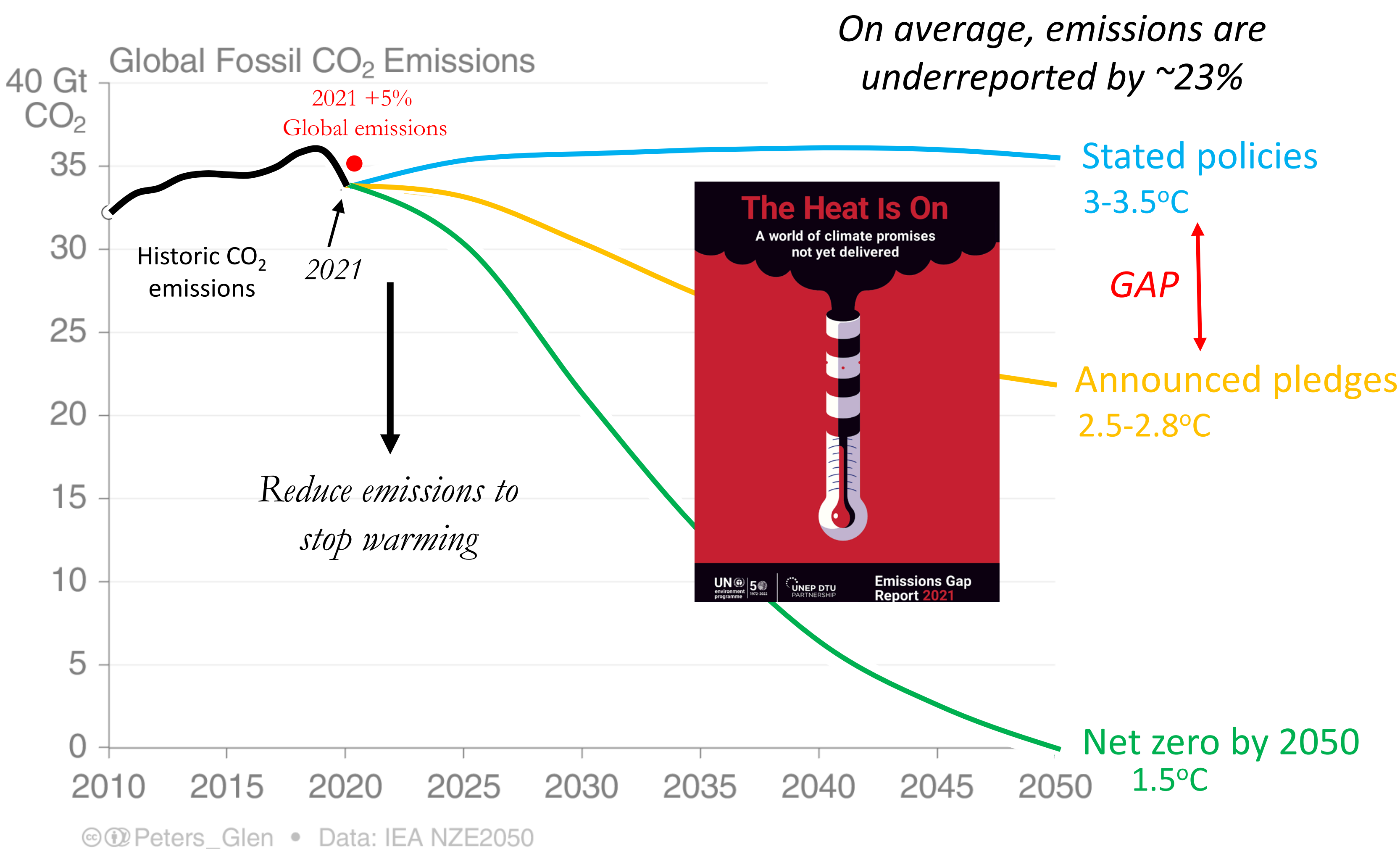
Emission Pathways



Fate of anthropogenic CO_2 emissions (2010–2019)

Sources = Sinks

34.4 $GtCO_2/yr$
86%

14%
5.7 $GtCO_2/yr$

Budget Imbalance:
(the difference between estimated sources & sinks)
0.4%
0.2 $GtCO_2/yr$

18.6 $GtCO_2/yr$
46%

~~31%~~
~~12.5 $GtCO_2/yr$~~

23%
9.2 $GtCO_2/yr$

Global Carbon Project (2020) Global energy growth is outpacing decarbonization: https://www.globalcarbonproject.org

- Plant photosynthesis removes CO_2 from the air
- Plant respiration releases CO_2 to the air
- Photosynthesis has a thermal maximum, past which:
  - Photosynthesis sharply declines
  - Respiration continues to increase
  - Carbon uptake by land plants is degraded
- With continued emissions,
  - **Carbon uptake may be degraded nearly 50% as early as 2040**
- This effect is **not accounted for** in National Policies

SCIENCE ADVANCES | RESEARCH ARTICLE

ENVIRONMENTAL STUDIES

How close are we to the temperature tipping point of the terrestrial biosphere?

Katharyn A. Duffy[1,2]*, Christopher R. Schwalm[2,3], Vickery L. Arcus[4], George W. Koch[2], Liyin L. Liang[4,5], Louis A. Schipper[4]

The temperature dependence of global photosynthesis and respiration determine land carbon sink strength. While the land sink currently mitigates ~30% of anthropogenic carbon emissions, it is unclear whether this ecosystem service will persist and, more specifically, what hard temperature limits, if any, regulate carbon uptake. Here, we use the largest continuous carbon flux monitoring network to construct the first observationally derived temperature response curves for global land carbon uptake. We show that the mean temperature of the warmest quarter (3-month period) passed the thermal maximum for photosynthesis during the past decade. At higher temperatures, respiration rates continue to rise in contrast to sharply declining rates of photosynthesis. Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040.

INTRODUCTION

The difference between gross primary productivity, carbon uptake by vegetation, and total ecosystem respiration, carbon loss to the atmosphere, comprises the metabolic component of the land carbon sink [net ecosystem productivity (NEP)]. To date, land ecosystems provide a climate regulation service by absorbing ~30% of anthropogenic emissions annually [mean ± 1 SD: 2.6 petagrams carbon (PgC) ± 0.8 year^{-1}] (*1*). While temperature functions as a key driver of year-to-year changes in the land carbon sink (*2*), its temperature response is still poorly constrained at biome to global scales (*3*, *4*), making the carbon consequences of anticipated warming uncertain.

Like all biological processes, metabolic rates for photosynthesis and respiration are temperature dependent; they accelerate with increasing temperature, reach a maximum rate, and decline thereafter. Yet, these carbon fluxes do not necessarily have the same temperature response, potentially resulting in sharp divergences in ecosystem carbon balance. For example, increasing respiration rates without corresponding increases in photosynthesis rates would decrease the efficacy of the terrestrial carbon sink. An observational constraint on the net difference in metabolic response across both gross fluxes is thus urgently needed to constrain projections of the future land carbon sink and, more specifically, isolate points of nonlinear and perhaps nonreversible change—tipping points (*5*). This is especially relevant given the highly divergent land carbon sink trajectories from Earth system models (*4*) that, nevertheless, agree on continued future increases in sink strength due to the CO_2 fertilization effect (*3*).

Given in situ evidence that regions of the terrestrial biosphere are experiencing temperature thresholds at which they switch from a carbon sink to source (*6*–*8*), we asked the following questions: (i) What are the thermal maxima of photosynthesis (T_P^{max}) and respiration (T_R^{max}) at biome to global scales? (ii) What is the thermal maximum for the land sink of carbon (T_{NEP}^{max}) and current mean temperature range with regard to this critical threshold? (iii) At what global and regional temperatures do we expect the land sink of carbon to decline? (iv) Are those temperatures in the foreseeable future?

To address these questions, we used measurements from the largest continuous carbon monitoring network, FLUXNET (*9*), as an observational constraint to determine the temperature dependence of global rates of photosynthesis and respiration. Across ~1500 site years of daily data from all major biomes and plant functional types, we applied a 30-day moving window partial correlation analysis at each flux tower site to extract the temperature signal (a change in photosynthesis or respiration solely attributable to changes in temperature, i.e., the signal excludes other climatic effects such as water availability and sunlight) from daytime partitioned gross primary productivity [photosynthesis (P)] and total ecosystem respiration (R). We then normalized each site-level temperature dependence curve and applied macromolecular rate theory (MMRT) (*10*) in conjunction with Monte Carlo resampling to avoid length-of-record bias. The curves were subsequently aggregated to the biome level and then area-weighted to arrive at a global constraint of temperature dependence (see Materials and Methods). MMRT is a framework rooted in the principles of thermodynamics, which provides a mechanistic basis to extract the temperature dependence of rates across scales from individual enzyme kinetics to organismal and ecosystem metabolism (see Materials and Methods) (*11*). This framework is based on classical transition state theory from physical chemistry (*12*) and describes temperature rate dependence using three parameters, with emphasis on a maximum or optimal temperature value, T^{max}, above which rates decline exponentially. The Arrhenius function is a special case of MMRT where the heat capacity term is zero and the temperature-rate relationship is exponential without a maximum (see Materials and Methods) (*10*). MMRT is applicable across a range of processes and levels of biological organization and has been successfully used to model the temperature dependence of enzyme kinetics (*13*), microbial growth (*14*), soil

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- The Amazon contains more than half of all tropical rainforest
- Logging, mining, hunting, deforestation, damming, drought, tree mortality (heating)
- *The Amazon lost 1/3 of all biomass between 2010 and 2019*
- From 2010 through 2019, Brazil's Amazon basin gave off *18.3 billion tons* of carbon dioxide equivalent, but only drew down *15.3 billion tons.*
- **It is now likely that the Amazon is a net source of greenhouse gas emissions.**

frontiers in Forests and Global Change

REVIEW
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Check for updates

Carbon and Beyond: The Biogeochemistry of Climate in a Rapidly Changing Amazon

Kristofer Covey[1*], Fiona Soper[2], Sunitha Pangala[3], Angelo Bernardino[4], Zoe Pagliaro[1], Luana Basso[5], Henrique Cassol[6], Philip Fearnside[7], Diego Navarrete[8], Sidney Novoa[9], Henrique Sawakuchi[10], Thomas Lovejoy[11], Jose Marengo[12], Carlos A. Peres[13], Jonathan Baillie[14], Paula Bernasconi[15], Jose Camargo[7], Carolina Freitas[16], Bruce Hoffman[17], Gabriela B. Nardoto[18], Ismael Nobre[19], Juan Mayorga[14,20], Rita Mesquita[7], Silvia Pavan[21], Flavia Pinto[22],Flavia Rocha[23], Ricardo de Assis Mello[24], Alice Thuault[15], Alexis Anne Bahl[14] and Aurora Elmore[14]

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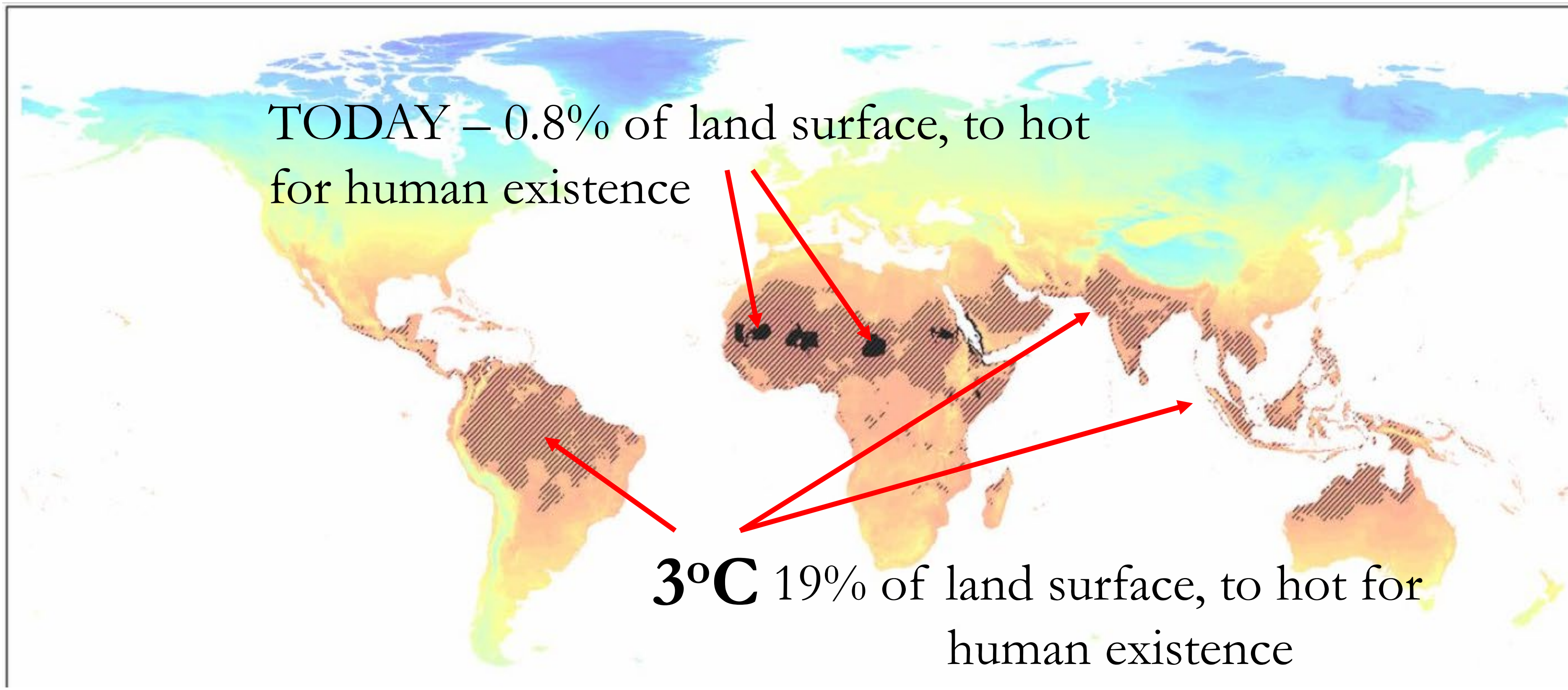
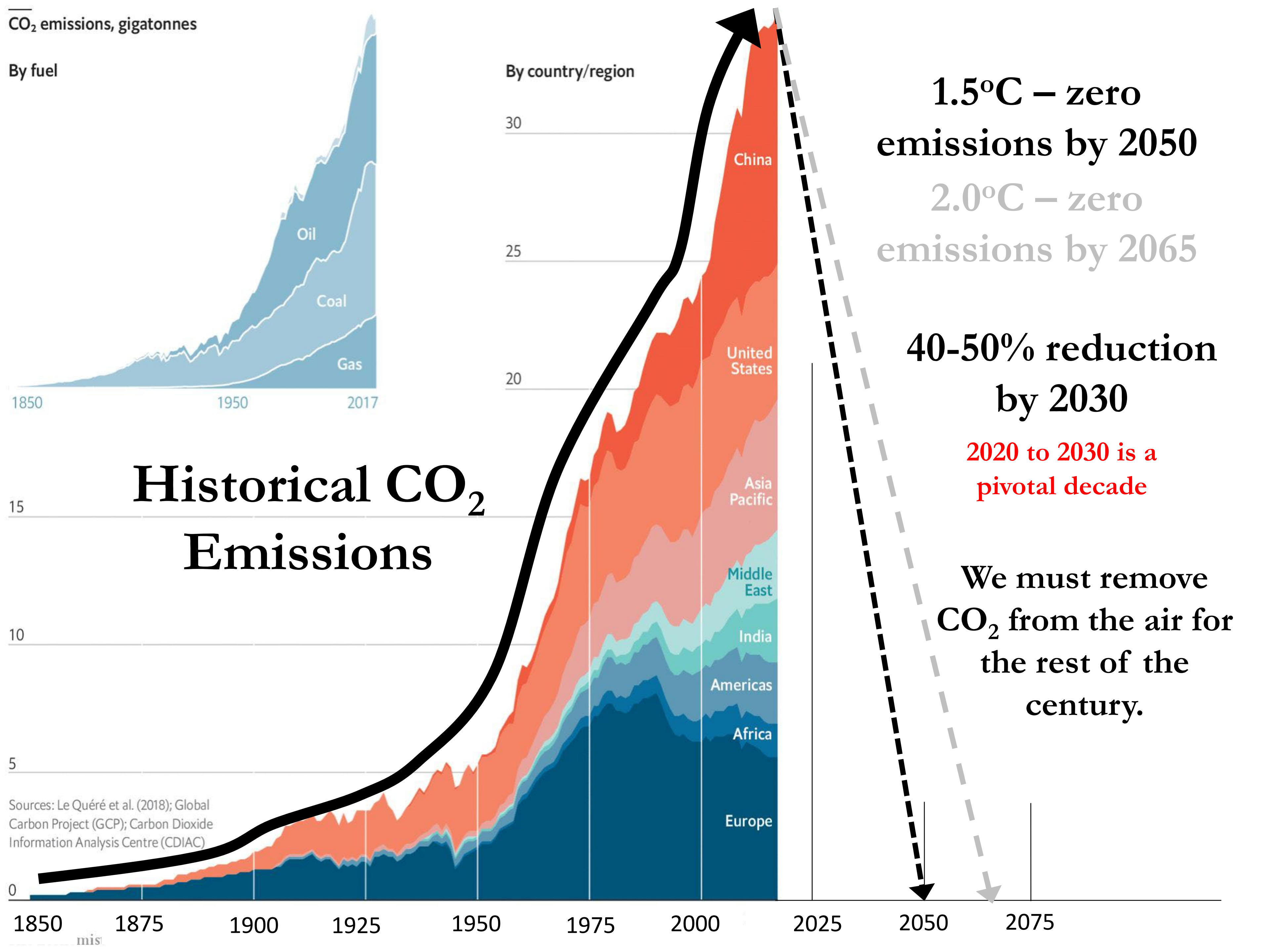
The Amazon Basin is at the center of an intensifying discourse about deforestation, land-use, and global change. To date, climate research in the Basin has overwhelmingly focused on the cycling and storage of carbon (C) and its implications for global climate. Missing, however, is a more comprehensive consideration of other significant biophysical climate feedbacks [i.e., CH_4, N_2O, black carbon, biogenic volatile organic compounds (BVOCs), aerosols, evapotranspiration, and albedo] and their dynamic responses to both localized (fire, land-use change, infrastructure development, and storms) and global (warming, drying, and some related to El Niño or to warming in the tropical Atlantic) changes. Here, we synthesize the current understanding of (1) sources and fluxes of all major forcing agents, (2) the demonstrated or expected impact of global and local changes on each agent, and (3) the nature, extent, and drivers of anthropogenic change in the Basin. We highlight the large uncertainty in flux magnitude and responses, and their corresponding direct and indirect effects on the regional and global climate system. Despite uncertainty in their responses to change, we conclude that current warming from non-CO_2 agents (especially CH_4 and N_2O) in the Amazon Basin largely offsets—and

Warming on Land

1 billion displaced for every 1°C of additional global warming



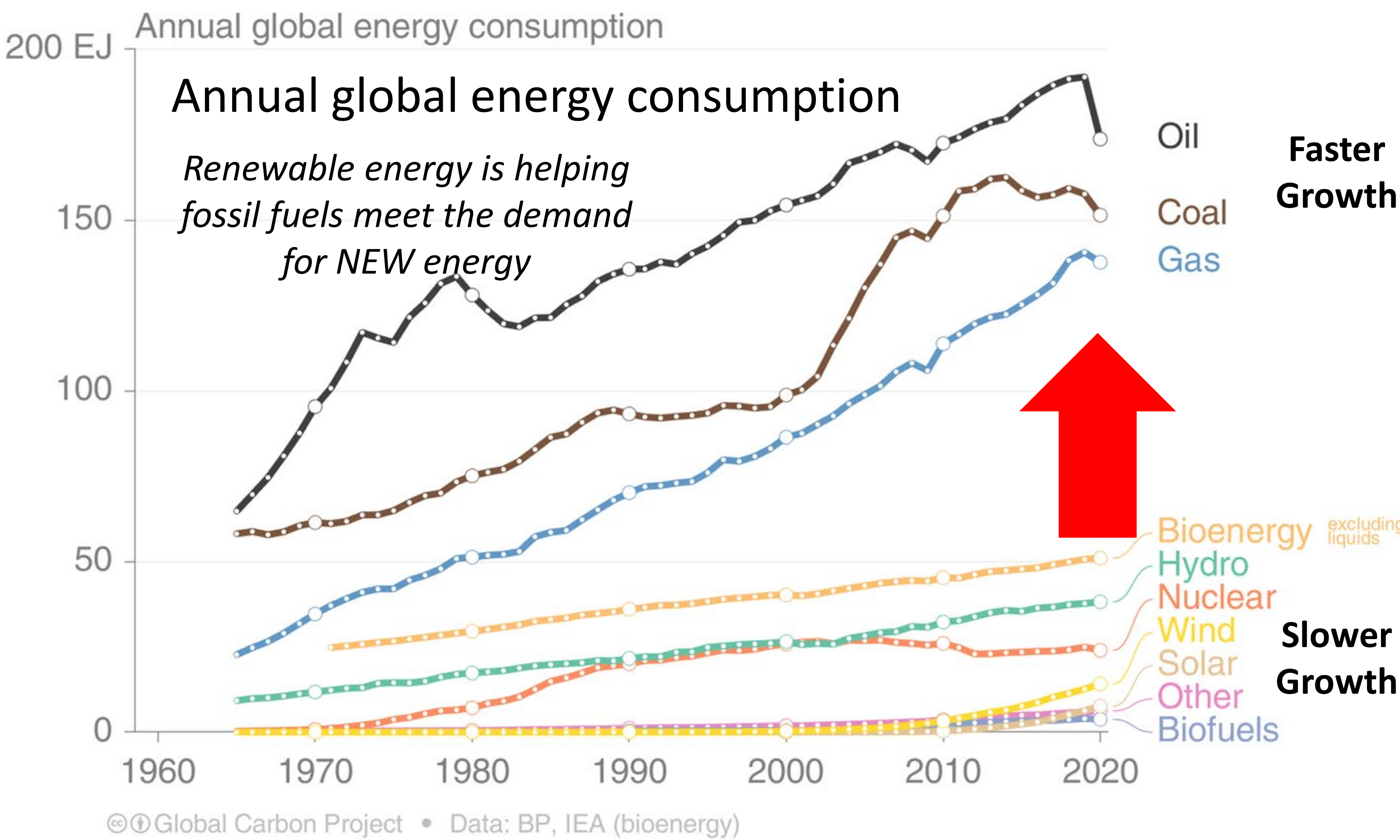
Xu, C., et al. (2020) Future of the human climate niche, *PNAS*, May 2020, 201910114; DOI:10.1073/pnas.1910114117



CO2 emissions, gigatonnes
By fuel
Oil
Coal
Gas
1850
1950
2017
By country/region
30
25
20
15
10
5
0
China
United States
Asia Pacific
Middle East
India
Americas
Africa
Europe
Historical CO2 Emissions
1.5oC – zero emissions by 2050
2.0oC – zero emissions by 2065
40-50% reduction by 2030
2020 to 2030 is a pivotal decade
We must remove CO2 from the air for the rest of the century.
Sources: Le Quéré et al. (2018); Global Carbon Project (GCP); Carbon Dioxide Information Analysis Centre (CDIAC)
1850
1875
1900
1925
1950
1975
2000
2025
2050
2075

Fossil fuel use is accelerating faster than renewable fuel use

Renewable energy is growing rapidly, but has been too low to offset fossil energy consumption.



Global Carbon Project (2020) Carbon Budget 2020: https://www.globalcarbonproject.org/index.htm