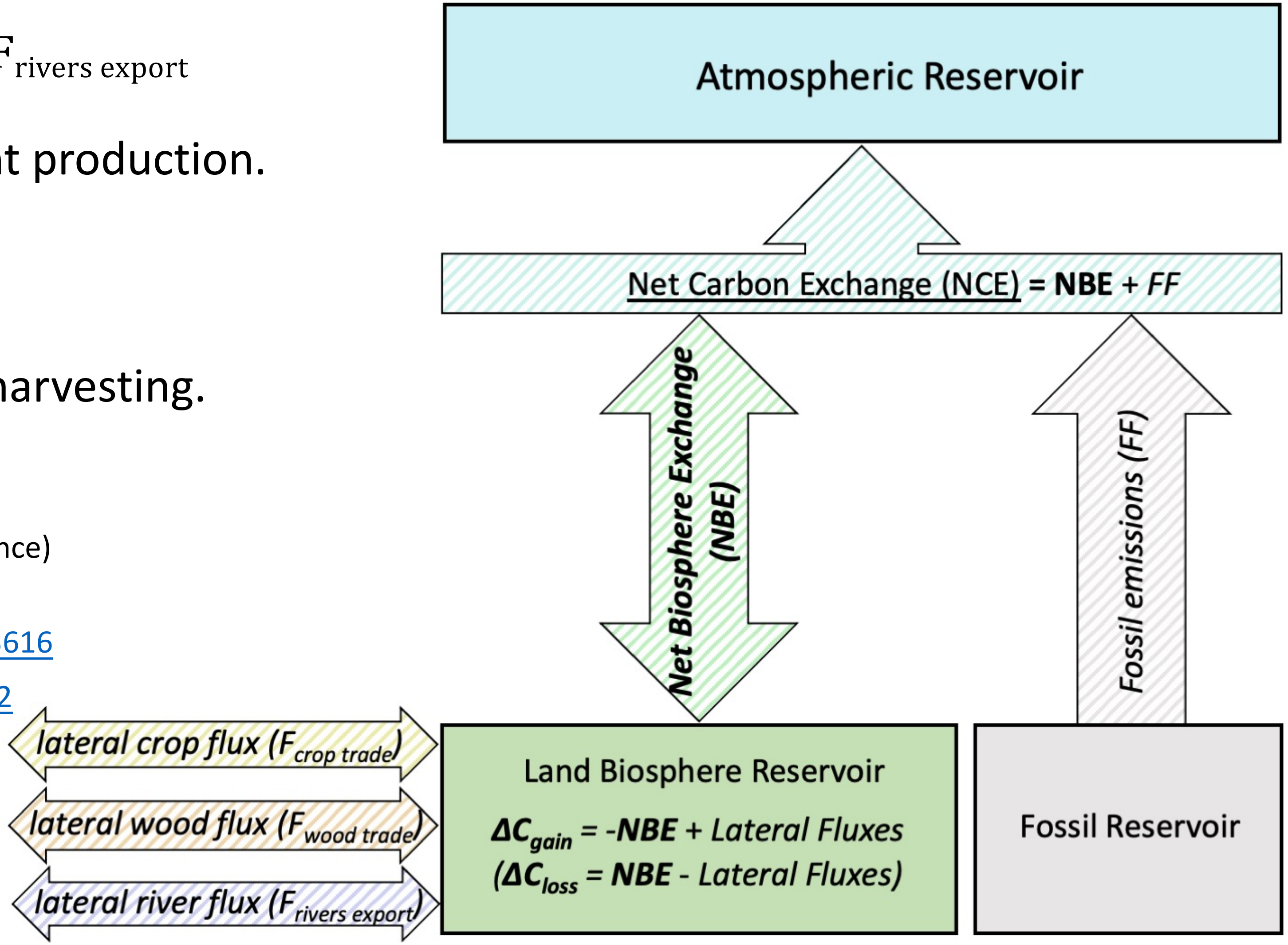
$F_{wood\ trade}$: lateral flux of carbon due to wood harvesting.
(Deng et al. 2022, assume std = 30%).

$F_{rivers\ export}$: lateral flux of carbon due to rivers.
(mean of Deng et al. 2022 and DLEM, Uncertainty = absolute difference)

Andres et al. (2014), Tellus B, https://doi.org/10.3402/tellusb.v66.23616

Deng et al. (2022), ESSD, https://doi.org/10.5194/essd-14-1639-2022

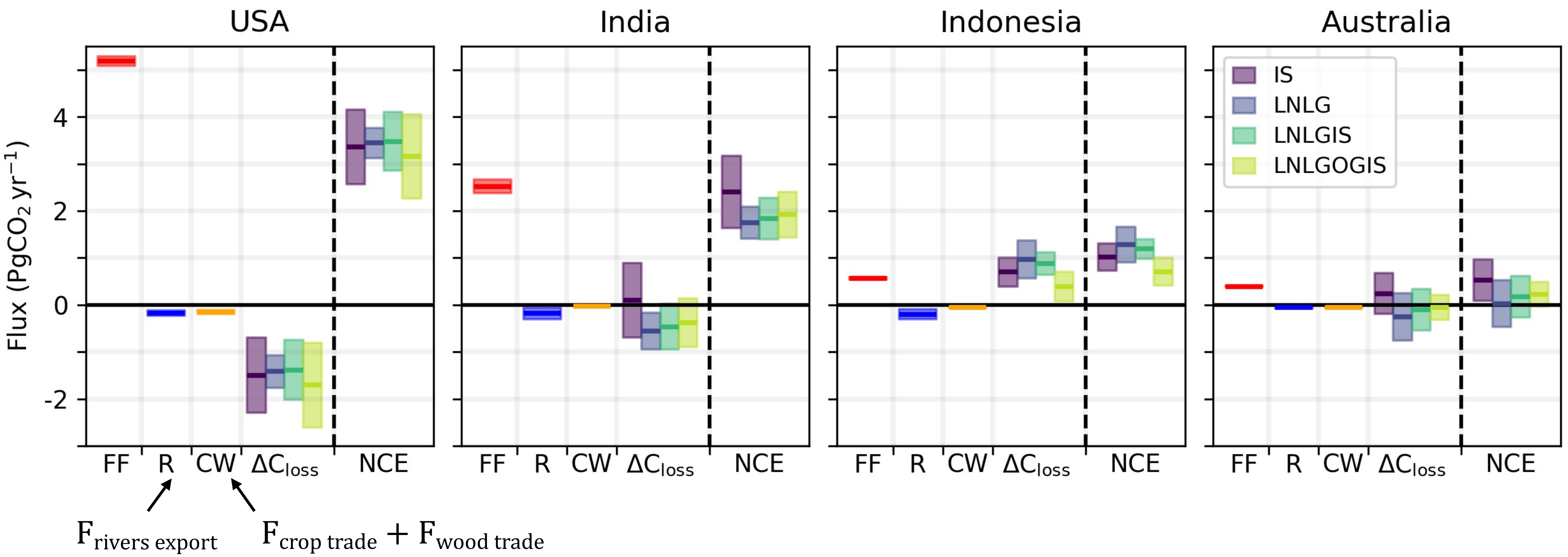
Carbon fluxes for a given land region



Results – carbon stock loss (ΔC_{loss})

Example 2015–2020 Carbon Budgets for Four Countries

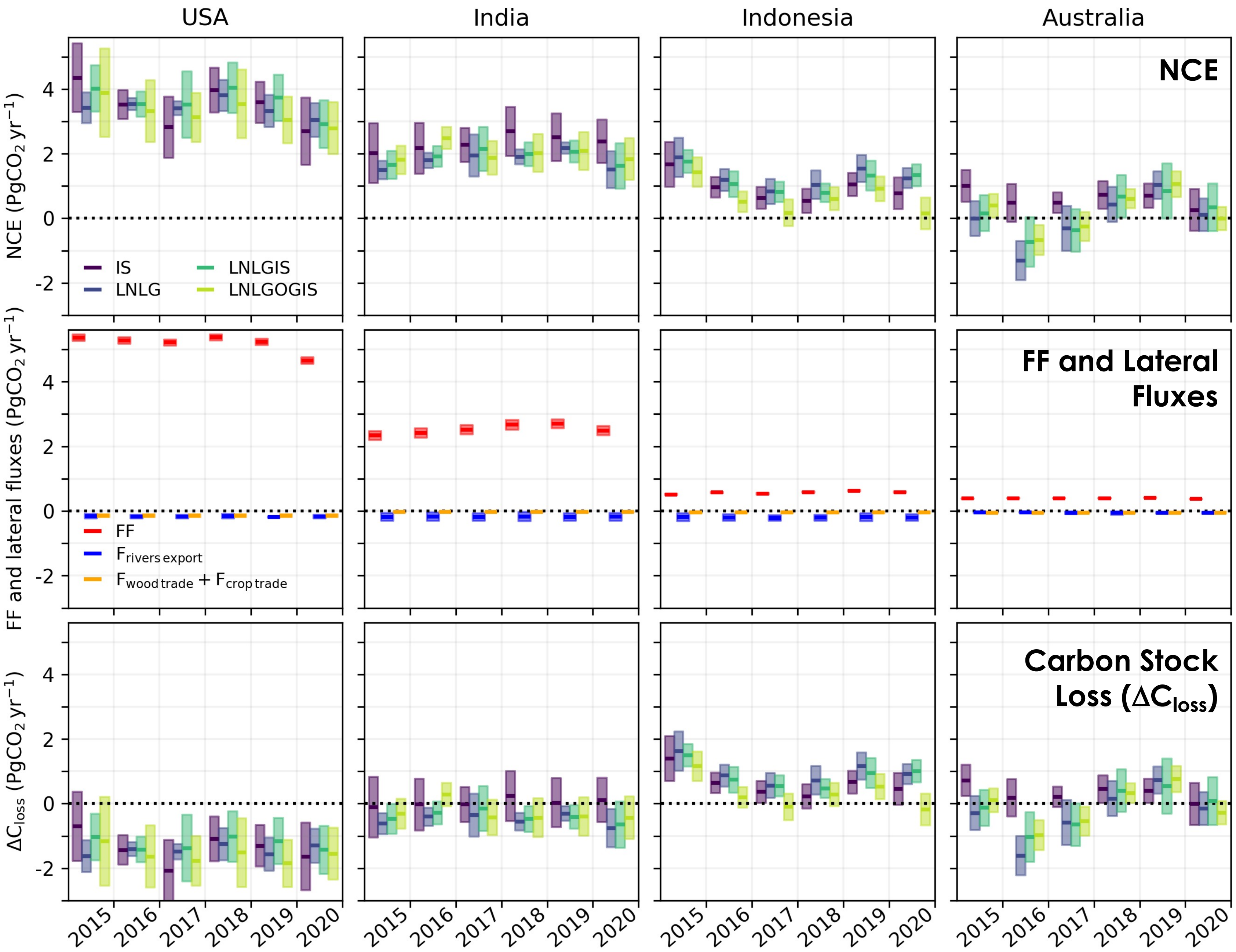
- Recall: $FF + F_{crop\ trade} + F_{wood\ trade} + F_{rivers\ export} + \Delta C_{loss} = NCE$
- Figure below shows how each component contributes to the NCE for a few specific countries, constrained by atmospheric CO_2 measurements.
- Increasing land carbon stocks decrease NCE relative to FF emissions for USA, but the opposite occurs for Indonesia.



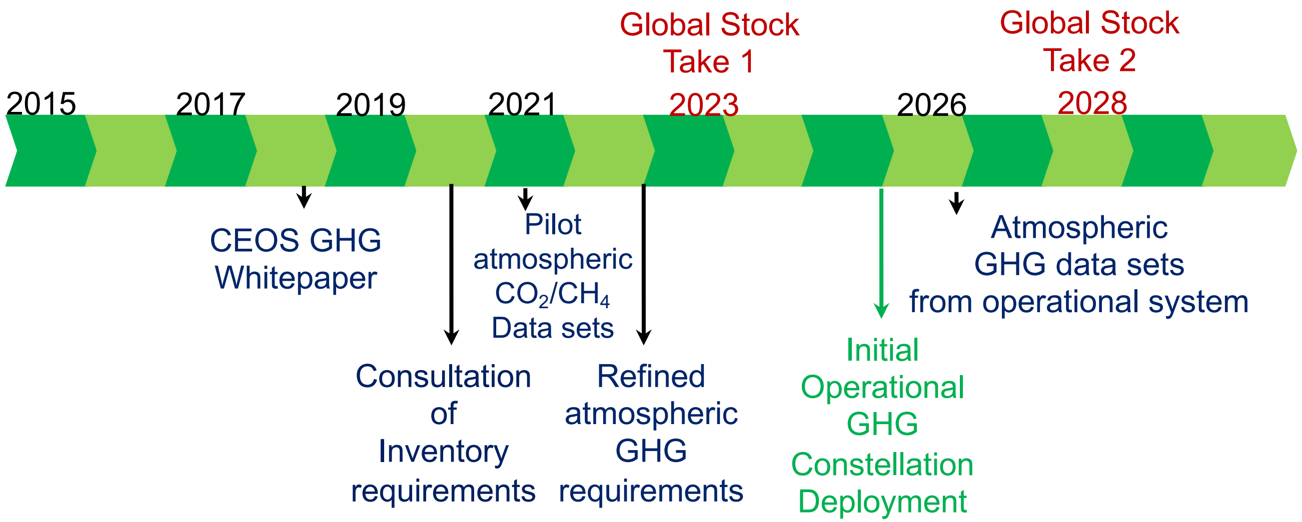
Results – carbon stock loss (ΔC_{loss})

Example Carbon Budget Time Series for Four Countries

- Provide annual net fluxes for six years covering 2015 through 2020.
- Interannual variations in NCE are driven primarily ΔC_{loss} due to climate variability and trends in FF.
- Droughts reduce carbon uptake by the ecosystem. Variability associated with El Niño in the tropics is a strong driver of variability in ΔC_{loss}.



Lessons learned and path forward



Lots of Obs in pipeline

- Data-dense GeoCarb, CO2M and GOSAT-GW
- Regional expansions of in situ measurements.

Keys to future success:

- **Increased ground-based and aircraft-based CO_2 measurements in poorly sampled regions will identify retrieval biases and improve confidence.** Some regions show substantial differences between OCO-2 and in situ inversions that are not well understood. Need more independent CO_2 data in tropics.

- **Uncertainty quantification should incorporate Bayesian uncertainties.** Spread between flux inversion ensemble members largely captures systematic errors (model transport, inversion set-up) but not Bayesian component.

- **Refine inversions systems.** Including adding missing processes (e.g., atmospheric CO_2 production).

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Where to access the data:

Byrne, B., Baker, D. F., Basu, S., Bertolacci, M., Bowman, K. W., Carroll, D., Chatterjee, A., Chevallier, F., Ciais, P., Cressie, N., Crisp, D., Crowell, S., Deng, F., Deng, Z., Deutscher, N. M., Dubey, M. K., Feng, S., Garc.a, O. E., Herkommer, B., Hu, L., Jacobson, A. R., Janardanan, R., Jeong, S., Johnson, M. S., Jones, D. B. A., Kivi, R., Liu, J., Liu, Z., Maksyutov, S., Miller, J. B., Miller, S. M., Morino, I., Notholt, J., Oda, T., O'Dell, C. W., Oh, Y.-S., Ohyama, H., Patra, P. K., Peiro, H., Petri, C., Philip, S., Pollard, D. F., Poulter, B., Remaud, M., Schuh, A., Sha, M. K., Shiomi, K., Strong, K., Sweeney, C., T., Y., Tian, H., Velazco, V. A., Vrekoussis, M., Warneke, T., Worden, J. R., Wunch, D., Yao, Y., Yun, J., Zammit-Mangion, A., and Zeng, N.: Pilot top-down CO2 Budget constrained by the v10 OCO-2 MIP Version 1, Committee on Earth Observing Satellites, https://doi.org/10.48588/npf6-sw92, Version 1.0, 2022.