Widespread sink limitations on forest biomass growth in the Northern Hemisphere

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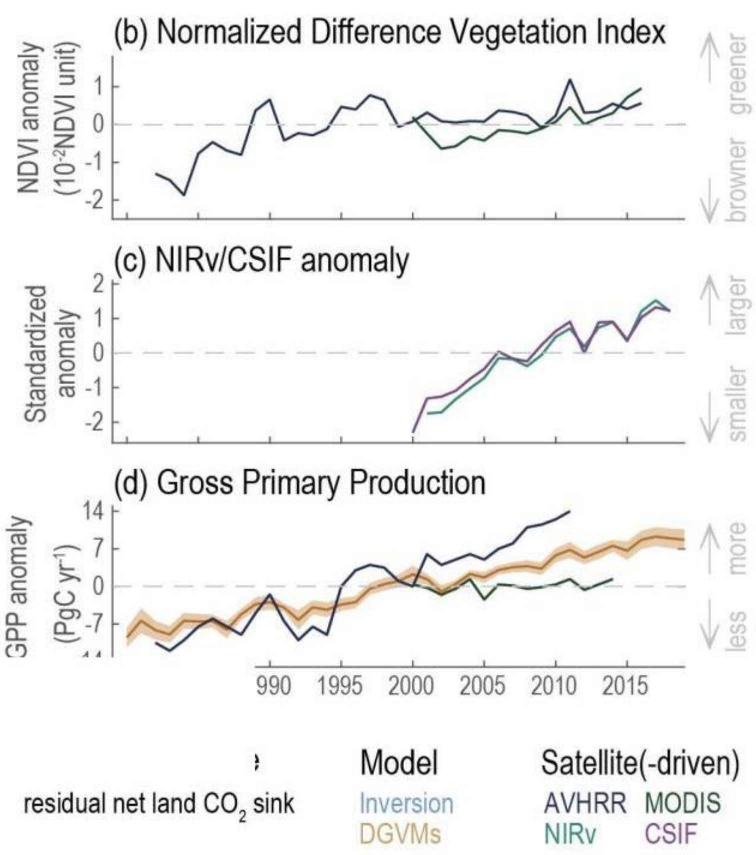
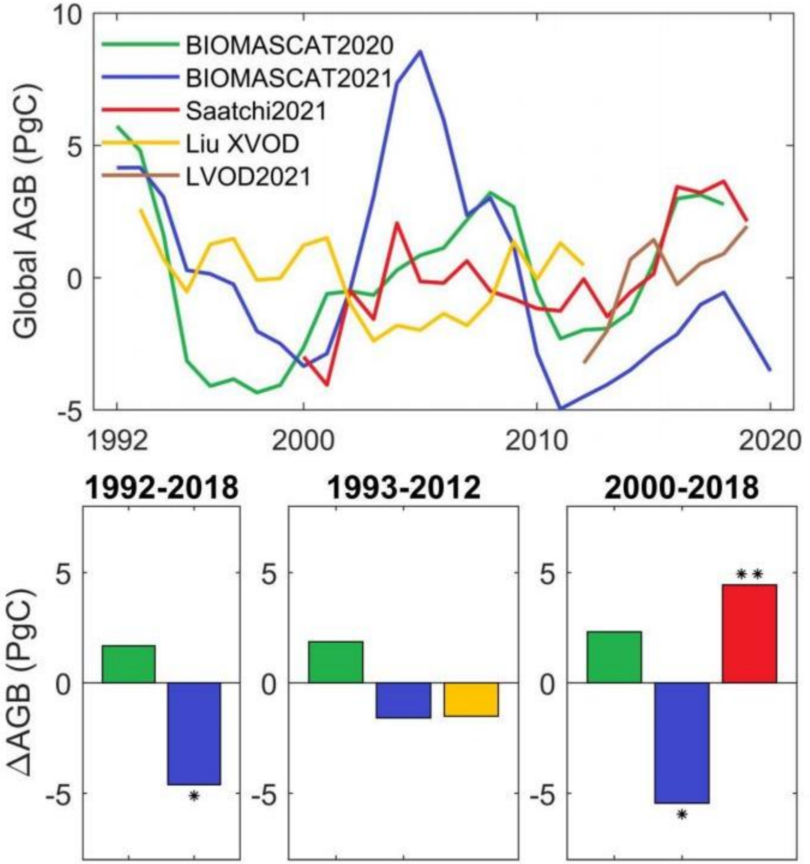
Motivation

- Vegetation productivity have increased significantly in recent decades.
- Vegetation carbon storage have not shown a clear or significant increase.



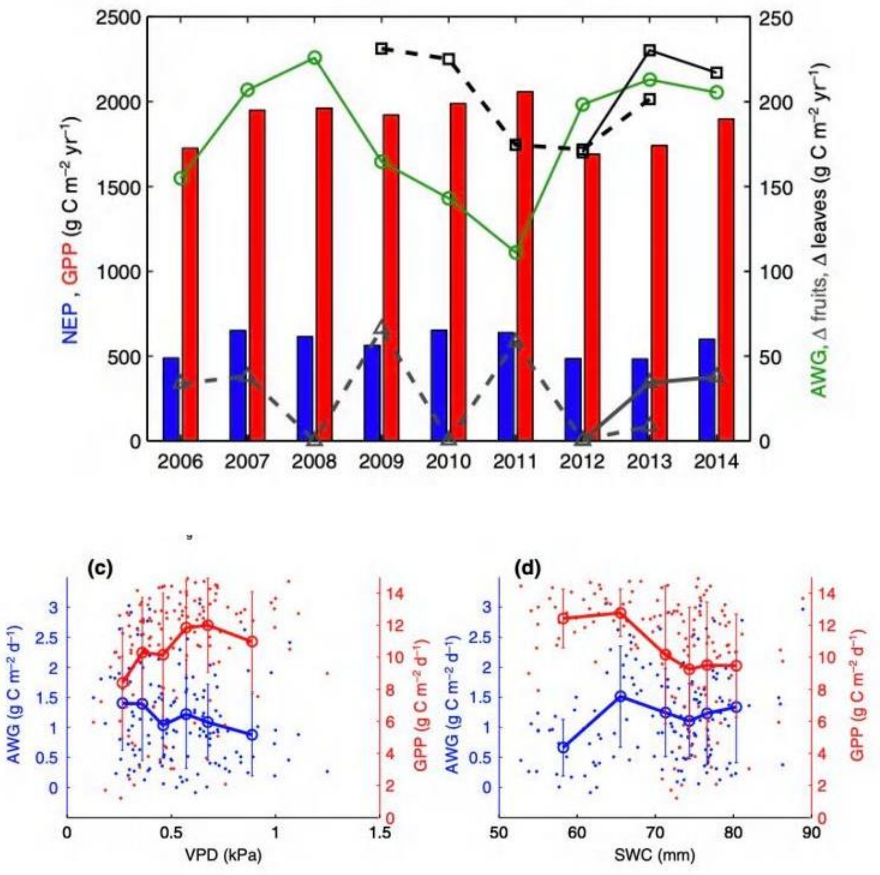


- Need to understand the relationship between vegetation carbon uptake and usage (storage).

(IPCC, AR6, Chapter 5)

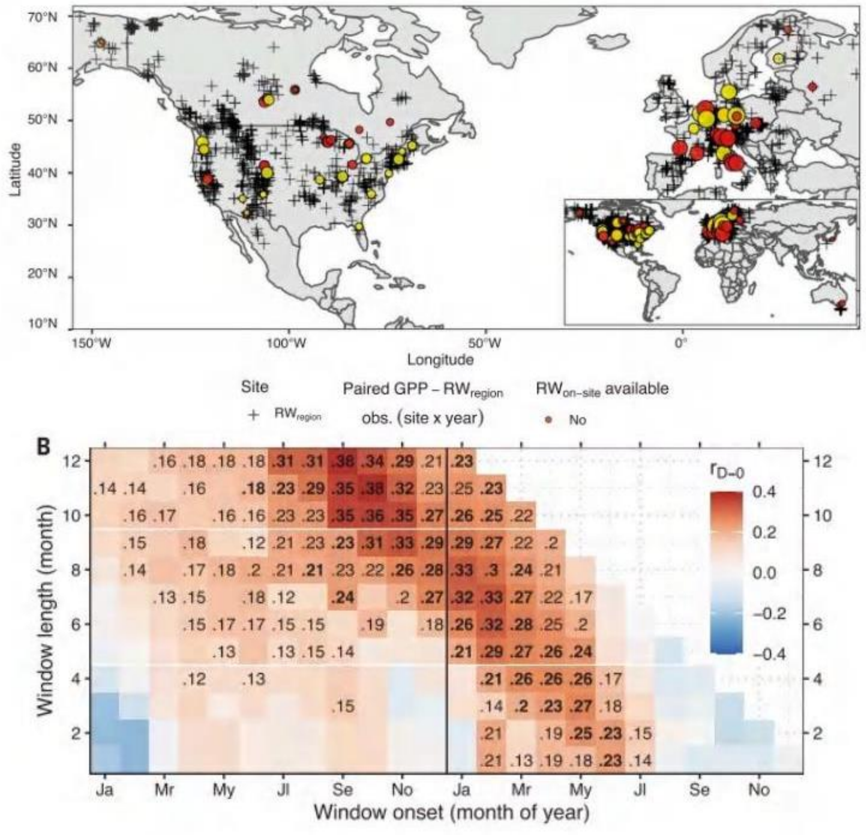
Introduction

- The Fontainebleau-Barbeau site (FR-Fon) temperate oak forest



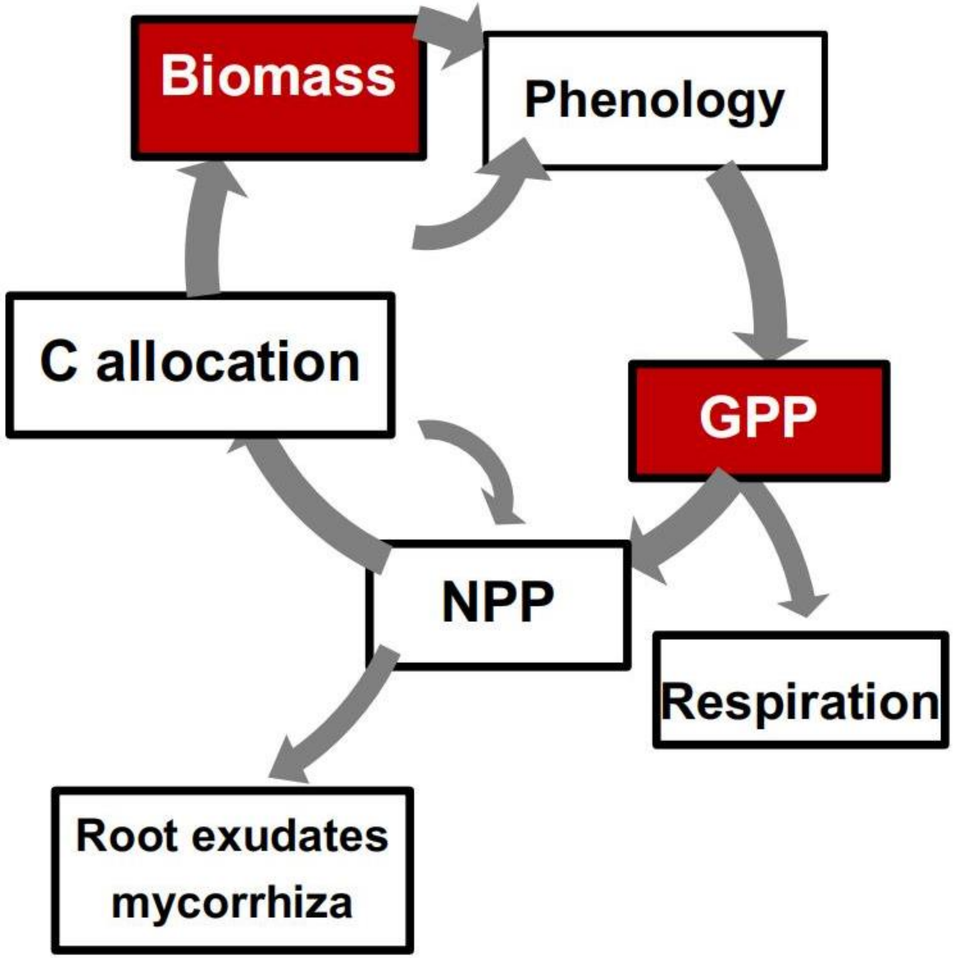
(Delpierre et al., NewPhytol., 2016)

- Eddy-covariance GPP records at 78 forest sites v.s. tree ring width



(Cabon et al., Science, 2020)

Introduction



I. **Natural biological decoupling**

- High metabolic activity
- Passive or active carbon allocation shifts
- Natural disturbances

II. Anthropogenic decoupling

- Disturbances (logging, fires, urbanization, ...)

Scientific questions

I. Where has carbon uptake (GPP) decoupled from carbon storage (AGB increment)?

Satellite-based high resolution GPP, biomass product; Northern Hemisphere

II. What are the driving factors influencing the degree of decoupling?

Vegetation properties, environmental conditions, human activities, ...

III. Can DGVMs capture such decoupling between carbon uptake and storage?

DGVMs typically assume a C source-limited scheme of tree growth, where tree growth is essentially proportional to the amount of C assimilated by photosynthesis.

Datasets

- MODIS MOD17A3HGF.061 GPP: total vegetation productivity

  (500 m spatial resolution, 2001-2020)

- CCI Biomass v5: (2024-07-14 version)
  - Above-ground biomass

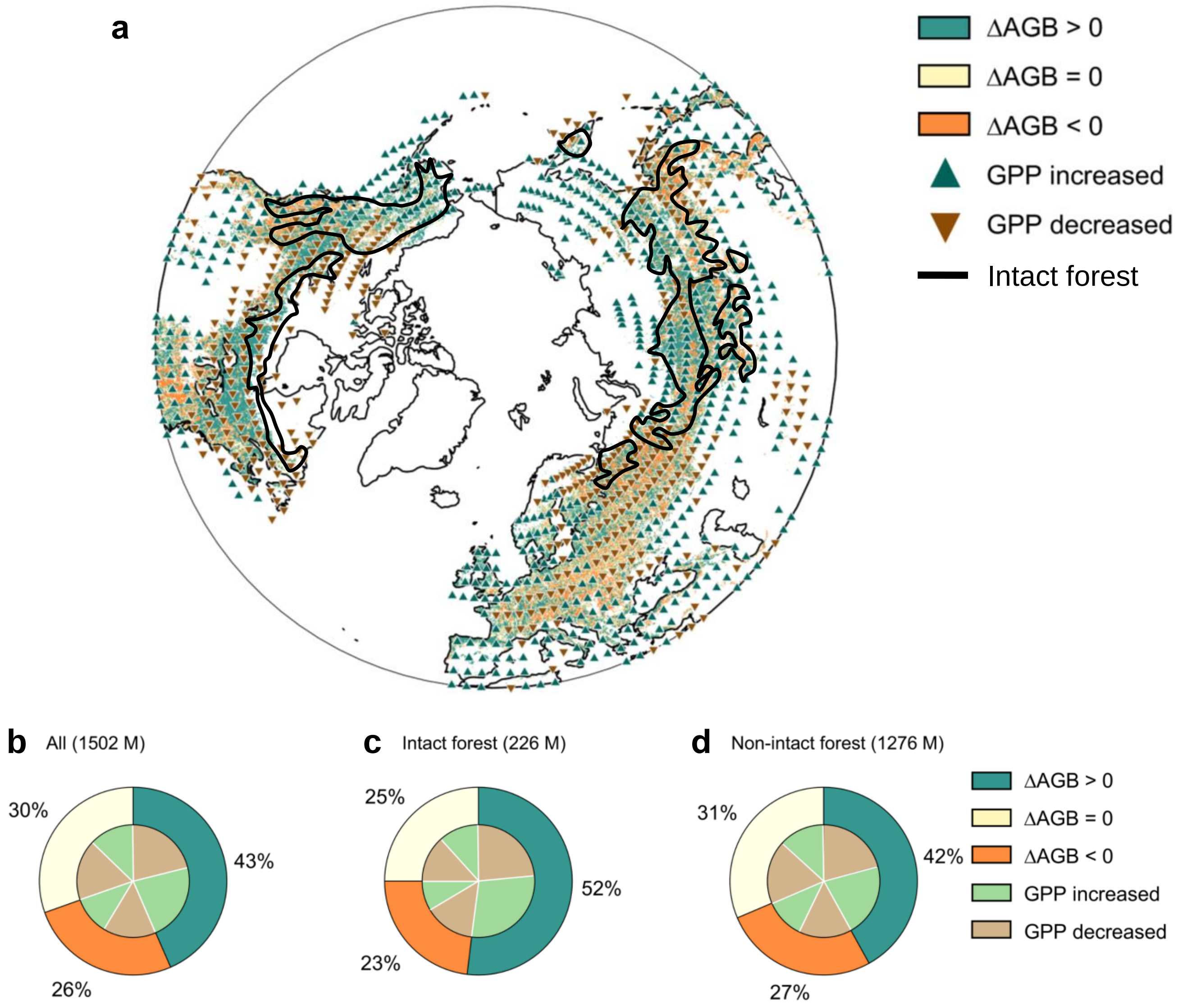
  (100 m spatial resolution; **2010**, 2015, 2016, 2017, 2018, **2020**)
  - Above-ground biomass change

  (1km spatial resolution, 2010-2020)

Aggregate AGB from 100m to 500m: $\frac{1}{n}\sum_{AGB>0} AGB_i$

Keep forest-dominant 500m pixel: *F*(AGB>100 Mg/ha) > 0.25

Widespread decoupling between ∑GPP and ΔAGB

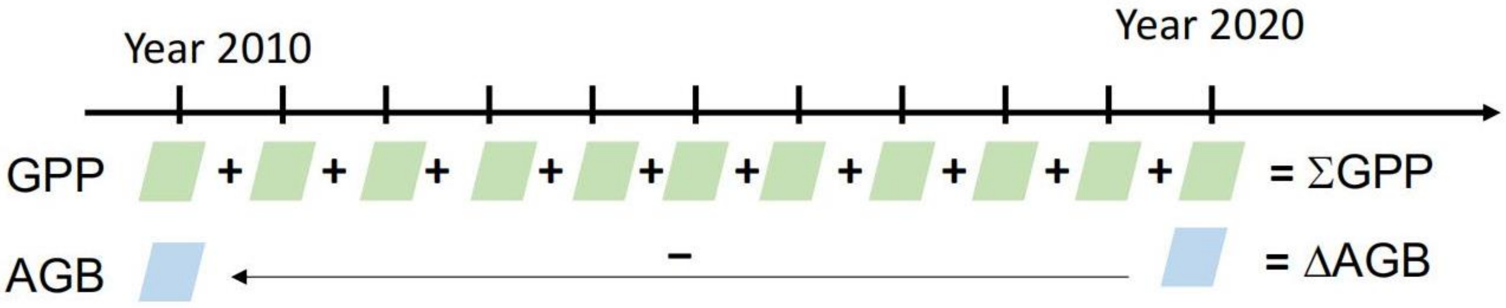


- Vegetation above-ground biomass growth is not always consistent with vegetation productivity trends. *(Fig. a)*
  - GPP trend from 2010 to 2020
    - triangle, regression coefficient more / less than zero
  - AGB change between 2010 and 2020.
    - Color pattern

- 24% of areas with increased productivity experienced declines in vegetation biomass, *(Fig. b)* particularly in non-intact forests *(Fig. c,d)*

Widespread decoupling between ∑GPP and ΔAGB

- For each 500m pixel,



  - $\Delta AGB_{\,2020-2010} = AGB_{2020} - AGB_{2010}$

$$= (AGB_{2020} - AGB_{2019}) - (AGB_{2019} - AGB_{2018}) - \cdots - (AGB_{2011} - AGB_{2010})$$

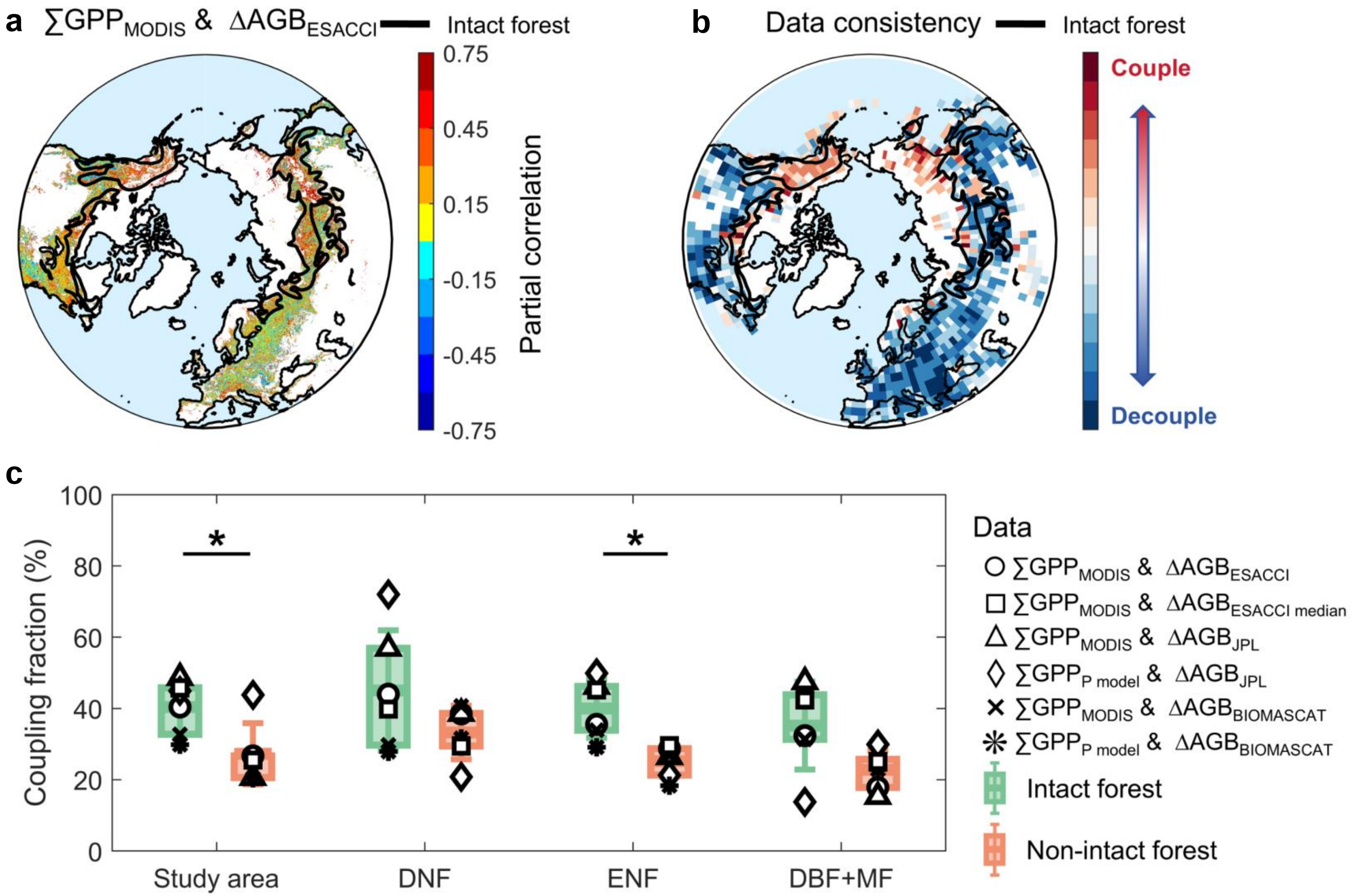
$$= \sum_{2011}^{2020} GPP - \frac{AGB_{2010}}{\tau}$$

- ”Spatial relationship between temporal changes in AGB and ΣGPP ”
  - In each **10 × 10 km (0.1º × 0.1º)** spatial window
  - The higher ΣGPP, the higher possibility with positive ΔAGB

    (when controlling *pixel mean c loss fraction*)

$$\Delta AGB = \Sigma GPP - k \times AGB_{2010}$$

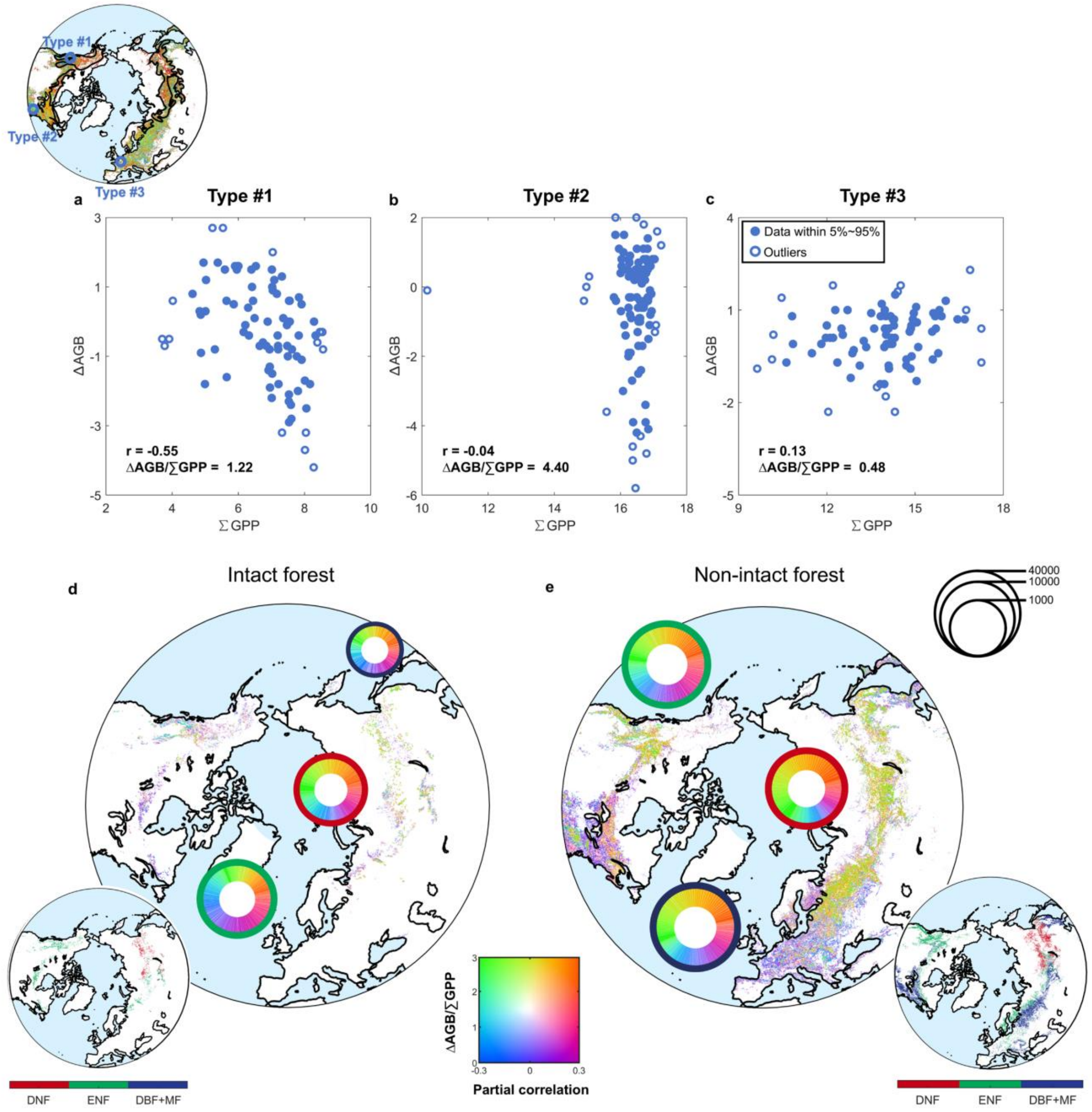
Widespread decoupling between ∑GPP and ΔAGB



- Extensive decoupling was observed **across Europe, western Russia and eastern Canada**. *(Fig. a,b)*
  - biomass changes were primarily driven by environmental or plant internal factors regardless of the amount of assimilated carbon

- Average fraction of decoupled area across datasets： *(Fig. c)*
  - Non-intact forest： **73** ± **9%**
  - **Intact forests： 60** ± **8%**

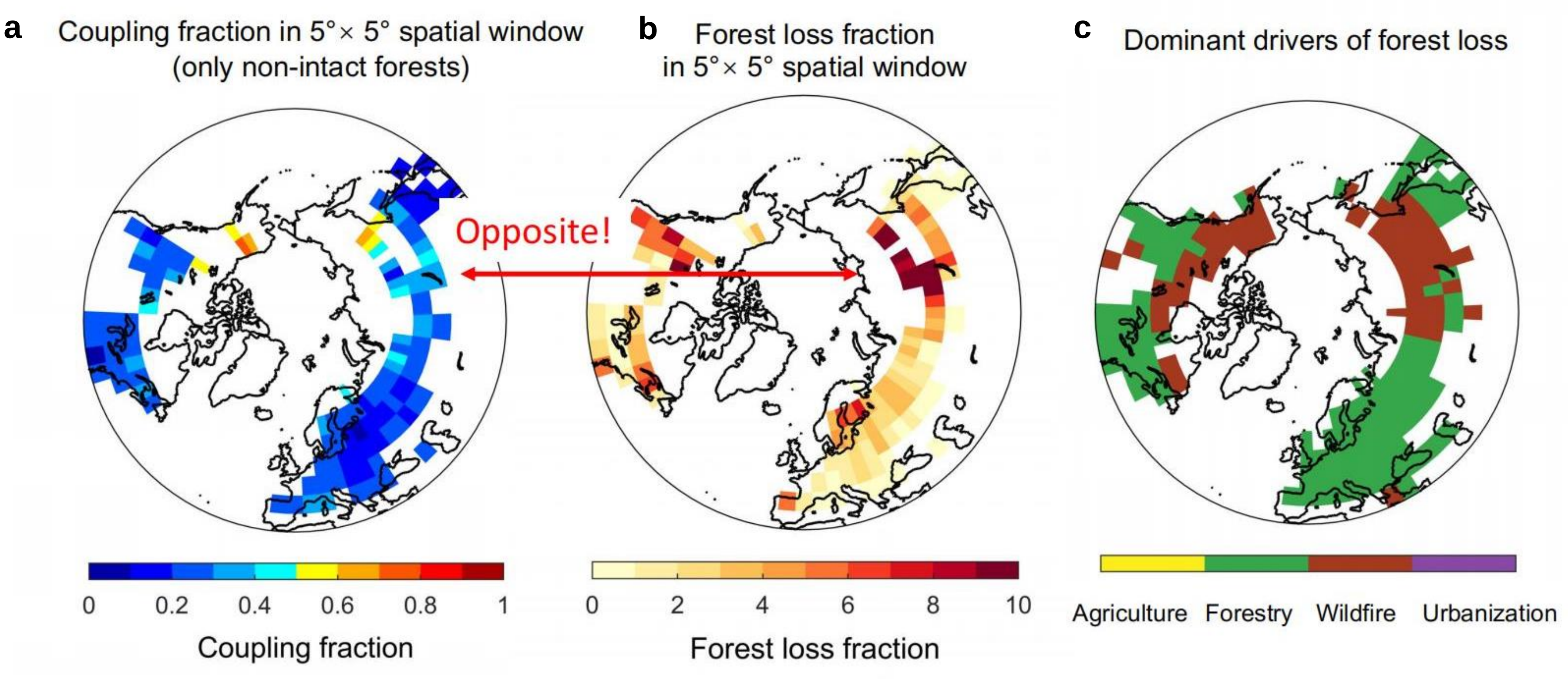
Three types of ∑GPP-ΔAGB decoupling



- **Type #1 and #2：stable productivity alongside biomass loss** *(Fig. a,b)*
  - abrupt biomass loss
  - across Russia, eastern Europe, and non-intact forests in western Canada *(Fig. d,e)*
- **Type #3：no biomass increment despite increased productivity** *(Fig. c)*
  - CO_2 fertilization and forest management / carbon saturation
  - European forests as well as in intact forests in western Canada. *(Fig. d,e)*

Factors influencing the level of [de]coupling

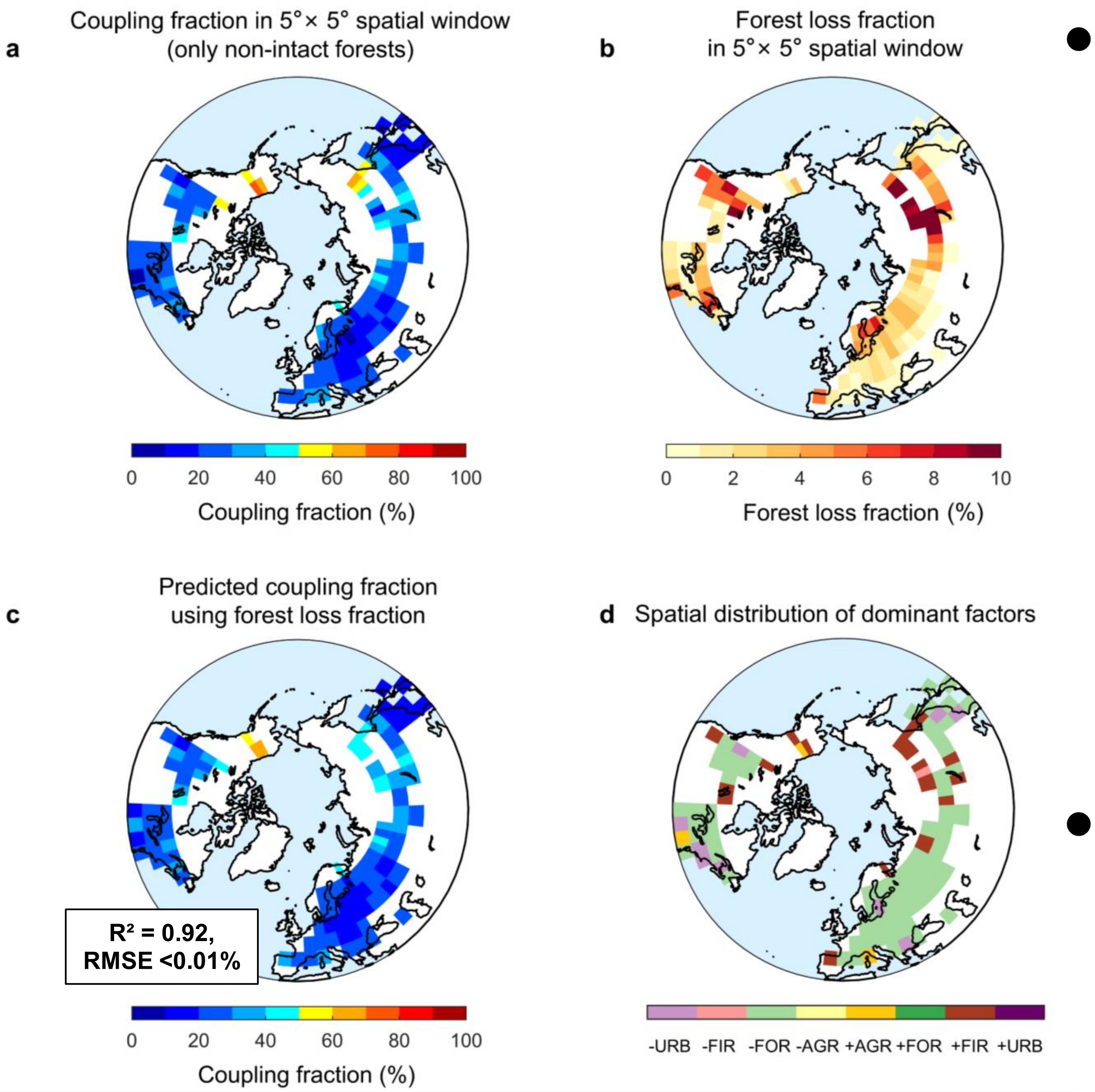
- Non-intact forests
  - We calculate coupled area fraction and forest loss fraction in 5° × 5° window *(Fig. b)*
  - Seemingly opposite: the higher forest loss, the higher coupling *(Fig. a, b)*
  - Due to different drivers of forest loss *(Fig. c)*



(Hansen et al., 2013)

(Curtis et al., 2013)

Factors influencing the level of [de]coupling

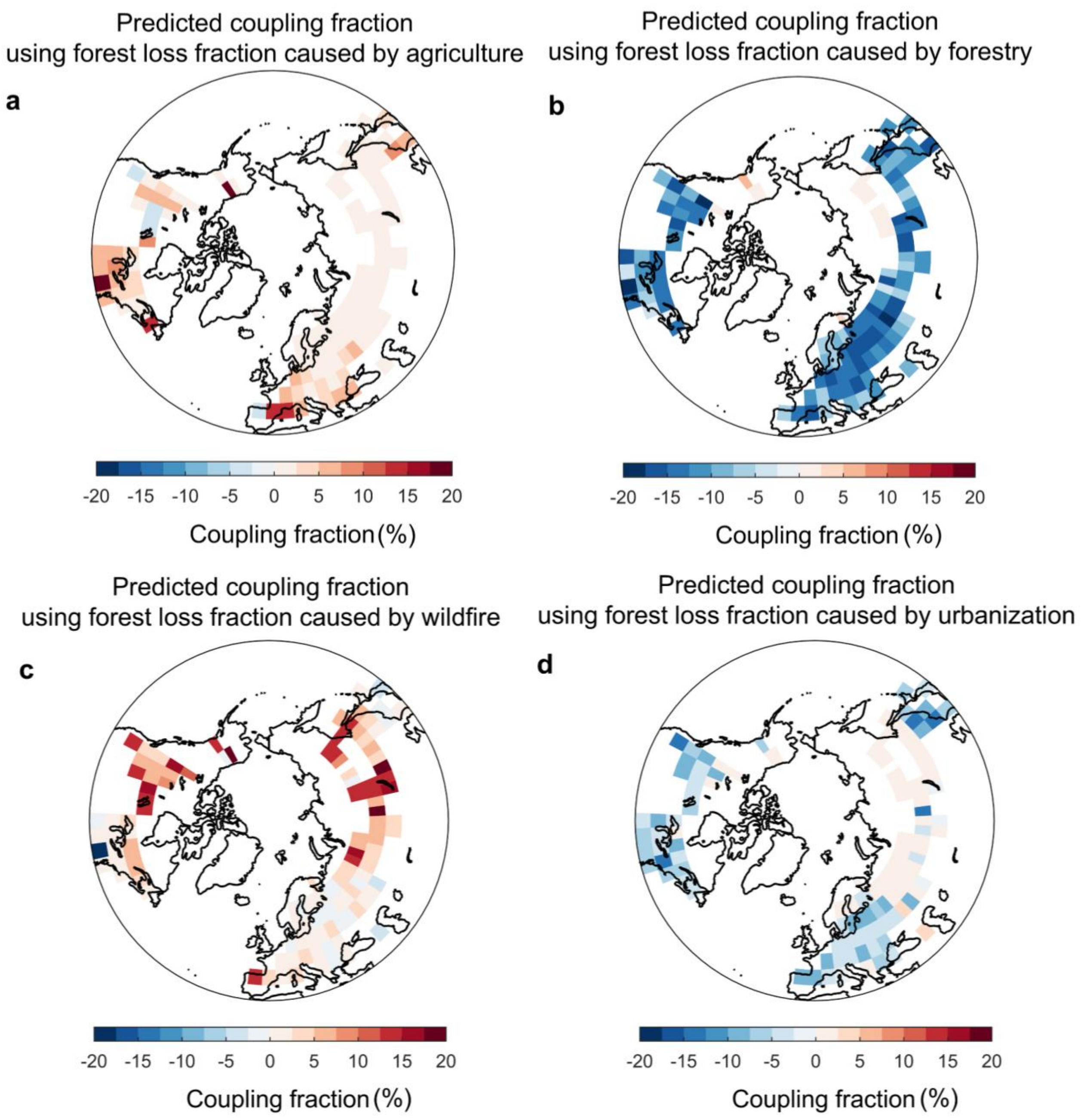


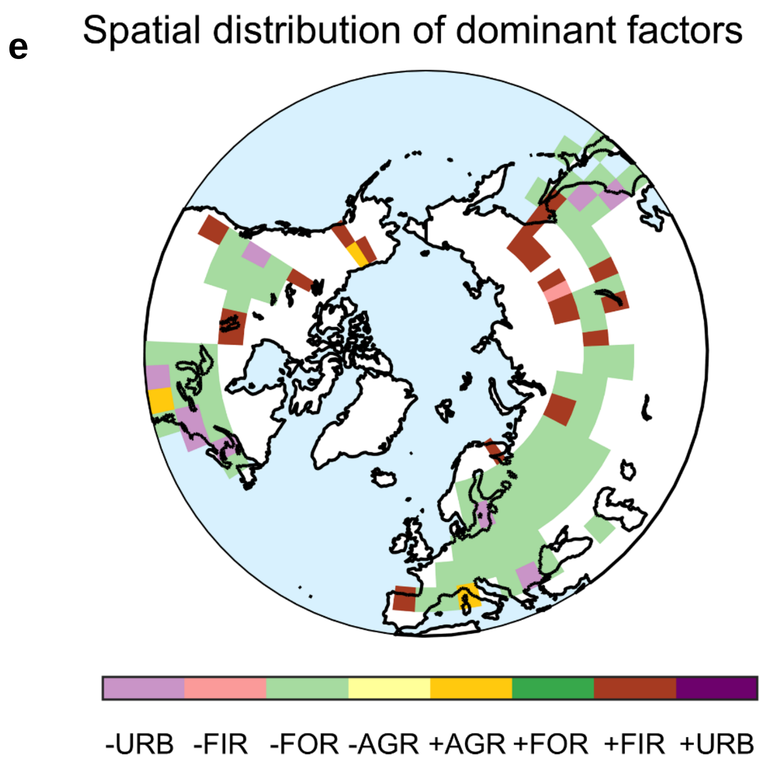
- Non-intact forests
  - Generalized Additive Model (GAM)
  - We calculate **coupled area fraction** ($f_{coupled\ pixels}$) and **forest loss fraction** (FL) caused by **anthropogenic disturbance factor** (agriculture, wildfire, forestry, urbanization) in 5° × 5° window
  - Their individual contribution were modeled as：

$$f_{coupled\ pixels} = \beta_0 + s(FL_{AGR}) + s(FL_{FOR}) + s(FL_{FIR}) + s(FL_{URB}) + \varepsilon$$

- The GAM model successfully explained 92% of the spatial variability in decoupling fraction across non-intact forests (**R^2 = 0.92**) with a low prediction error (**RMSE <0.01%;** *Fig. c*).

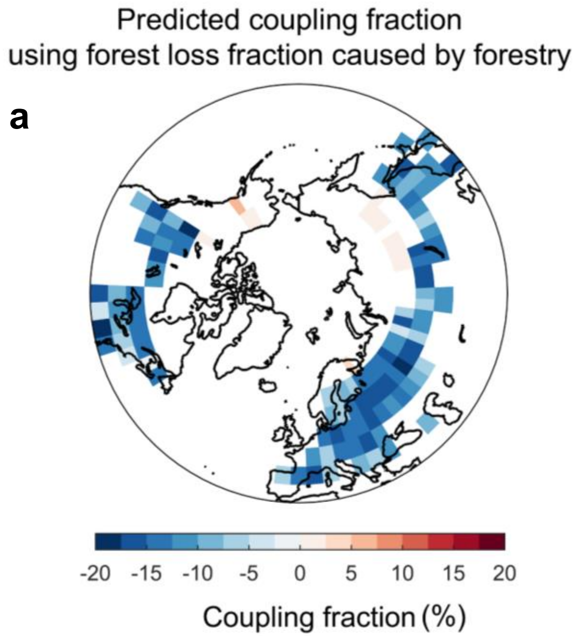
Factors influencing the level of [de]coupling

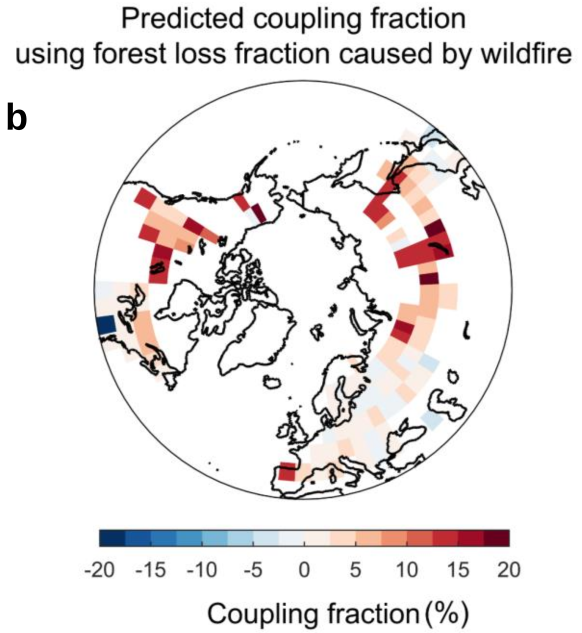




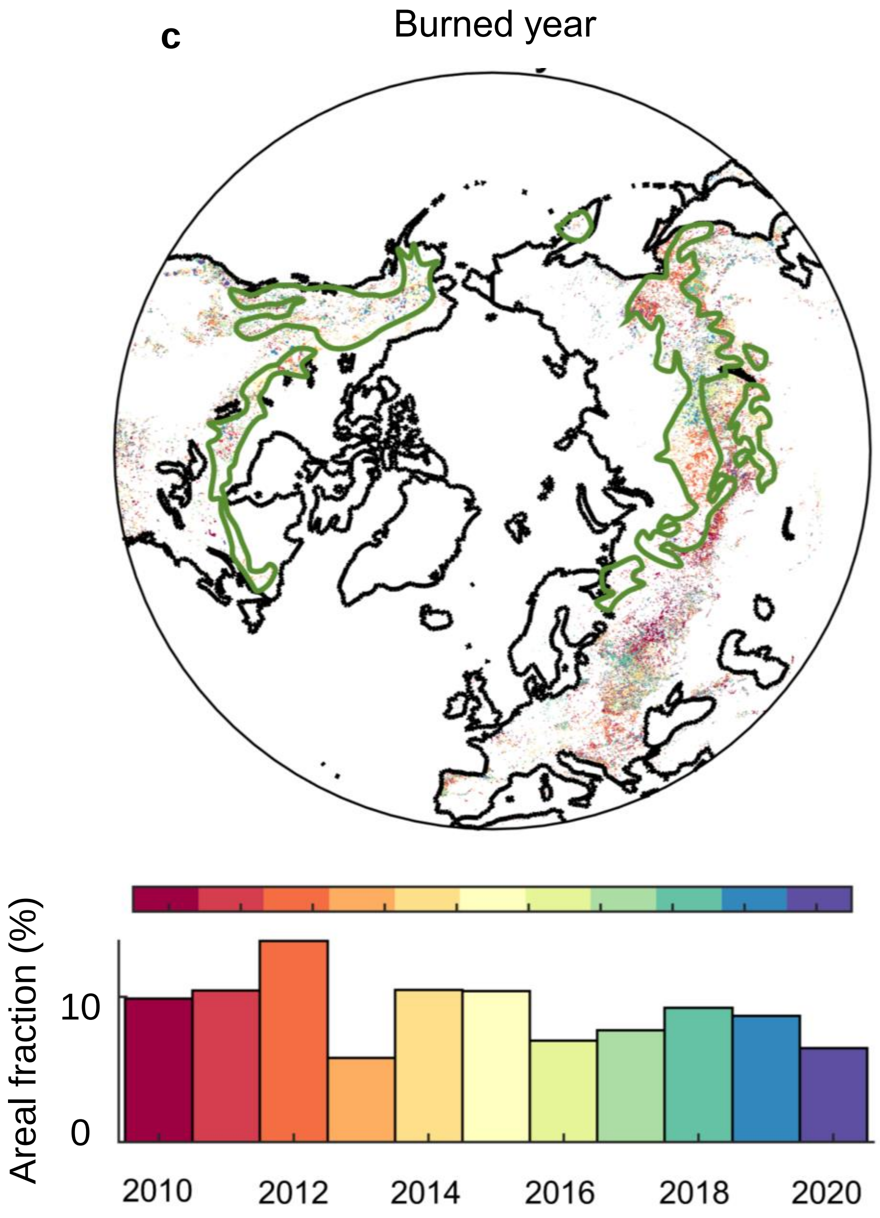
- Non-intact forests
  - Forestry in Eastern Europe and Eastern Canada had a strong negative impact reducing coupling fraction by **10.60 ± 5.52%** *(Fig. b)*
  - Wildfires in Siberia and Western Canada had a positive impact increasing coupling fraction by **4.5 ± 6.4%** *(Fig. c)*

Factors influencing the level of [de]coupling





- Non-intact forests
  - The positive impacts of wildfires in Siberia dominates *(Fig. b),* partially **offsetting** the negative impacts of forestry *(Fig. a)*
  - Wildfires' positive effects major fires occurring in the early 2010s (*Fig. c*), followed by **rapid vegetation regrowth** before the end of our study period.
    - carbon assimilated through photosynthesis is **primarily used for growth**



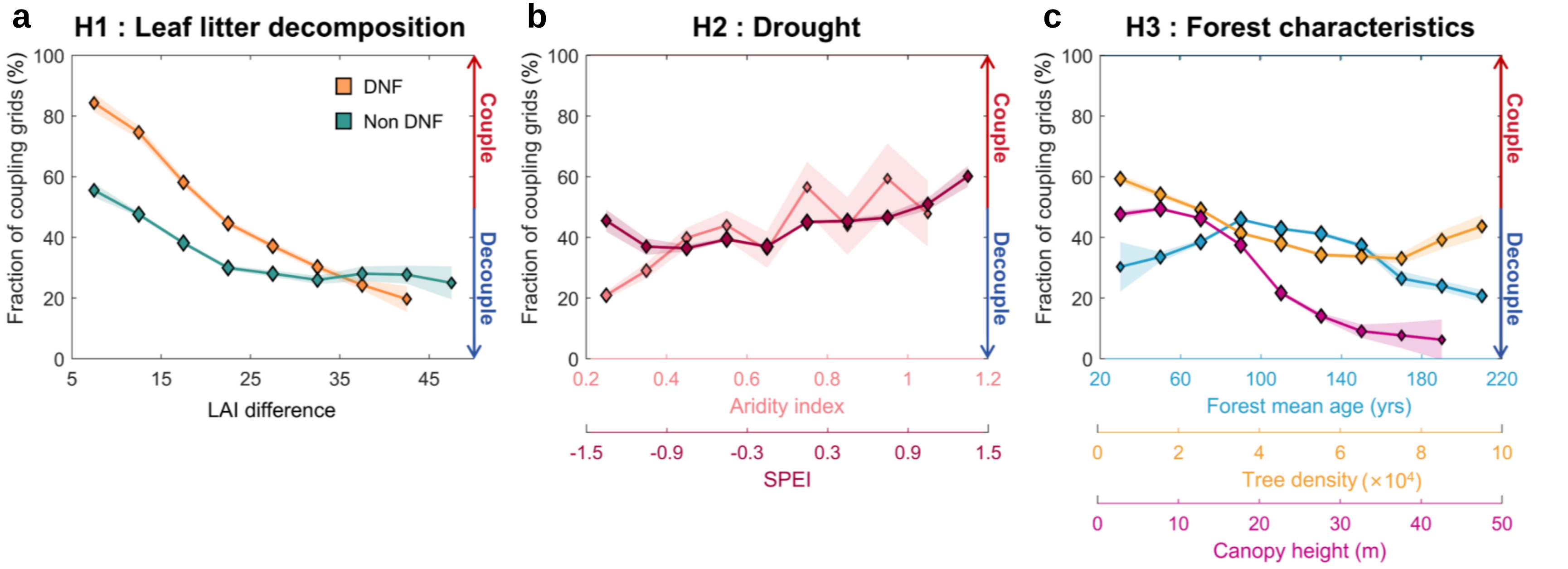
Factors influencing the level of [de]coupling

- Intact forests

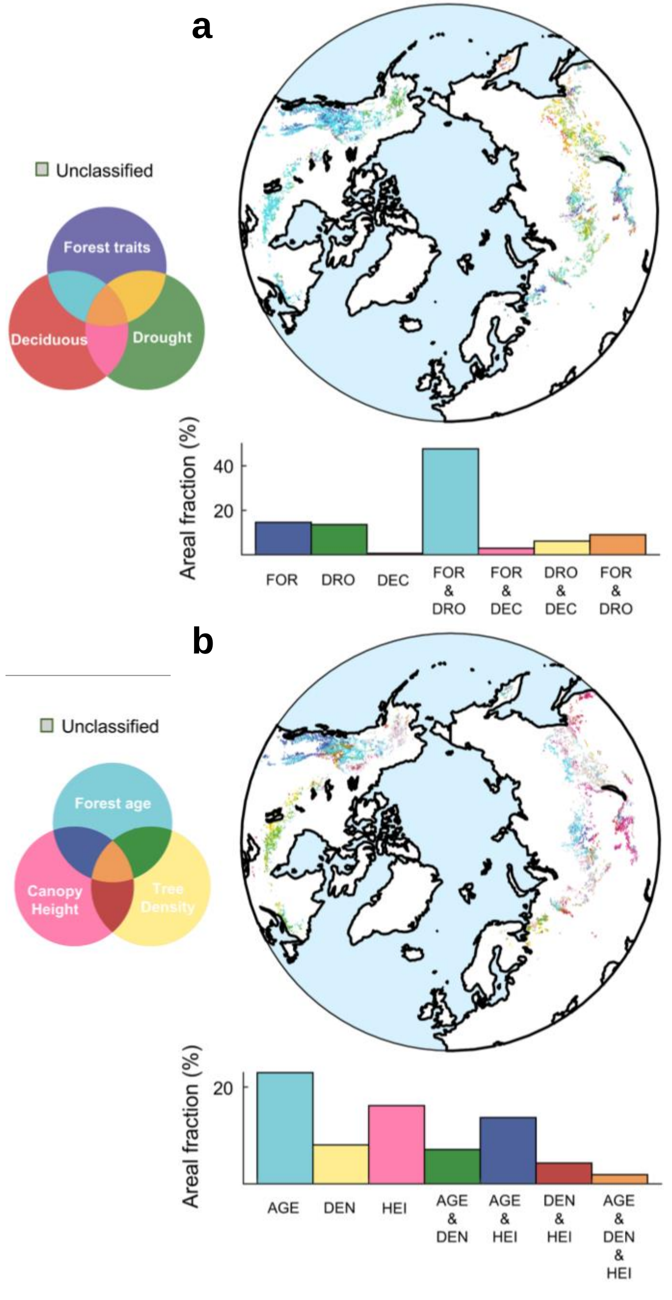
- **H1**：assimilated carbon was allocated to tissues with **fast turnover rates** such as leaves and fine roots 【Deciduous classification, including ΔLAI_{gs}, *Fig. a*】

- **H2**：under drier conditions, assimilated carbon is allocated as **nonstructural carbohydrates** 【Drought classification, including aridity index and 1-month SPEI, *Fig. b*】

- **H3**：tall, old-growth and dense forests have **limited capability for biomass growth** due to high metabolic demand, intense competition, or high mortality risk 【Forest trait classification, including mean forest age, tree density and canopy height, *Fig. c*】



Factors influencing the level of [de]coupling



- Intact forests

  - Their individual contribution were modeled as：

$$log\left(\frac{P(X)}{1-P(X)}\right) = \beta_0 + s(SPEI_1) + s(AI) + s(\Delta LAI_{gs}) + s(AGE) + s(DEN) + s(HEI) + \varepsilon$$

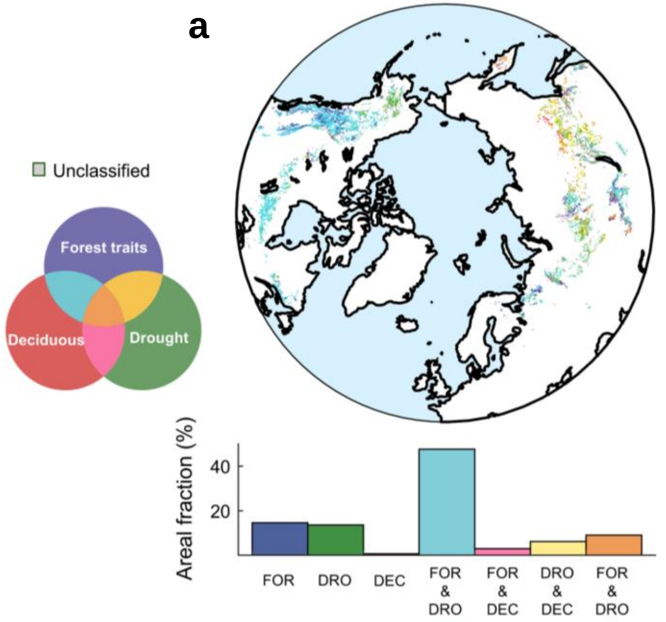
  - *P(X)*： the probability of pixels being classified as coupled.

  - $SPEI_1, AI, \Delta LAI_{gs}, AGE, DEN$ and HEI： 1-month SPEI, aridity index, the difference between maximum and minimum leaf area index values during growing season, mean forest age, tree density and canopy height

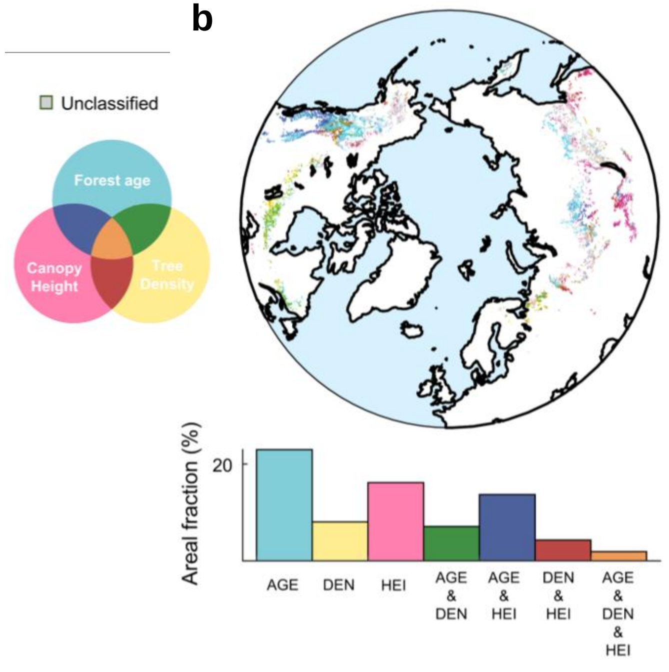
  - **Influencing factors** for decoupling were defined as those **reducing increasing the probability of being classified as decoupled by over 3%**(This threshold balances minimizing unclassified areas and maximizing effect values, *Fig a, b*)

Factors influencing the level of [de]coupling

a

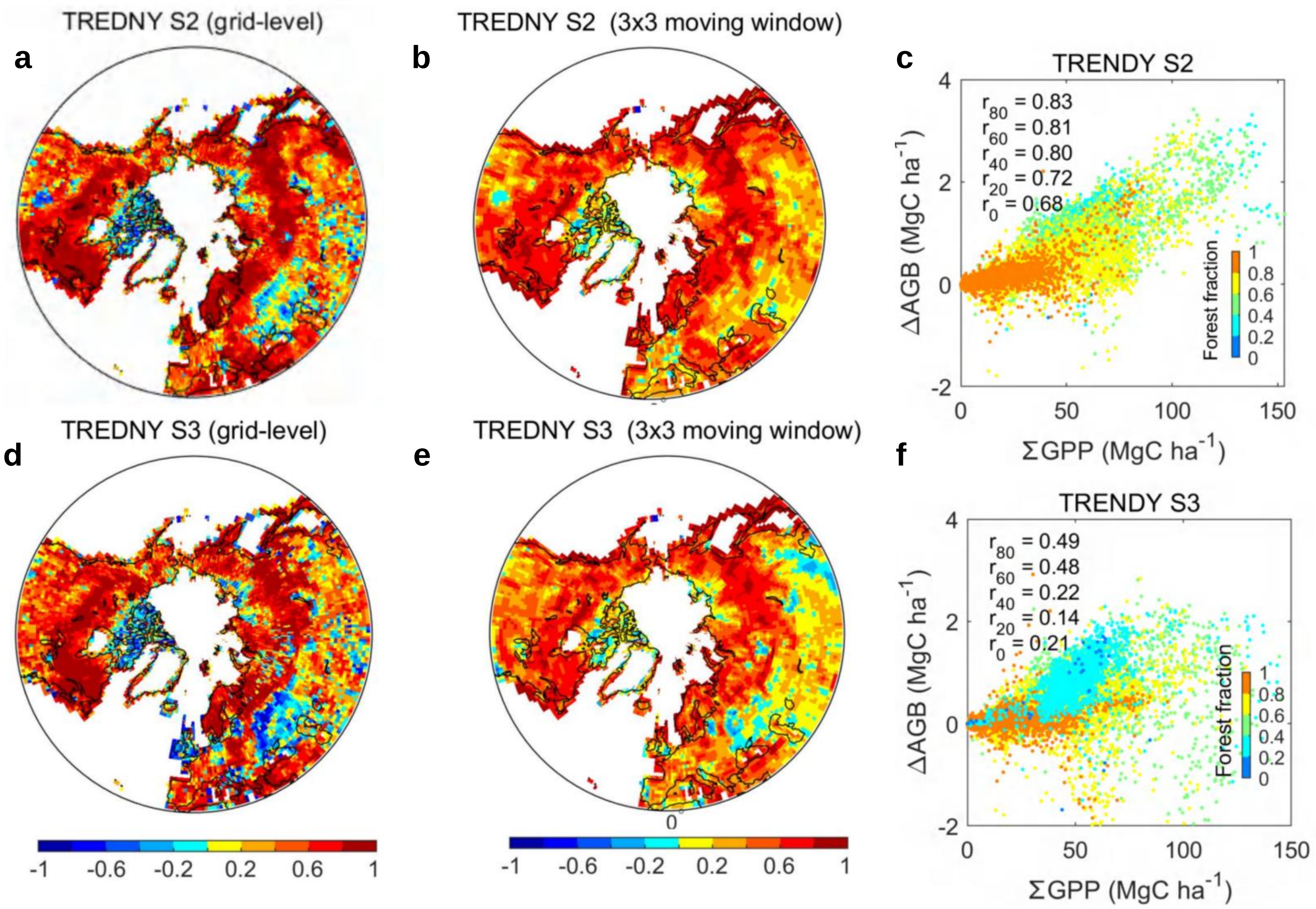


b



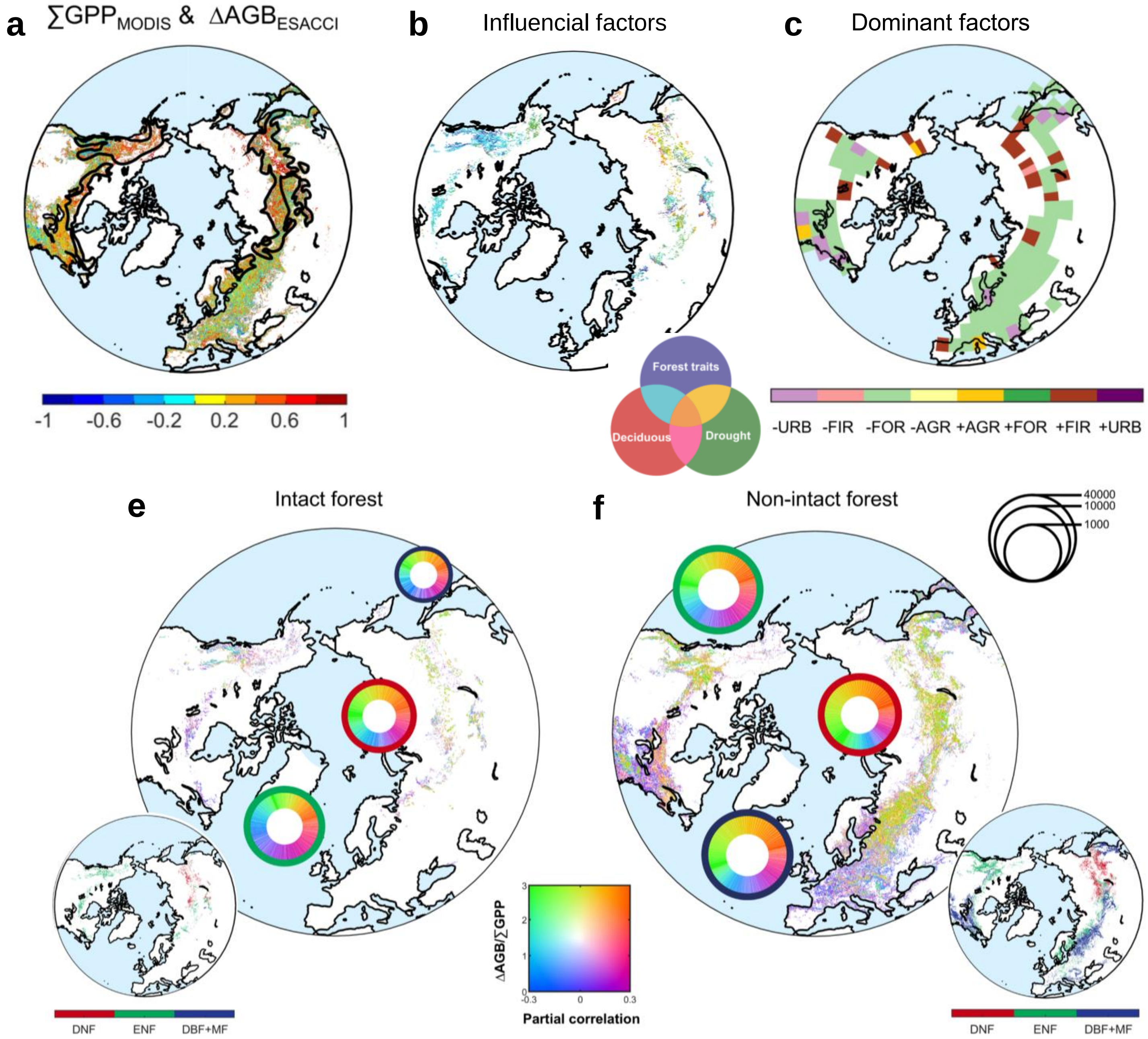
- Intact forests
  - GAM classification overall accuracy：66%
  - high accuracy (80%) in observed decoupled forests
  - Decoupling signals in **intact forests** were mainly associated with **water stress and forest traits**, accounting for 80% of decoupled intact forests (*Fig. a*)
  - Eurasia and eastern Europe：**drought** (*Fig. a*)
  - Canada：**forest-specific characteristics** (*Fig. a*)
    - **Aging** and **tall intact forests** maintain high productivity through photosynthesis, yet **enhanced carbon assimilation does not translate into biomass growth**—possibly due to elevated metabolic activity or intrinsic growth-mortality trade-offs (*Fig. b*)

Strong source limitation in vegetation biomass growth from DGVMs



- TRENDY 14 DGVMs, S2 & S3. 1980-2019
    - Partial correlation were calculated using ∑GPP and ΔAGB every 10 years, 1980-1989, 1985-1994,…, 2010-2019
- Current DGVMs are predicting **forest** biomass growth as a proportional function of the amount of carbon assimilated, *(Fig. c, f)* reflecting strong source limitation of plant growth. *(Fig. a-b, d-e)*
- **In herbaceous vegetation**, carbon **residence time is shorter than one year,** preventing significant biomass accumulation despite carbon uptake during the growing season

Summary



- The fraction of decoupled area in non-intact forest is **73 ± 9%,** significantly higher than in the intact forest. Extensive decoupling was observed across Europe, Russia and Canada. *(Fig. a)*

- Even in **intact forests**, **60 ± 8%** still exhibited the decoupling signals *(Fig. a)*

- In **western Russia**, this decoupling appears to be driven by **droughts**, likely due to **carbon allocation shifts** to support metabolism and critical plant functions, thereby constraining biomass growth. *(Fig. b,e)*

- In **western Canada**, decoupling was found in **old-growth, or dense** intact forests, where high decomposition, competition, or mortality may result in **stable or declining forest biomass** over time. *(Fig. b,e)*

- The **positive** impacts of **wildfires** in Siberia dominates *(Fig. c),* partially **offsetting** the **negative** impacts of **forestry** *(Fig. f)*


THANKS