# Surface Infrared Forcing as a Primary Driver of Contemporary Global Warming: A Synthesis of Biophysical, Spectral, and Land-Use Evidence

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(the paper is a non peer reviewed preprint submitted to EarthArXiv)

*Drawing on: Duveiller et al. (2018) · Erb et al. (2018) · Ruddiman (2003–2018)*
*Fyfe et al. · UNCCD Global Land Outlook · Atmospheric Radiative Transfer Physics*

**Keywords:** *land surface forcing, longwave infrared radiation, biophysical climate effects, urban heat island, desertification, spectral overlap, water vapour feedback, attribution*

## ABSTRACT

The prevailing attribution of observed global warming to the radiative forcing of well-mixed greenhouse gases — principally $CO_2$ — rests on a framework that systematically underrepresents a class of forcings operating at the land-atmosphere interface. This paper synthesises evidence from satellite remote sensing (Duveiller et al., 2018), planetary biomass accounting (Erb et al., 2018), palaeoclimatic reconstruction (Ruddiman, 2003–2018), CMIP model diagnostics (Fyfe et al.), United Nations Convention to Combat Desertification (UNCCD) monitoring data, and first-principles atmospheric spectral physics to construct the case that anthropogenic transformation of the land surface — through enhanced longwave infrared (LW-IR) emission from thermally elevated, evapotranspiration-suppressed surfaces — constitutes a primary climate forcing of the first order.

We demonstrate that: (i) the biophysical surface temperature effects of land cover change are locally comparable to or exceed the column-averaged radiative forcing of $CO_2$ doubling; (ii) land surface LW-IR emission peaks in the 8–13 μm atmospheric window, a spectral region where $CO_2$ and $CH_4$ absorption is weakest, providing a mechanistically independent forcing pathway; (iii) $CO_2$'s primary absorption band is approaching saturation in the lower troposphere, reducing its marginal forcing relative to surface-driven mechanisms; (iv) the spatial pattern of observed anomalous warming — concentrated in drylands, continental interiors, and Arctic regions — is better predicted by surface LW-IR forcing than by the uniform column forcing of a well-mixed gas; (v) standard CMIP attribution models structurally underrepresent land surface biophysics, misattributing water vapour amplification of surface warming to $CO_2$ forcing; and (vi) the complete inventory of surface-modifying human activities — including urban sprawl, ice loss, fallow agriculture, wildfires, and direct thermal discharge from fossil and nuclear fuel use — compounds the LW-IR forcing signal substantially beyond the ecological degradation component alone. We conclude that land surface change, operating through direct LW-IR emission into the lower atmosphere, is at minimum a co-primary driver of observed warming and merits fundamental reassessment in climate attribution frameworks. The policy implication — that ecological and land surface restoration constitutes a direct climate intervention rather than a secondary mitigation strategy — is correspondingly urgent.

## 1. INTRODUCTION

The scientific consensus on anthropogenic climate change, as expressed in successive IPCC Assessment Reports, attributes the majority of observed surface warming since pre-industrial times to the enhanced greenhouse effect — principally the radiative forcing of elevated atmospheric $CO_2$ concentrations arising from fossil fuel combustion and land use change treated primarily as a carbon source (IPCC, 2021). This framework has achieved extraordinary institutional and scientific authority, supported by robust physical theory, isotopic evidence, and general circulation model attribution studies.

Yet this consensus framework rests on modelling tools and attribution methods that contain structural limitations with respect to a specific class of climate forcings: those arising from the direct biophysical transformation of the land surface and its effect on the longwave infrared (LW-IR) energy budget of the lower troposphere. These limitations are not disputed in the technical literature — they are acknowledged in land surface modelling reviews and in diagnostics of CMIP model performance (Fyfe et al.; Pitman et al., 2009; de Noblet-Ducoudré et al., 2012) — but their implications for top-level attribution have not been systematically examined.

This paper undertakes that examination. We argue that the biophysical pathway by which anthropogenic land surface change forces climate — through direct LW-IR emission from thermally elevated, evapotranspiration-suppressed surfaces into the lower troposphere — has been underweighted in attribution science for structural reasons related to model representation, and that when this pathway is properly characterised alongside the full inventory of surface-modifying human activities, the case for surface LW-IR forcing as a primary driver of observed warming is compelling.

The argument proceeds through seven analytical steps: establishing the biophysical temperature signal from land cover change (Section 2); quantifying the spatial scale of surface transformation (Section 3); demonstrating the spectral independence of LW-IR surface forcing from greenhouse gas forcing (Section 4); examining the historical precedent of land-driven climate forcing (Section 5); documenting the anomalous warming pattern consistent with surface forcing (Section 6); characterising the complete inventory of LW-IR forcing activities (Section 7); and addressing the water vapour feedback attribution problem (Section 8). Section 9 presents the integrated synthesis and policy implications.

## 2. THE BIOPHYSICAL SURFACE TEMPERATURE SIGNAL

### *2.1 Duveiller et al. (2018): Satellite Evidence*

Duveiller and colleagues' landmark analysis of Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature data provided the most spatially comprehensive quantification yet achieved of the biophysical temperature effects of land cover transitions (Duveiller et al., 2018, Nature Communications). By comparing surface temperatures in geographically adjacent areas with differing land cover types — controlling for climate, topography, and soil type — the authors effectively conducted a natural experiment at continental scale across all major biomes.

Their principal findings are directly relevant to the LW-IR forcing argument. Tropical deforestation is associated with local surface warming of up to 2°C relative to forested controls, with the dominant mechanism being the suppression of evapotranspiration rather than albedo change. In mid-latitude agricultural regions, the seasonal signal is complex — summer warming, winter cooling — but the annual mean energy budget is substantially altered. The evapotranspiration pathway dominates in warm, humid, and semi-arid environments, which collectively constitute the majority of the Earth's agricultural and degraded land surface.

The physical mechanism is straightforward. A forest canopy maintains surface temperatures significantly below the theoretical radiative equilibrium temperature through two pathways: (i) high albedo reflecting incoming shortwave radiation; and (ii) latent heat flux, whereby transpired water absorbs approximately 2.45 MJ per kilogram, consuming energy that would otherwise heat the surface. When vegetation is removed, both pathways are disrupted. Bare soil absorbs more shortwave radiation and dissipates it almost entirely as sensible heat, elevating surface temperature substantially.

The Stefan-Boltzmann law quantifies the radiative consequence. For a surface with emissivity $\varepsilon \approx 0.95$ (typical mineral soil), the LW-IR emission power is $P = \varepsilon\sigma T^4$. An increase in surface temperature from 295 K (22°C, typical vegetated tropical surface) to 303 K (30°C, consistent with Duveiller's deforestation warming signal) increases LW-IR emission by approximately 15.3 W $m^{-2}$. This per-unit-area forcing is approximately 4.1 times the direct radiative forcing attributed to a doubling of atmospheric $CO_2$ ($\Delta F \approx 3.7$ W $m^{-2}$), though it is locally concentrated rather than globally uniform.

### *2.2 The Evapotranspiration Collapse*

The physical centrality of evapotranspiration to the surface energy budget cannot be overstated. At the global scale, land evapotranspiration returns approximately 70% of terrestrial precipitation to the atmosphere as water vapour — a flux of some 70,000 $km^3$ of water per year, consuming approximately 42,000 terawatts of energy in the phase transition process. This latent heat flux constitutes the primary mechanism by which vegetated land surfaces export energy without raising surface temperature.

When vegetation is removed or stressed to the point of stomatal closure — through drought, desertification, agricultural bare-fallow cycling, or urban impervious surface replacement — the latent heat pathway collapses. The Bowen ratio (sensible heat flux / latent heat flux) shifts dramatically toward sensible heat. Energy that was previously exported as water vapour instead elevates the surface temperature and is radiated upward as LW-IR. This is not a secondary or feedback effect: it is the primary, instantaneous thermodynamic response to vegetation loss.

## 3. THE SCALE OF ANTHROPOGENIC SURFACE TRANSFORMATION

### *3.1 Erb et al. (2018): Planetary Biomass Accounting*

The spatial scale of anthropogenic land surface transformation is routinely underestimated in climate discourse, partly because the primary metric — atmospheric $CO_2$ concentration — is a global mean quantity that obscures geographic heterogeneity. Erb and colleagues (2018, Nature) provided the most comprehensive accounting of anthropogenic impacts on terrestrial biomass, integrating archaeological, historical, and remote sensing data across the full Holocene.

Their principal findings establish the planetary scale of the forcing: humans have removed approximately 450 Gt C-equivalent of terrestrial biomass since the onset of agriculture — representing roughly half of all pre-agricultural terrestrial biomass. The spatial footprint of this transformation encompasses approximately 75% of the ice-free land surface bearing significant human modification, including active agricultural land, managed forests, urban areas, degraded drylands, and secondary vegetation on previously cleared land.

The climatic significance of this finding lies not in the carbon flux — which is captured, albeit incompletely, in atmospheric $CO_2$ records — but in the surface energy flux transformation. Each hectare of converted forest, grassland, or wetland is a hectare of altered surface energy partitioning, with the direction of change universally toward higher surface temperatures and enhanced LW-IR emission. The cumulative effect across 75% of the planet's land surface represents a distributed, spatially pervasive forcing that has no analogue in the instrumental climate record.

### *3.2 The UNCCD Dimension: Dryland Degradation*

The United Nations Convention to Combat Desertification's Global Land Outlook documents the accelerating degradation of dryland ecosystems, which cover approximately 41% of Earth's land surface and support roughly 3 billion people. UNCCD monitoring data indicate that approximately 12 million hectares of land is degraded to the point of productive loss annually, with total degraded land area estimated at approximately 3.2 billion hectares — comparable to the combined area of China and the United States.

From a surface LW-IR forcing perspective, dryland degradation represents the most intense concentration of the mechanism described in Section 2. Degraded dryland soils exhibit near-zero evapotranspiration rates, high emissivity (0.92–0.97 for mineral soils), high thermal responsivity to solar forcing, and — critically — extremely high peak surface temperatures. Bare soil surfaces in subtropical and tropical drylands routinely reach 55–70°C under peak insolation, producing LW-IR emission intensities substantially above any vegetated surface and comparable in per-unit-area terms to low-grade industrial heat sources.

UNCCD data further document that dryland regions are warming at rates 20–40% above the global mean surface temperature trend — a spatial anomaly that is difficult to explain under $CO_2$ column forcing, which has no dryland-preferential absorption mechanism, but which is a direct prediction of the surface LW-IR forcing hypothesis.

# 4. SPECTRAL PHYSICS: INDEPENDENCE OF THE SURFACE LW-IR FORCING PATHWAY

### *4.1 The Atmospheric Window and Surface Emission*

A physically decisive feature of the land surface LW-IR forcing mechanism is its spectral location relative to the primary greenhouse gas absorption bands. Terrestrial surface emission follows the Planck blackbody function modified by surface emissivity. For surface temperatures in the range 285–320 K — characteristic of warm land surfaces — emission peaks in the range 9–10 μm and is broadly distributed across the 7–14 μm region.

This spectral range coincides with the atmospheric window — the region of relative infrared transparency defined by the absence of strong $CO_2$ or water vapour absorption lines. $CO_2$ absorbs primarily at 15 μm (4.3 μm fundamental, but climatically the 15 μm bending mode is dominant), with significant absorption at 9.4 and 10.4 μm (weaker combination bands) but rapidly declining cross-sections toward shorter wavelengths. $CH_4$ absorbs at 3.3 μm and 7.7 μm but is essentially transparent across most of the 8–13 μm window. Water vapour dominates absorption at wavelengths above approximately 16 μm and below 8 μm, with the 8–13 μm window representing the principal gap in its absorption spectrum.

The consequence is that enhanced LW-IR emission from thermally elevated land surfaces — radiating predominantly in the 8–13 μm atmospheric window — enters the lower troposphere through a spectral channel in which greenhouse gas competition for photon absorption is at its minimum. This is not a fortuitous coincidence: it is a necessary consequence of the Planck function for surfaces at Earth-relevant temperatures. Surface LW-IR forcing and greenhouse gas forcing are, to a first approximation, spectrally orthogonal mechanisms — they force the atmospheric energy budget through different wavelength ranges, and their effects are physically additive rather than mutually exclusive.

### *4.2 $CO_2$ Band Saturation in the Lower Troposphere*

A further spectral consideration bearing on the relative magnitudes of the two mechanisms is the saturation state of the $CO_2$ 15 μm absorption band in the lower troposphere. At current atmospheric $CO_2$ concentrations (~420 ppm), the line centres of the primary $CO_2$ absorption features are effectively optically saturated in the lower troposphere — meaning that photons at those wavelengths are absorbed within metres to tens of metres of the surface, with negligible change in absorption rate from further concentration increases. Additional $CO_2$ forcing derives primarily from the far wings of the absorption lines and from weaker spectral features, producing the well-known logarithmic relationship between $CO_2$ concentration and radiative forcing ($\Delta F \approx 5.35 \ln(C/C_0)$ W $m^{-2}$).

The physical implication is that the marginal forcing per unit of $CO_2$ concentration increase is declining as concentrations rise above saturation thresholds. Surface LW-IR forcing, by contrast, scales with $T^4$ — superlinearly with surface temperature — and operates in spectral space where no saturation constraint applies. As global surface temperatures rise and land degradation continues, the surface LW-IR forcing may be expected to grow at a faster rate than the $CO_2$ concentration-forcing relationship.

### *4.3 Methane Spectral Overlap and Effective Forcing*

Methane's global warming potential is conventionally quoted at approximately 84× $CO_2$ over a 20-year horizon (GWP-20), a figure that has received substantial attention in climate policy discussions. However, the GWP calculation is performed under standard atmospheric conditions and does not account for the spectral pre-emption of $CH_4$ forcing by water vapour absorption in humid environments.

$CH_4$'s primary climatically relevant absorption band at 7.7 μm overlaps significantly with water vapour rotational-vibrational transitions in the same spectral region. In the warm, humid boundary layer above agricultural and degraded land surfaces — precisely the environment in which land surface forcing is greatest — a substantial fraction of $CH_4$'s potential radiative forcing at this band is pre-empted by water vapour already absorbing those photons. The effective GWP of $CH_4$ in high-humidity lower tropospheric conditions is therefore materially lower than its standard headline value. This further diminishes the greenhouse gas forcing budget relative to the surface LW-IR forcing that acts through the largely water-vapour-transparent atmospheric window.

## 5. HISTORICAL PRECEDENT: THE RUDDIMAN EARLY ANTHROPOCENE HYPOTHESIS

The temporal depth of the land surface forcing argument is substantially established by Ruddiman's Early Anthropocene Hypothesis (Ruddiman, 2003, 2007, 2013, 2018). Drawing on ice-core records of atmospheric $CO_2$ and $CH_4$ concentrations over the late Quaternary, Ruddiman observed that Holocene greenhouse gas concentrations diverge from the trajectory predicted by Milankovitch orbital forcing approximately 8,000 years ago for $CO_2$ and 5,000 years ago for $CH_4$ — the periods corresponding to the widespread adoption of forest clearance for agriculture and the expansion of irrigated rice cultivation, respectively.

Ruddiman's synthesis argues that the cumulative effect of pre-industrial agricultural land clearance was sufficient to raise atmospheric $CO_2$ by approximately 40 ppm and $CH_4$ by approximately 250 ppb above their Milankovitch-predicted trajectories — and that without this anthropogenic perturbation, Earth's climate should be in an orbitally forced cooling phase potentially approaching glacial inception. The implication — supported by comparison with earlier interglacials that followed the predicted Milankovitch cooling pattern — is that land-driven climate forcing reversed a natural ice age trajectory.

For the present argument, Ruddiman's hypothesis establishes two critical points. First, land surface change is a mechanism of millennial-scale and glacier-forcing magnitude — not a regional or secondary perturbation. Second, the $CO_2$ signal associated with land clearance and the biophysical surface signal are coeval and co-originated: both arise from the same land transformation, but only the $CO_2$ signal has been systematically attributed in formal climate accounting. The biophysical surface signal — the direct LW-IR forcing from cleared land surfaces — has been largely invisible to attribution frameworks that did not exist when the forcing occurred and that would struggle to resolve it even today.

The industrial acceleration of land transformation — occurring at rates and spatial extents that dwarf pre-industrial clearance — therefore builds upon a multi-millennial baseline of surface forcing whose cumulative effects are embedded in the current climate state.

## 6. SPATIAL PATTERN OF OBSERVED WARMING: A DIAGNOSTIC TEST

A fundamental diagnostic test of any proposed primary forcing mechanism is whether the spatial pattern of observed warming is consistent with the spatial distribution of that forcing. This test favours the surface LW-IR hypothesis over the $CO_2$ column forcing hypothesis in several important respects.

### *6.1 Dryland Amplification*

As noted in Section 3.2, UNCCD data document dryland warming rates 20–40% above the global mean. $CO_2$, as a well-mixed atmospheric gas with globally uniform concentration, provides no mechanism for preferential dryland warming at the surface. The surface LW-IR mechanism, by contrast, directly predicts maximum warming in regions of maximum evapotranspiration suppression and maximum bare soil surface temperature elevation — precisely the dryland environments where UNCCD data show anomalous warming.

### *6.2 Arctic Amplification and Ice-Albedo Feedback*

Arctic surface air temperatures are rising at approximately 3–4 times the global mean rate — a phenomenon termed Arctic amplification. The standard explanation invokes the ice-albedo feedback: as sea ice retreats, darker ocean surfaces absorb more solar radiation, warming the surface further. This is physically correct and well-supported. However, it is itself a surface forcing mechanism — the thermal elevation of the Arctic surface consequent on ice loss drives enhanced LW-IR emission from newly exposed ocean and permafrost surfaces into the boundary layer, directly heating the lower troposphere. This is precisely the surface LW-IR mechanism operating in the polar context.

Permafrost thaw across the approximately 15 million km² of permafrost-underlain terrain further exposes dark, wet organic soils with near-zero albedo and high emissivity, creating additional LW-IR forcing. The integrated surface energy budget transformation from Arctic ice and permafrost loss is a leading-order contributor to observed polar warming that is partially, but not fully, captured in $CO_2$-forced model simulations.

### *6.3 Continental Interior and Agricultural Region Warming*

Continental interiors warm faster than coastal regions in the observational record, and heavily agricultural regions — particularly in central Asia, sub-Saharan Africa, and the North American interior — show warming rates above the global mean. These regions are characterised by intensive land modification, large fallow-bare soil cycles, and distance from moderating oceanic moisture sources. This pattern is consistent with surface LW-IR forcing and less readily explained by $CO_2$ column forcing alone.

### *6.4 Urban Heat Islands as Local Forcing Proxies*

Urban heat islands — the well-documented phenomenon whereby urban areas record systematically higher surface temperatures than surrounding rural areas — provide the cleanest observational analogue for the surface LW-IR mechanism in isolation from $CO_2$ effects, since $CO_2$ concentrations above urban and rural sites are not sufficiently different to explain the observed 5–12°C temperature differentials. Urban warming is unambiguously a surface physical effect — high thermal mass, low albedo, suppressed evapotranspiration, and waste heat discharge. That cities warm substantially more than their surroundings despite similar atmospheric compositions is direct empirical evidence that surface properties can drive significant local warming independently of greenhouse gas forcing.

## 7. THE COMPLETE INVENTORY OF SURFACE LW-IR FORCING ACTIVITIES

The ecological land degradation case, while substantial, represents only a portion of the anthropogenic surface LW-IR forcing budget. A comprehensive inventory must include the following additional categories of human surface modification and thermal discharge, each of which increases LW-IR emission into the lower atmosphere through distinct but physically related pathways.

### *7.1 Urban and Industrial Sprawl*

Global urban land area exceeds 1 million km² and is expanding at approximately 1 million hectares per year. Urban surfaces — concrete, asphalt, brick, glass, and steel — have thermal properties that amplify surface LW-IR emission relative to the vegetated land they replace. High thermal mass absorbs daytime solar radiation and stores heat for nocturnal re-emission, extending the period of elevated surface temperature and LW-IR output. Low albedo increases solar absorption. Near-zero evapotranspiration eliminates the latent heat export that would otherwise moderate surface temperatures.

Beyond surface physics, urban and industrial zones discharge waste heat directly from energy conversion processes — heating, transportation, manufacturing, and data infrastructure. Global anthropogenic waste heat production is estimated at approximately 16–17 TW continuously. While small relative to solar input (~170,000 TW), it is intensely concentrated in urban-industrial corridors and constitutes a continuous, geographically fixed source of thermal energy injection into the lower atmosphere that is entirely absent from pre-industrial surface energy budgets.

### *7.2 Loss of Ice and Snow Cover*

The loss of sea ice, glaciers, ice sheets, and seasonal snowpack constitutes a particularly important category of surface LW-IR forcing because it operates through two simultaneous mechanisms. The albedo transition from highly reflective ice or snow (albedo 0.7–0.9) to open ocean (albedo 0.06) or bare soil (albedo 0.15–0.25) dramatically increases shortwave absorption, elevating surface temperatures. The elevated surface temperature then produces substantially greater LW-IR emission: open Arctic ocean at 10°C emits approximately 366 W $m^{-2}$, compared to approximately 315 W $m^{-2}$ for sea ice at −10°C — a difference of approximately 51 W $m^{-2}$ per unit area.

Across the approximately 12 million km² of Arctic sea ice that has been lost since the mid-20th century, this surface forcing is substantial. The approximately 15 million km² of permafrost-underlain land, with progressive surface layer thaw exposing dark organic soils, represents an additional, ongoing surface forcing component whose full magnitude is not yet captured in global energy budget assessments.

### *7.3 Fallow and Bare Arable Land*

Between 1.5 and 2 billion hectares of potentially arable or recently cultivated land lies fallow or bare at any given time, through a combination of deliberate agricultural management (fallow cycles, set-aside schemes), post-harvest bare soil periods, land abandonment following degradation, and preparation tillage. This area, comparable in extent to the entire cultivated agricultural area of the planet, represents a massive intermittent source of enhanced LW-IR emission.

Bare agricultural soils in subtropical and temperate regions reach surface temperatures of 50–70°C under peak summer insolation — substantially exceeding the temperatures of vegetated surfaces or even urban materials. A bare soil surface at 60°C (333 K) with $\varepsilon = 0.95$ emits approximately 702 W $m^{-2}$, compared to approximately 395 W $m^{-2}$ for a vegetated surface at 25°C — a difference of over 300 W $m^{-2}$. Even accounting for the intermittent nature of the fallow cycle, the aggregate annual LW-IR forcing from this source across 1.5–2 billion hectares is very large.

### *7.4 Wildfires*

Global wildfire area has increased substantially over recent decades, driven by the interaction of warming, drying, land management changes, and the accumulated fuel loads from decades of fire suppression. The 2019–20 Australian fire season burned approximately 18.6 million hectares; Siberian fire seasons have repeatedly exceeded 15 million hectares in the 2020s; North American annual burn area shows a statistically significant increasing trend.

Wildfires contribute to the LW-IR forcing budget through three distinct pathways. Active fire emission at temperatures of 600–1100°C produces LW-IR and near-IR emission intensities orders of magnitude above any surface or industrial source — global fire radiative power measured from satellites routinely exceeds 1,000 GW during peak fire seasons. Post-fire charred surfaces exhibit near-zero albedo (albedo 0.05–0.10) and high emissivity, producing elevated LW-IR emission for months to years after fire passage. Black carbon deposition on snow and ice from wildfire smoke accelerates ice loss, extending the ice-albedo forcing described in Section 7.2. The net effect of increasing wildfire activity is a substantial and growing contribution to the surface LW-IR forcing budget that is not captured in emissions-based $CO_2$ accounting.

### *7.5 Direct Thermal Discharge from Fossil and Nuclear Fuel Use*

The combustion of fossil fuels and the operation of nuclear reactors inject thermal energy into the environment through pathways that are physically distinct from their atmospheric chemistry effects. Every joule of primary energy ultimately becomes heat in the environment; at a global consumption rate of approximately 600 EJ $yr^{-1}$, this represents a continuous thermal discharge of approximately 19 TW. While small relative to solar forcing in global mean terms, this energy is entirely new to the Earth system — it represents the liberation of geologically stored chemical and nuclear energy that was not part of the pre-industrial surface energy budget, and it is concentrated in precisely the urban-industrial regions showing anomalous warming.

Gas flaring at oil and gas production facilities deserves specific attention. NOAA Visible Infrared Imaging Radiometer Suite (VIIRS) satellite monitoring identifies over 15,000 active flaring sites globally, combusting approximately 140 billion cubic metres of gas annually and generating an aggregate continuous thermal output of approximately 400–500 GW at flame temperatures of 1,000–1,400°C. This represents an intense, geographically fixed, and largely unmitigated source of high-temperature IR radiation into the atmosphere that is entirely absent from pre-industrial energy budgets.

Nuclear power plants discharge approximately 750 GW of waste heat continuously to aquatic environments through cooling systems, elevating receiving water temperatures and driving enhanced LW-IR emission from warmed water surfaces. While this source carries no $CO_2$ emissions, its direct thermal contribution to the surface energy budget is physically identical in character to fossil fuel waste heat.

## 8. THE WATER VAPOUR FEEDBACK AND THE ATTRIBUTION TRAP

### *8.1 Water Vapour as the Dominant Amplifier*

Water vapour is responsible for approximately 50% of the total atmospheric greenhouse effect under clear-sky conditions — substantially more than $CO_2$ in terms of instantaneous column absorption. The Clausius-Clapeyron relation requires that atmospheric saturation vapour pressure increases by approximately 7% per degree Kelvin of surface temperature increase. Combined with the tendency of relative humidity to remain approximately constant in the free troposphere under warming, this produces a specific humidity increase of approximately 7% $K^{-1}$, which translates to an amplification factor for any initial surface forcing of approximately 1.6–2.0× under realistic atmospheric conditions.

This amplification is thermodynamically agnostic as to the source of the initial warming: it operates identically whether the surface temperature increase is driven by $CO_2$ radiative forcing or by land surface LW-IR forcing. A surface warmed by 1°C through evapotranspiration suppression triggers the same water vapour feedback as one warmed by 1°C through enhanced downwelling $CO_2$ radiation.

### *8.2 The Attribution Trap*

Standard climate attribution methodology, as implemented in CMIP model ensembles, partitions observed warming into contributions from individual forcings by running models with individual forcing agents switched on or off and comparing simulated temperature responses. This methodology contains a structural limitation when applied to land surface forcing: because CMIP land surface schemes historically underrepresent the biophysical evapotranspiration pathway (de Noblet-Ducoudré et al., 2012; Pitman et al., 2009; Lawrence et al., 2016), models do not correctly simulate the surface temperature elevation from land cover change. Consequently, the water vapour increase that this surface warming would trigger is also absent from the model simulation.

When observed atmospheric water vapour concentrations rise — as they have, consistently with warming surface temperatures — and this increase cannot be attributed to the underrepresented land surface mechanism, attribution frameworks assign the water vapour increase and its consequent warming to the $CO_2$ forcing that is correctly represented in the model. The land surface signal is thus laundered through the water vapour feedback and re-emerges in attribution analyses as apparent $CO_2$-driven warming. This is not an artefact of bad data or bad modelling in an ordinary sense: it is a systematic structural bias arising from the known underrepresentation of a specific physical mechanism.

### *8.3 The Self-Reinforcing Dryland Desiccation Feedback*

A further feedback loop operating through the land surface-water vapour interaction compounds the above effect. Land degradation and deforestation simultaneously suppress local evapotranspiration (reducing the moisture flux to the atmosphere) and elevate surface temperatures (increasing the atmospheric moisture demand through higher saturation vapour pressure). The net effect is regional atmospheric drying — reduced precipitation recycling — that further stresses surviving vegetation and reduces evapotranspiration further. This creates a self-reinforcing trajectory from vegetated moisture-recycling equilibria toward degraded hot-dry equilibria that is largely independent of $CO_2$ forcing and that standard GCMs, with limited land-atmosphere moisture recycling representation, do not adequately simulate.

The operational consequence is that once land degradation reaches a threshold in a given region, the feedback loop tends toward further degradation and further surface LW-IR forcing, in a manner that is self-sustaining and not readily reversible by $CO_2$ concentration reduction alone.

## 9. SYNTHESIS AND IMPLICATIONS

### *9.1 The Integrated LW-IR Forcing Budget*

Table 1 summarises the principal components of the anthropogenic surface LW-IR forcing inventory identified in this synthesis. While precise global quantification of each component would require dedicated measurement and modelling efforts beyond the scope of this paper, the order-of-magnitude characterisation is sufficient to establish that the aggregate surface LW-IR forcing is substantial and likely of primary-driver magnitude.

| Forcing Source | Primary Mechanism | Indicative Magnitude |
|---|---|---|
| Deforestation / land degradation | Evapotranspiration suppression → surface warming → LW-IR | +15 W $m^{-2}$ per affected ha (local) |
| Dryland desertification | Near-zero ET, bare high-emissivity soils, 55–70°C peaks | Warming 20–40% above global mean |
| Urban & industrial sprawl | High thermal mass, waste heat, suppressed ET | UHI +5–12°C; ~17 TW waste heat |
| Arctic ice & snow loss | Albedo flip → +51 W $m^{-2}$ LW-IR from open ocean vs. ice | ~12M $km^2$ sea ice lost; 3–4× global warming rate |
| Fallow / bare arable land | Bare soil at 50–70°C, near-zero ET, high emissivity | 1.5–2 Bn ha globally |
| Wildfires (increasing) | Direct fire emission + post-fire black surface | >1,000 GW fire radiative power at peak |
| Gas flaring | 1,000–1,400°C direct IR emission | ~400–500 GW continuous; 15,000+ sites |
| Fossil fuel waste heat | Direct thermal injection from stored energy | ~19 TW global; concentrated in industrial zones |
| Nuclear waste heat | Thermal discharge to water bodies → LW-IR | ~750 GW continuous |

*Table 1. Summary of principal anthropogenic surface LW-IR forcing components.*

### *9.2 What This Framework Does and Does Not Claim*

This synthesis does not assert that $CO_2$ and other well-mixed greenhouse gases are climatically irrelevant. The spectral physics of $CO_2$ absorption is well-established, experimentally verified, and not in dispute. The logarithmic forcing relationship is real, the stratospheric cooling fingerprint is observed, and the isotopic evidence for anthropogenic $CO_2$ is compelling. Nothing in the surface LW-IR forcing argument negates these observations.

What this framework claims is: (i) that $CO_2$ column forcing has been assigned primary driver status partly by default, owing to the structural invisibility of surface LW-IR forcing in the modelling and attribution tools that generated the consensus; (ii) that the spatial pattern of observed warming is more consistent with a surface-forcing-primary explanation than with a $CO_2$-primary explanation; (iii) that the spectral and physical mechanisms of surface LW-IR forcing are entirely distinct from greenhouse gas forcing and have been underweighted, not because of their physical insignificance but because of their poor representation in standard attribution frameworks; and (iv) that when the complete inventory of anthropogenic surface LW-IR forcing is properly characterised alongside the ecological degradation component, the aggregate forcing is of first-order climate significance.

### *9.3 The Model Representation Gap*

The work of Fyfe and colleagues on CMIP model performance diagnostics, and the broader literature on land surface model limitations (Pitman et al., 2009; de Noblet-Ducoudré et al., 2012; Lawrence et al., 2016), documents systematic divergences between model-simulated and observed warming, particularly over continental interiors and dryland regions — precisely the areas where surface LW-IR forcing is predicted to be strongest. When land surface schemes are enhanced to include more realistic evapotranspiration coupling and surface energy partitioning, regional model-observation agreement improves. This is not conclusive attribution evidence, but it is consistent with the hypothesis that the model gap reflects the underrepresented surface mechanism.

### *9.4 Policy Implications*

The policy implications of the surface LW-IR forcing framework differ materially from those of the $CO_2$-primary framework, and in one crucial respect they are more tractable. $CO_2$ concentration reduction requires decarbonisation of energy systems — a multi-decadal, capital-intensive transition that faces profound technological, economic, and geopolitical obstacles. Surface LW-IR forcing reduction, by contrast, can be addressed through ecological and land surface restoration — revegetation of degraded land, wetland restoration, soil regeneration, urban greening, cessation of gas flaring, and cooling of industrial and urban surfaces — using technologies and practices that are available now, at lower cost, and with immediate local cooling effects.

If surface LW-IR forcing is indeed a primary driver of observed warming, then ecological restoration is not merely a carbon sequestration strategy to be valued for its atmospheric $CO_2$ drawdown. It is a direct, first-order climate intervention that reduces the surface temperature forcing at source, suppresses the water vapour feedback at its trigger point, and restores the moisture recycling systems that moderate regional climates. The UNCCD target of land degradation neutrality by 2030, the Convention on Biological Diversity ecosystem restoration targets, and national reforestation commitments would, on this reading, constitute climate interventions of potentially greater immediate impact than equivalent carbon reduction measures.

Gas flaring elimination — technically straightforward, economically rational, and already mandated under existing voluntary agreements that are routinely violated — would remove approximately 400–500 GW of direct atmospheric thermal loading immediately. Urban cooling through green infrastructure, reflective surfaces, and restored urban hydrology could reduce UHI forcing across the most intensely warming urban environments. These are not speculative future technologies: they are policy decisions.

## 10. CONCLUSIONS

This synthesis advances the following principal conclusions:

**1.** Land surface transformation drives large, physically well-characterised surface temperature elevations through evapotranspiration suppression, consistent with Duveiller et al.'s satellite observations showing local warming comparable to global GHG forcing per unit area.

**2.** The scale of anthropogenic surface modification (Erb et al.: 75% of land surface; UNCCD: 41% affected by desertification) is sufficient to constitute a planetary-scale forcing, not a regional perturbation.

**3.** Surface LW-IR emission peaks in the 8–13 μm atmospheric window where $CO_2$ and $CH_4$ are spectrally weakest, providing a mechanistically independent forcing pathway that is not in spectral competition with greenhouse gas forcing.

**4.** $CO_2$'s 15 μm absorption band approaches saturation in the lower troposphere, and $CH_4$'s 7.7 μm band is substantially pre-empted by water vapour absorption in humid boundary layers, reducing the marginal forcing of both gases relative to the headline figures derived under standard atmospheric conditions.

**5.** The spatial pattern of observed warming — anomalously strong in drylands, Arctic regions, continental interiors, and urban areas — is better predicted by surface LW-IR forcing than by $CO_2$ column forcing alone.

**6.** Standard CMIP attribution models underrepresent land surface biophysical evapotranspiration physics (Fyfe et al.; de Noblet-Ducoudé et al.), creating a structural bias that misattributes water vapour amplification of surface warming to $CO_2$ forcing.

**7.** The complete inventory of anthropogenic surface LW-IR forcing — including urban sprawl, ice loss, fallow agriculture, wildfires, gas flaring, and thermal waste discharge — substantially exceeds the ecological degradation component alone and constitutes a sustained, distributed source of boundary-layer heating operating independently of atmospheric $CO_2$ concentration.

**8.** Ruddiman's Early Anthropocene Hypothesis establishes that land surface forcing was of glacier-forestalling magnitude even at pre-industrial spatial extents, providing deep temporal validation of the mechanism's power.

We conclude that land surface change, operating through enhanced longwave infrared emission into the lower atmosphere, constitutes at minimum a co-primary driver of observed global warming and merits fundamental reassessment in attribution science and climate policy frameworks. The $CO_2$ signal is real and consequential. But the ground beneath our feet — hotter, barer, drier, and more infrared-active than at any point in the Holocene — may be doing more of the warming than the sky above it. If that proposition is correct, restoring the living surface of the

Earth is not an alternative to climate action. It is climate action, in its most immediate and powerful available form.

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