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# EarthN: a new model of the Earth system nitrogen cycle

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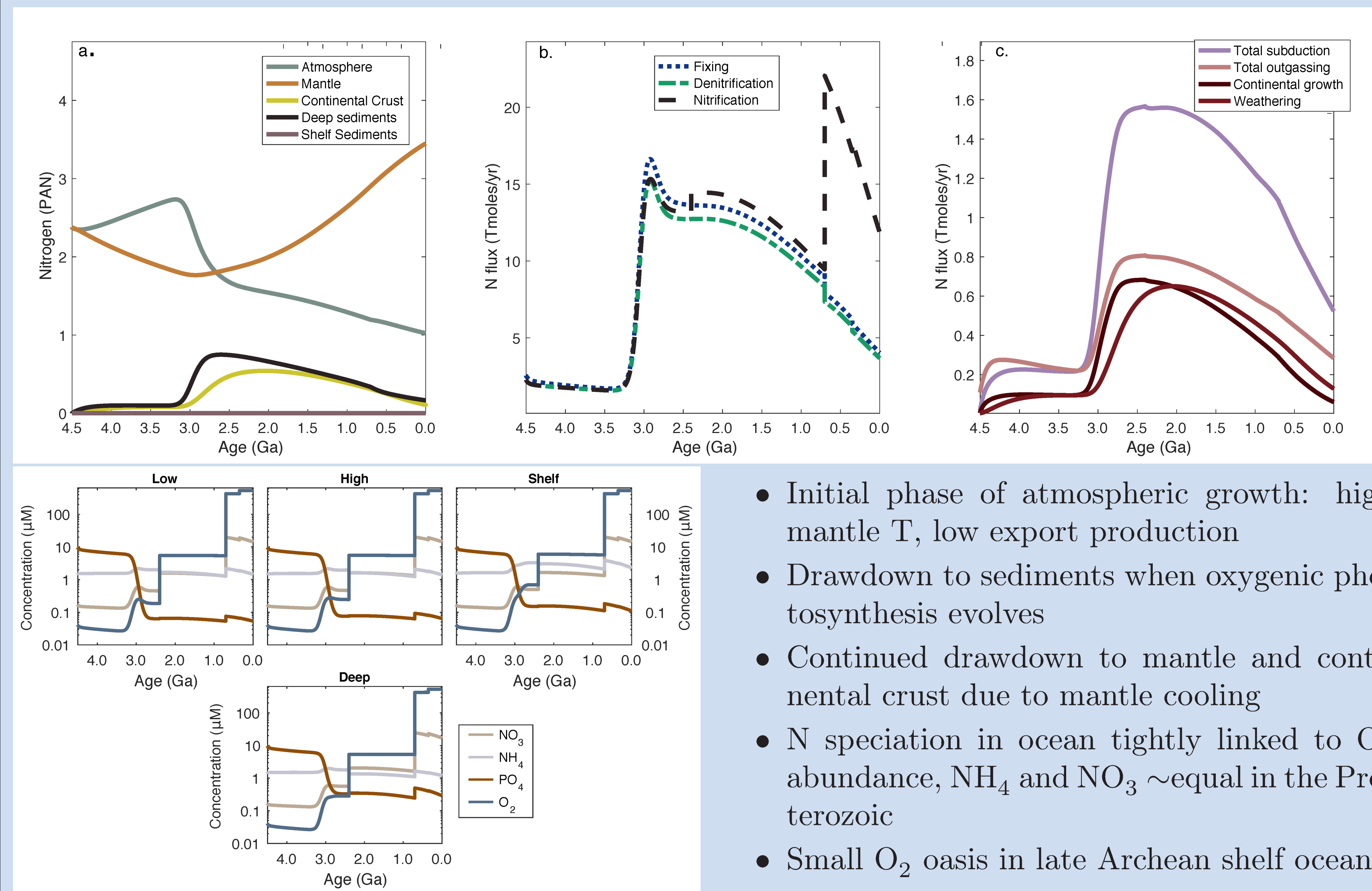
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## Earth System Nitrogen Cycle

- Nitrogen is the main component of the atmosphere, a key nutrient for organisms, and exerts control over climate via direct warming, as  $N_2O$ , and indirect effects, including pressure-broadening
- Previous models linked N to C, and typically only considered biologic or geologic fluxes in detail, focusing on sedimentary rocks. These studies suggest atmospheric mass steady over Earth history, which does not match new geochemical and physical paleobarometers
- New approach is to more completely include biologic and geologic fluxes, and link N behavior to  $PO_4$  and  $O_2$  abundance through time
- This approach is consistent with large-scale changes in atmospheric mass through time, up to 3 present atmospheric masses of nitrogen ( $1 \text{ PAN} = 4 \times 10^{18} \text{ kg N}$ ) supporting geochemical proxies that indicate atmospheric drawdown through time

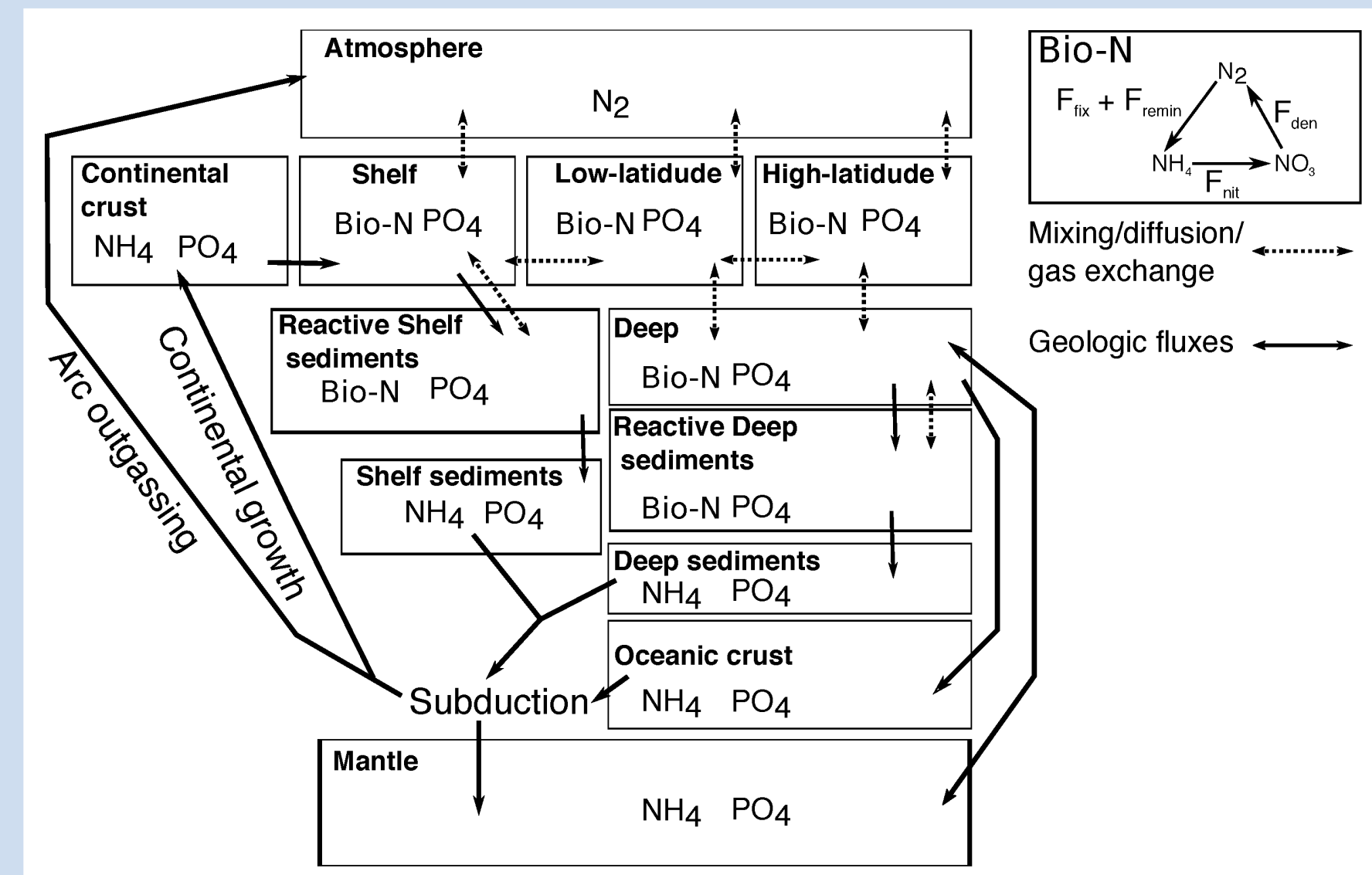
## Standard run results: atmospheric drawdown

- 4.75 PAN total N, equal amounts starting in atmosphere and mantle
- Mantle cooling, subduction rate, crust production from Korenaga, 2010
- Oxygenic photosynthesis evolves at 2.8 Ga
- Hydrothermal alteration is fixed volume flow ( $5 \times 10^{16} \text{ L yr}^{-1}$ )



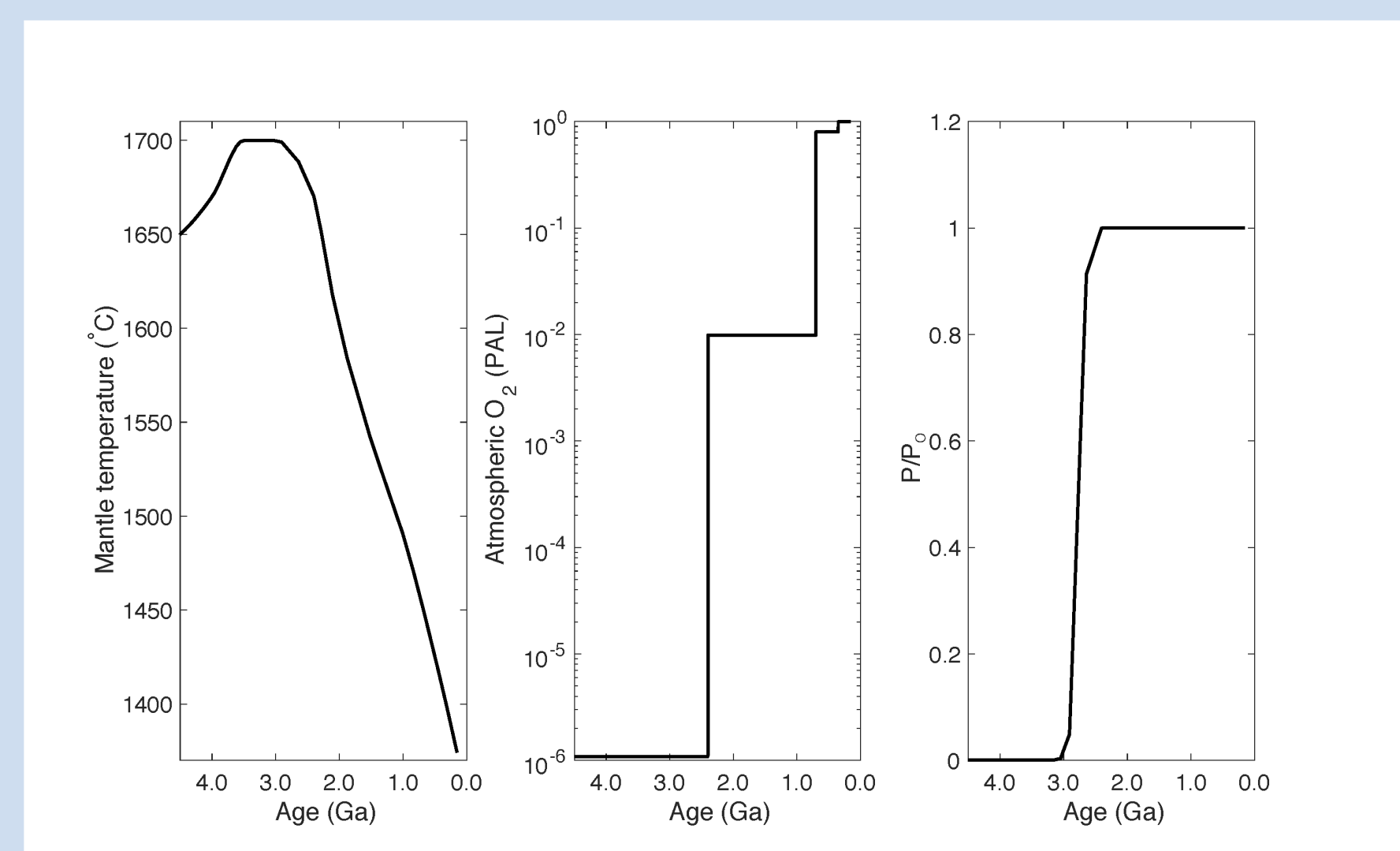
- Initial phase of atmospheric growth: high mantle T, low export production
- Drawdown to sediments when oxygenic photosynthesis evolves
- Continued drawdown to mantle and continental crust due to mantle cooling
- N speciation in ocean tightly linked to  $O_2$  abundance,  $NH_4$  and  $NO_3$  ~equal in the Proterozoic
- Small  $O_2$  oasis in late Archean shelf ocean

## EarthN model setup



- Biologic fluxes: export production from fixed N and newly-fixed N ( $F_{fix}$ ), remineralization ( $F_{remin}$ ), nitrification ( $F_{nit}$ ), and denitrification ( $F_{den}$ ). Export production occurs shallow ocean (Shelf, high-latitude, low-latitude), all nitrogen fluxes occur in all ocean boxes and upper sediments (i.e., reactive shelf and deep sediments)
- Geologic fluxes: include burial, subduction, outgassing, hydrothermal alteration of ocean crust, and continental weathering
  - Subduction efficiency is linked to mantle temperature: hot mantle  $\Rightarrow$  more N returns to atmosphere at subduction zones, cooler mantle  $\Rightarrow$  more N sequestered to mantle
  - Remineralization and production efficiency linked to  $O_2$ : oxygenic photosynthesis is more effective at primary production, deep water  $O_2$  leads to more efficient remineralization

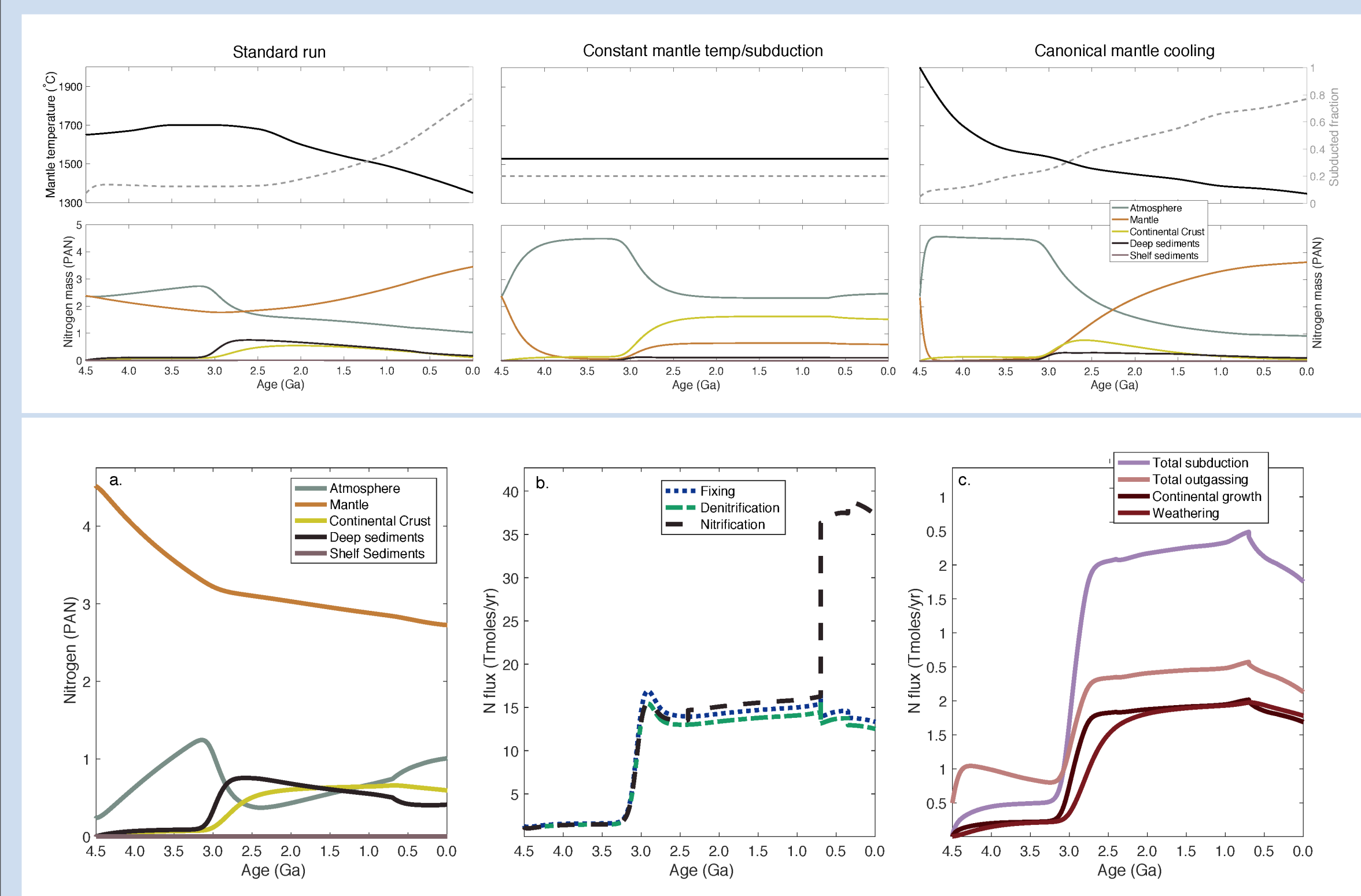
- Run model for 4.5 Gyr
- Model is driven by mantle cooling, atmospheric  $O_2$ , and export production ( $P/P_O$ , where  $P_O$  is modern efficiency) (below)



## Monte Carlo results

Parameter	Range
Upwelling	0.16–16 Sv
Ox. photo.	2.4–3 Ga
Hydrothermal flow	$0.5\text{--}50 \times 10^{16} \text{ L yr}^{-1}$
Total N	2–12 PAN
Initial atm.	0–100%

## Model sensitivities: mantle cooling and low $pN_2$ ?



- Mantle temperature has strong control on atmospheric mass
- Large changes in N distribution possible, depending on mantle cooling history
- Highlights importance of mantle N cycle: strong relationship between solid Earth history and atmospheric evolution
- low  $pN_2$  in Archean and Proterozoic only reproduced in model with very specific conditions: low starting atmospheric mass, sluggish upwelling (5 Sv), and constant and inefficient subduction (10%)

Results from 1000 runs. Total N has strong control on final (after 4.5 Gyr) atmospheric mass, independent of starting atmospheric mass. At low total N, N-fixing and subduction is larger than outgassing, so the mantle contains the majority of N. At high total N, N-fixing is too low ( $PO_4$ -limited) to draw down massive atmosphere.

## Conclusions

- By linking with  $PO_4$ , we show that this nutrient interacts with N to control N distribution
- Incorporating geologic fluxes (sedimentation, subduction) provides new depth
- Planetary atmospheres with  $N_2$  can vary substantially over time in the presence of life with direct implications for sustained habitability
- Total planetary N has strong control on distribution, but more detailed mantle cycle needed
- Model as constructed can make predictions, including atmospheric mass, fluxes, and eventually isotopic record