The Clean Paper

WHAT THE PAPER SAYS · WHAT IT DOESN'T · WHY IT MATTERS

# Lafti hanga yoomitti magariisa ta'ee turuu danda'a? Climate model ranges kenna, doomsday date miti

*Three-dimensional climate simulations 29 Earth photosynthetic biosphere'f different limits roughly 1.35 fi 1.87 billion years from now gidduu kaa'u. Values deliberately simplified paths rock weathering, heat fi lowest carbon-dioxide levels plants use gochuu danda'an irratti depend godhu. All plants, all life, civilization ykn planet yoom end godhu hin predict godhan.*

Written by Cinzia Vaglio · Cross-checked by Matteo · Edited by Michele Renda · Figures by Cinzia Vaglio and Nova Vela · AI-assisted, human-reviewed

Paper: *Maximum Lifetime of the Vegetative Biosphere*, Jacob Haqq-Misra and Eric Wolf, Journal of Geophysical Research: Atmospheres 131, e2025JD045586 (2026) · DOI: 10.1029/2025JD045586

# Lafti hanga yoomitti magariisa ta'ee turuu danda'a? Climate moodeela ranges kenna, doomsday date miti

Baalli tokko waliigaltee dhiphaa keessa jira. Ifa, bishaan, kaarboonii daayooksaayidii fi ho'a chemistry isaa tolerate gochuu danda'u barbaada. Namaa lifetime keessatti, Aduu waliigaltee kana keessaa dhaabbataa kutaa fakkaata. Billion waggoota keessatti garuu miti.

Aduun ijoo sequence irratti yeroo dulloomu, suuta suuta caalaatti ifaa ta'a. Sunlight dabalachuun Lafa ho'isa, garuu pilaaneetii long-term deebii qaba: rainwater, kaarboonii daayooksaayidii fi silicate dhagaa gidduu reactions kaarboonii daayooksaayidii atmosphere keessaa keessaa baasuu danda'u. Kun greenhouse dhiibbaa dadhabsiisee warming muraasa offset godha. Deebii pilaaneetii qabbaneessu sanuma yeroo tokko photosynthetic uumamoota lubbuu qaban kaarboonii living tishuu ijaaruuf fayyadaman irraa dhabuuf geessuu danda'a.

Journal of Geophysical Research: Atmospheres barruu haaraan daangaa kam dursee dhufa gaafata: ho'a baay'ee moo kaarboonii daayooksaayidii xiqqaa? Deebiin date Lafa itti du'u miti. Deliberately simplified fuuldura paths lama keessatti, adopted daangaalee photosynthetic jireenya gara **1.35 hanga 1.87 billion waggoota irraa amma** gidduu kufu.

Daangaa kun **vegetative biosphere** irratti: kutaa Lafa's living sirna photosynthetic uumamoota lubbuu qaban'n sustained, keessumaa plants fi biraa jireenya ifa fi kaarboonii daayooksaayidii biological maateriyaalii'tti jijjiiru. Every microbe forecast miti. Namaa civilization lifetime miti. Pilaaneetii lifetime miti.

# Planetary thermostat settings uncertain lama qaba

Central shakkii **silicate weathering** dha. Kaarboonii daayooksaayidii rainwater keessatti dissolve godha, silicate dhagaa waliin react godha, eventually oceans fi sediments garaa carried. Volcanoes geologic yeroo keessatti kaarboonii daayooksaayidii deebi'anii atmosphere'tti fidan. Together adeemsoota kun carbonate-silicate marsaa keessaa kutaa ta'u, planetary thermostat jedhamee ibsamu.

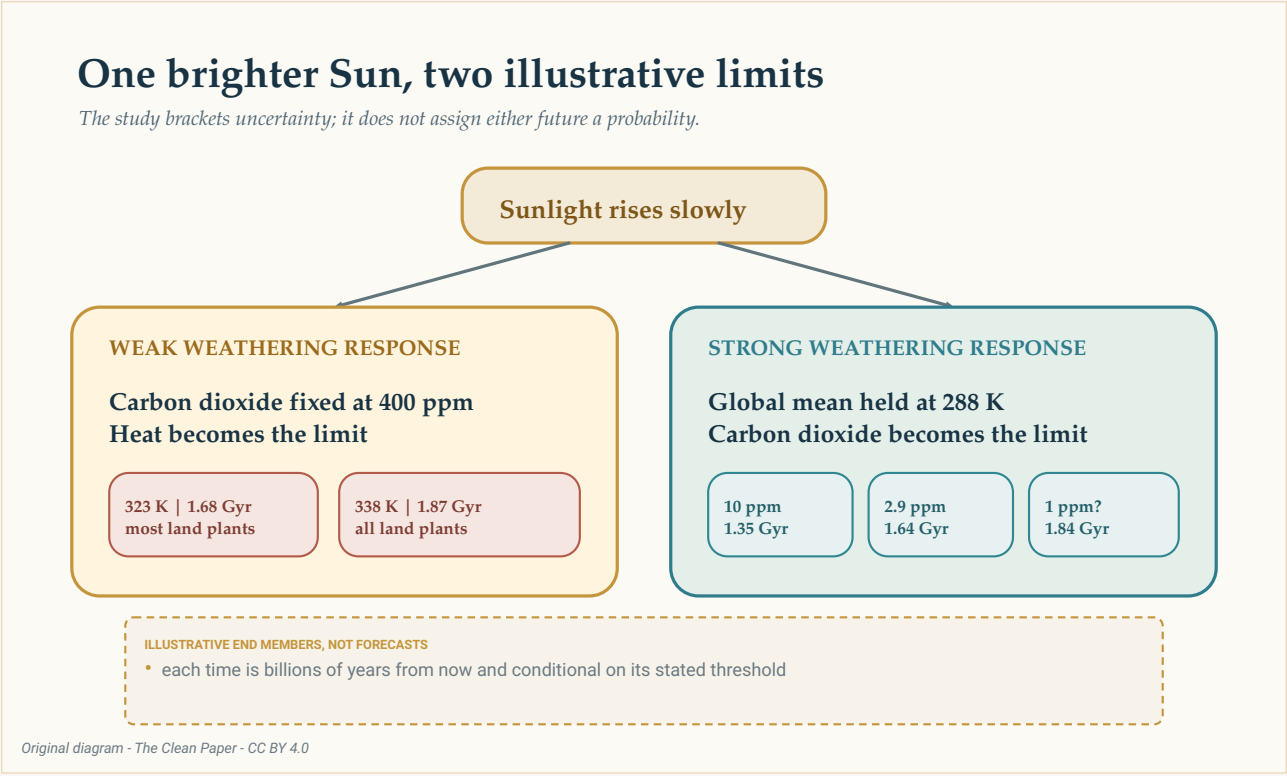
Warmer, wetter world keessatti, weathering accelerate godhee kaarboonii daayooksaayidii faster keessaa baasuu danda'a. Garuu scientists brighter fuuldura Sun jalatti deebii kun Lafa hammam strongly govern godha hin beekan. Jacob Haqq-Misra fi Eric Wolf kanaaf supposedly sirrii path tokko hin filanne. **End members** lama moodeela godhan: intentionally extreme haalawwan shakkii bracket gochuuf.

- **Weak-weathering end member** keessatti, atmospheric kaarboonii daayooksaayidii 400 kutaalee miliyoona tokko keessatti irratti hafe, brightening Sun ho'a ol kaasa.
- **Strong-weathering end member** keessatti, waliigalaa giddugaleessa fuula ho'a 288 kelvin, waa'ee 15 degrees Celsius, irratti hafe, sunlight dabalaa yeroo kaarboonii daayooksaayidii gadi harkifama.

Branch tokko iyyuu Lafa's dhugaa fuuldura ta'ee hin dhiyaanne. Jalqabaa ho'a maal godha yoo kaarboonii daayooksaayidii ol-aanaa ta'ee hafe gaafata. Lammaffaa kaarboonii starvation maal godha yoo weathering waliigalaa ho'a near har'a's giddugaleessa irratti qabe gaafata.

### Weathering thermostat fakkaatee akkamitti hojjeta?

Analogy feedback irratti, literal to'annoo knob miti. Warm climate chemical weathering saffisiisu yeroo, atmospheric kaarboonii daayooksaayidii caalaan dissolved maateriyaalii, albuudota fi sediments keessa xumuramuu danda'a. Greenhouse gas sana remove gochuun jalqabaa warming muraasa morma. Very dheeraa timescales irratti volcanic outgassing kaarboonii daayooksaayidii deebisa.
Tokkoon tokkoon link strength rainfall, saaxilame dhagaa, erosion, baayoloojii, tectonics fi ocean chemistry irratti hunda'a. Kanaaf barruu thermostat beekamaa machine fakkeessuu mannaa limiting deebiiwwan qora.




Barruu uncertain fuuldura lama illustrative end members'n bracket godha. Weathering weakly respond yoo godhe, rising ho'a adopted land-plant daangaalee ga'a. Strongly respond yoo godhe, falling kaarboonii daayooksaayidii adopted photosynthesis daangaalee ga'a. Kun conditional moodeela branches dha, carraawwan ykn countdown dates miti.

# Moodeela worlds settled digdamii sagal, movie two-billion-year tokko miti

Researchers ExoCAM, three-dimensional waliigalaa climate moodeela, fayyadamuun **29 steady-state climates** stronger sunlight fi gadi-aanaa kaarboonii daayooksaayidii combinations keessatti shallagu. Haala tokko tokko moodeela waggoota 70 raawwatame. As moodeela waggaa tokko simulated annual marsaa dhaabbataa haalawwan jalatti; runtime nam-tolchee climate settle gochuuf, year-by-year Lafa's fuuldura forecast keessatti tarkaanfii tokko miti. Dhumaa 20 waggoota simulated climate settle booda averaged.

Haalawwan 29 sun adda moodeela worlds dha. Raawwii tokko grid keessatti qabxii tokko, "chosen pair sunlight fi kaarboonii daayooksaayidii kanaaf settled climate akkamii?" deebisa. Kompiitara har'a's Lafa irraa jalqabee atmosphere, dhagaa, oceans fi living wantoota next lama billion waggoota continuously evolve hin godhne. Barreessitoonni precomputed qabxiilee sana keessa schematic weathering paths lama trace godhan; path qabxiilee gidduu itself simulated miti.

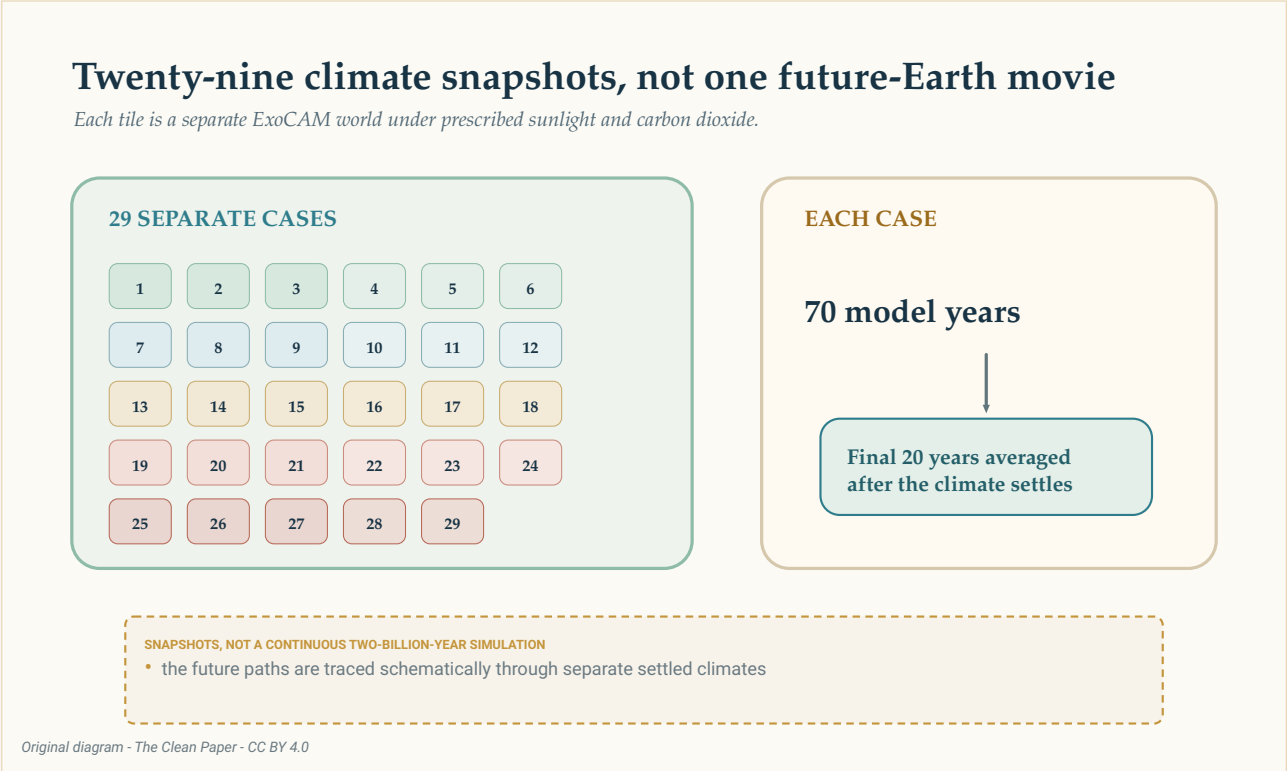
Table official model-data kuusaa ragaa keessa sunlight fi carbon-dioxide combinations deebisee uumu. Haala IDs dubbisuu aids as kuusaa ragaa order keessatti dabalaman. **S/S0** walbira qabamee solar dhaabbataa dha: incoming solar anniisaa moodeela keessatti, present-day gatii S0'n divided. Gatii 1.2 jechuun 20 dhibbeentaa caalaa incoming solar anniisaa than har'a. **CO2 (ppm)** atmospheric carbon-dioxide mixing reeshiyoo molekiyuulota miliyoona tokko keessatti atmospheric molekiyuulota dha.

| Haala ID | S/S0 | CO2 (ppm) |
|---|---|---|
| 1 | 1.0 | 400 |
| 2 | 1.0 | 180 |
| 3 | 1.0 | 11.25 |
| 4 | 1.0 | 1.40625 |
| 5 | 1.044 | 400 |
| 6 | 1.044 | 180 |
| 7 | 1.044 | 135 |
| 8 | 1.044 | 11.25 |
| 9 | 1.044 | 1.40625 |
| 10 | 1.081 | 400 |
| 11 | 1.081 | 180 |
| 12 | 1.081 | 11.25 |
| 13 | 1.081 | 1.40625 |
| 14 | 1.091 | 400 |
| 15 | 1.091 | 180 |
| 16 | 1.091 | 34 |
| 17 | 1.091 | 11.25 |
| 18 | 1.091 | 1.40625 |
| 19 | 1.143 | 400 |
| 20 | 1.143 | 180 |

| Haala ID | S/S0 | CO2 (ppm) |
|---|---|---|
| 21 | 1.143 | 11.25 |
| 22 | 1.143 | 6 |
| 23 | 1.143 | 1.40625 |
| 24 | 1.2 | 400 |
| 25 | 1.2 | 180 |
| 26 | 1.2 | 11.25 |
| 27 | 1.2 | 1.40625 |
| 28 | 1.2 | 0.45 |
| 29 | 1.2 | 0 |

Moodeela Lafa recognizable dha, garuu intentionally limited. Earth-sized fi present-day geography fayyadama. Guutummaatti circulating ocean mannaa simplified slab ocean qaba, atmospheric dhiibbaa gara Lafa's ammaa gatii (tokko bar), dhaabbataa methane. Orbit perfectly circular (zero eccentricity), rotation axis tilt hin qabu (zero obliquity). Explicit soils, vegetation ykn feedback changing biosphere hin qabu. Hunda caalaa, climate moodeela dynamically rock-weathering moodeela waliin coupled miti. Jecha biraatiin, ExoCAM weathering calculate godhee kaarboonii daayooksaayidii update godhee next climate feedback loop keessatti raawwii hin godhu. Researchers qooda prescribed limiting paths lama trace godhan 29-haala climate grid keessa.

> **"Steady haala" climate moodeela keessatti maal?**
>
> Steady-state haala moodeela climate chosen Sun fi atmosphere tokko jalatti settle gochuuf hayyamame. Fakkeessuu keessaa weather day-to-day fi year-to-year ammallee jijjiirama, garuu long-term averages cimaa drift dhaabu.
> Kun "haalawwan kanaaf climate akkamii?" gaafachuuf faayidaa qabu dha. Dhugaa Lafa haalawwan set tokko irraa next set garaa sirrii route akkamitti sochoosa tilmaamu irraa adda.




Tile tokko adda ExoCAM climate raawwii moodeela waggoota 70, dhumaa 20 waggoota averaged. Qorannoo prescribed sunlight fi carbon-dioxide haalawwan keessatti 29 settled climates saamudaa godhe; tokko continuously evolving Lafa for lama billion waggoota hin simulate godhne.



# End member tokko: kaarboonii daayooksaayidii gahaa, ho'a baay'ee

Weak-weathering branch keessatti kaarboonii daayooksaayidii dhaabbataa 400 kutaalee miliyoona tokko keessatti. Solar galtee rise yeroo ho'a limiting faaktara ta'a.

Barruu duraa hojii irraa waliigalaa giddugaleessa ho'a daangaalee lama fayyadama:

- **323 kelvin**, waa'ee **50 degrees Celsius** waliigalaa annual giddugaleessa irratti, world irra caalaa land plants'f too hot treated. Moodeela daangaa sana waa'ee **1.68 billion waggoota** keessatti ga'a.
- **338 kelvin**, waa'ee **65 degrees Celsius** waliigalaa annual giddugaleessa irratti, world hunda land plants'f too hot treated. Moodeela daangaa sana waa'ee **1.87 billion waggoota** keessatti ga'a.

Kun adopted biological daangaalee dha, universal temperatures photosynthetic uumama lubbuu qabu hundi necessarily fail godhu miti. Waliigalaa giddugaleessa regional garaagarummaa gurgud-daa dhoksa. Qorannoo addaan combinations ho'a fi water eessa suitable hafu danda'an ilaala, garuu climate kaartaa label tokko every fuuldura refuge ykn adaptation catalogue gochuu hin danda'u.

# End member lama: ho'a tolerable, kaarboonii daayooksaayidii baay'ee xiqqaa

Strong-weathering branch keessatti waliigalaa giddugaleessa ho'a 288 kelvin, waa'ee 15 degrees Celsius, irratti dhaabbataa; atmospheric kaarboonii daayooksaayidii gadi bu'a. As deebii kaarboonii pathways adda hammam little kaarboonii fayyadamu danda'an irratti hunda'a.

- Traditional **10 kutaalee miliyoona tokko keessatti** daangaa irratti — every miliyoona atmospheric molekiyuulota keessatti carbon-dioxide molekiyuulota 10 — C4 photosynthesis daangaa waa'ee **1.35 billion waggoota** keessatti dhufa. C4 photosynthesis plants maize fi sugar cane dabalatee fayyadaman, enzyme kaarboonii sirreessu naannoo kaarboonii daayooksaayidii walitti qabuu.
- Duraa hojii keessatti discussed alternative **2.9 kutaalee miliyoona tokko keessatti** C4 daangaa fayyadamuun gara waa'ee **1.64 billion waggoota**tti sochoosa.
- Tentative **1 kutaa miliyoona tokko keessatti** daangaa, danda'amaa persistence CAM plants muraasa — crassulacean acid metabolism fayyadaman, nighttime carbon-dioxide uptake daytime fayyadama irraa adda godhu — ykn aquatic plants dissolved bicarbonate fayyadamuu danda'an waliin associated, gara waa'ee **1.84 billion waggoota**tti sochoosa.

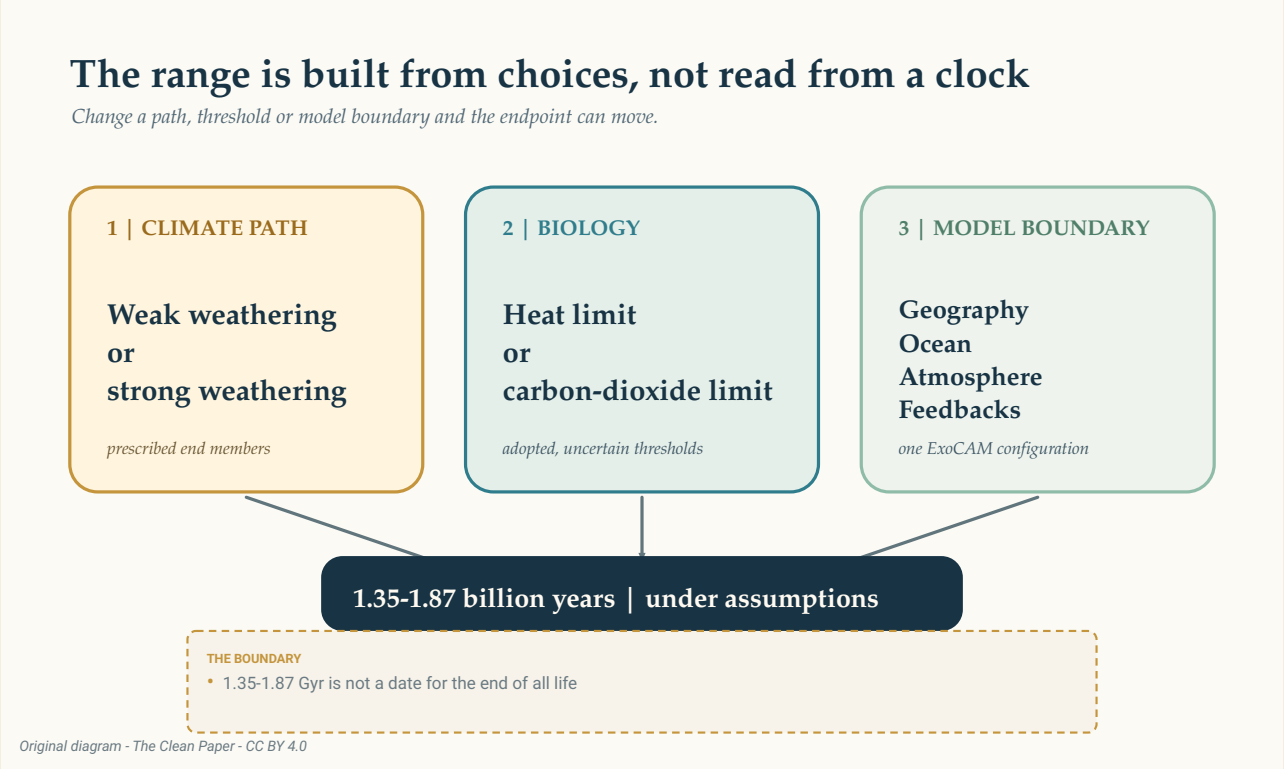
Last lakkoofsa isa guddaa biological caveat qaba. Barreessitoonni one-part-per-million daangaa tentative jedhu. Future-Earth haalawwan jalatti hunda CAM plants ykn aquatic vegetation survival daangaa experimentally established miti.

> **C3, C4 fi CAM strategies dha, ladder miti**
>
> Plants biochemical routes adda kaarboonii capture gochuuf fayyadamu. **C3 photosynthesis** irra caalaa baramaa. **C4 photosynthesis**, maize fi sugar cane dabalatee, kaarboonii daayooksaayidii enzyme kaarboonii sirreessu naannoo concentrate godhee kaarboonii daayooksaayidii scarce yeroo caalaatti gaarii hojii gochuu danda'a. **Crassulacean acid metabolism (CAM)** kaarboonii uptake fi fayyadama night/day keessa adda godha, plants hedduu water conserve gochuuf gargaara.
> Kun families strategies species-level garaagarummaa hedduu waliin dha, successive ranks "caalaatti gaarii" plants miti. Barruu's very gadi-aanaa carbon-dioxide daangaalee yaadota bu'uuraa danda'amaa daangaalee explore gochuuf, fuuldura ecosystem evolve godhee isaan fayyadama guarantee miti.

# Maaliif 1.86 billion waggoota expiry date miti

Barruu's mata-duree tilmaama waa'ee **1.86 billion waggoota** optimistic gubbaa madaallii dhumaa lama giddugaleessa dha: 1.84 billion waggoota carbon-dioxide-limited branch fi 1.87 billion waggoota heat-limited branch. Compact cuunfaa scenarios adda lamaa dha. Sadaffaa moodeela bu'aa greater sirrummaa qabu miti, best-estimate date miti.

Even broader 1.35-to-1.87-billion-year span carraa tokko hin qabu. Gadi-aanaa fi gubbaa gatiiwwan weathering yaadota bu'uuraa adda, biological daangaalee adda fi tokko climate-model configuration irratti depend godhu. Daangaa yaalii choices hammam safaru, yeroo akkuma safaru.




1.35-to-1.87-billion-year span weathering path, biological daangaa fi moodeela daangaa choose godhamee booda qofa emerge godha. Yaada bu'uuraa kaartaa dha, clock hunda jireenya extinction irratti xumuru miti.



# Daangaalee biroo dursee dhufuu danda'u

Longest vegetative-biosphere tilmaamota adda uncertain daangaa bira ga'u: moist ykn runaway greenhouse guddaa ocean dhabamuu sochii gochuu danda'u. Climate moodeelota increasing sunlight jalatti haalawwan kun yoom jalqabu irratti substantially disagree, keessumaa present haalawwan irraa fagoo. Tilmaamota muraasni irra caalaa optimistic photosynthesis daangaa dura kaa'u.

Kana jechuun gubbaa branch promise Lafa oceans, familiar ardiiwwan ykn habitable fuula haalawwan 1.87 billion waggoota irraa amma hanga keep godha jedhamee dubbifamuu hin qabu. Moodeela fuuldura tektooniksii pleetii, land bal'ina jijjiiramoota, evolving ecosystems ykn guutummaatti dynamic ocean hin dabalatu. Shallaggiiwwan atmosphere anniisaa absorb fi emit akkamitti godhu illee cimaa sunlight fi extremely gadi-aanaa kaarboonii daayooksaayidii regimes, moodeelota diverge godhan, keessatti push godhaman.

Evolutionary adaptation fi technological intervention barruu discussion keessatti possibilities ta'anii

mul'atu. 29 climate fakkeessuuwwan bu'aawwan miti. Moodeela fuuldura uumamoota lubbuu qaban one-part-per-million photosynthetic karaa evolve godhan hin agarsiisu, civilization atmosphere billion waggoota manage godhu hin agarsiisu.

## Kun har'a's climate crisis irratti bu'aa miti

Solar brightening hundreds millions to billions waggoota keessatti hojjeta. Ammayyaa human-driven warming rapidly increasing greenhouse gases decades fi centuries keessatti irraa dhufa. Isaan forcings adda, radically adda timescales, gaaffilee adda.

Qorannoo kun present climate jijjiirama ragaa hin laaffisu ykn gocha delay godhu hin jedhu. Biosphere distant moodeela scenario tokko keessatti photosynthetic jireenya muraasa retain gochuu danda'u, climate har'a's societies fi ecosystems secure ta'anii hafu waliin wal-fakkaataa thing miti.

Barruu valuable sababni fagoo irraa gaaffii discipline caalaa itti fida. Earlier, simpler moodeelota sunlight daballii yeroo kaarboonii daayooksaayidii dhaabbataa ta'ee ho'a too much uuman ta'uu danda'u agarsiisa, fi photosynthetic jireenya persistence routes tokko canonical kaarboonii daangaa suggests caalaa hedduu qabaachuu danda'u agarsiisa. Akkasumas every extra fraction billion waggoota yaadota bu'uuraa chain waliin attach ta'uu agarsiisa.

Aduun baala nyaachisu suuta jijjiiramaa jira. Lafa kan biraa 1.35, 1.87 ykn biraa lakkoofsa billion waggoota green ta'ee hafu, dhagaa, water, atmosphere fi jireenya together deebii kennu irratti hunda'a. Honest bu'aa date miti. Bargain sana broader view dha.

## Cuunfaa gabaabaa

Three-dimensional climate qorannoo Lafa vegetative — photosynthetic — biosphere Sun slowly brightens yeroo hammam persist godhu danda'a gaafata. Researchers adda steady-state climates 29 shallagu illustrative end members lama keessa trace godhan. Dadhabaa weathering fi kaarboonii daayooksaayidii dhaabbataa 400 kutaalee miliyoona tokko keessatti waliin, adopted ho'a daangaalee land plants waa'ee 1.68 fi 1.87 billion waggoota irraa amma irratti occur. Cimaa weathering fi waliigalaa giddugaleessa ho'a dhaabbataa 288 kelvin, waa'ee 15 degrees Celsius, waliin, adopted carbon-dioxide daangaalee photosynthesis waa'ee 1.35, 1.64 fi, tentative daangaa fayyadamuun, 1.84 billion waggoota irratti occur. Often-quoted 1.86 billion waggoota simply rounded giddugaleessa optimistic gubbaa madaallii dhumaa lamaa. Kun scenario-dependent moodeela ranges dha, date Lafa, humanity ykn hunda jireenya itti end godhu miti. Moodeela prescribed paths, present geography, slab ocean fi lakki explicit soil–vegetation ykn climate–weathering coupling fayyadama; longest tilmaamota uncertain greenhouse fi ocean-dhabamuu daangaalee bira ga'u.

# Sakatta'a ifaa

**Wanti barruu agarsiisu:** ExoCAM configuration kana keessatti, three-dimensional climates increasing sunlight fi dhaabbataa kaarboonii daayooksaayidii jalatti simplified moodeelota walbira qabuu'f fayyadaman caalaa generally xiqqaa warm. Prescribed weathering end members lama fi adopted biological daangaalee hedduu keessatti, vegetative biosphere daangaalee gara 1.35 fi 1.87 billion waggoota irraa amma gidduu kufu.

**Wanti amansiisaa garuu miti established:** CAM plants muraasni ykn aquatic plants dissolved bicarbonate fayyadaman near tokko kutaa miliyoona tokko keessatti atmospheric kaarboonii daayooksaayidii photosynthesis sustain gochuu; adaptation ykn technology photosynthetic jireenya farther extend gochuu; dhugaa climate-weathering path moodeela end members lamaan gidduu hafu.

**Wanti hin agarsiifne:** Dhaabbataa date hunda plants, hunda jireenya, namaa civilization, Lafa's oceans ykn pilaaneetii end godhu; tokko continuous fakkeessuu next lama billion waggoota; ykn present human-caused climate jijjiirama discount gochuuf sababa.

**Ijoo limitations:** Steady-state haalawwan digdamii sagal tokko climate-model family irraa; prescribed mannaa dynamically coupled weathering paths; present-day geography; slab ocean; dhaabbataa methane; zero obliquity fi eccentricity; lakki explicit soils, vegetation ykn biosphere feedback; uncertain ho'a fi carbon-dioxide daangaalee; moist/runaway greenhouse haalawwan near wide moodeela disagreement.

**Dubbisaan waliigalaa hammam amantaa qabaachuu qaba?** Qorannoo amansiisaa moodeela daangaa broaden godhu fi controlling yaadota bu'uuraa adda baasuu irratti amantaa guddaa. Lakkoofsaa span keessatti kana moodeela faayidaa qabu bracket ta'uu irratti amantaa giddu-galeessaa. Sirrii date irratti amantaa gadi-aanaa, sababni irra caalaa distant madaallii dhumaa deliberately extreme climate paths fi uncertain baayoloojii irratti depend godhan.

## Maddoota

Haqq-Misra & Wolf, Maximum Lifetime of the Vegetative Biosphere, Journal of Geophysical Research: Atmospheres 131, e2025JD045586 (2026)
https://doi.org/10.1029/2025JD045586

Haqq-Misra & Wolf, Maximum Lifetime of the Vegetative Biosphere: Model Data, Zenodo record 16584870
https://doi.org/10.5281/zenodo.16584870