Part of the Series:
Soil & Climate

The Soil Carbon Sponge: Restoring Earth's Hydrological Cooling System for Climate Stability

About Save Soil:

Save Soil is a global people's movement launched by Conscious Planet to address the rapid degradation of agricultural soils. Over the last three decades, Save Soil has implemented a holistic strategy for soil revitalization through scalable farmer-driven projects, policy advocacy, and citizen awareness campaigns. The movement is working with a number of governments across the globe to shape soil policies, and is supporting over 250,000 farmers in India to transition to various other regenerative agricultural practices including tree based agriculture (often referred to as agroforestry). Save Soil is backed by the UN Environment Program, UN Food and Agricultural Organisation, UN Convention to Combat Desertification, World Food Program, and IUCN amongst others.

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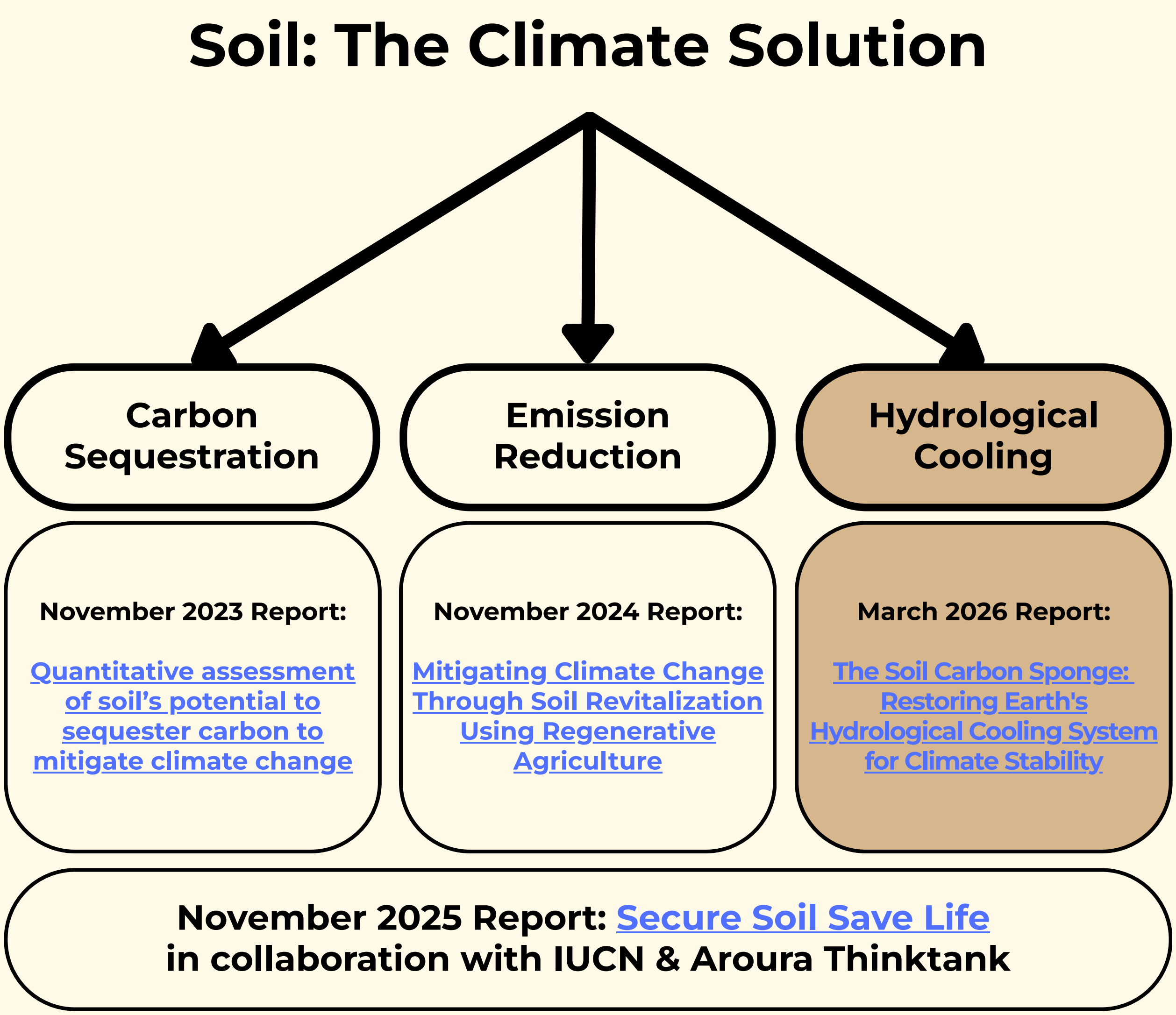
Soil & Climate Series

This publication is part of the series Soil & Climate, which explores the various ways in which improved soil health through the application of sustainable soil management practices can address the global climate crisis in terms of both mitigation and adaptation. An overview of the series is given below:



In addition, Save Soil published detailed analysis on UNFCCC COP30:

- Soil as a Lead Indicator of the Global Goal on Adaptation (GGA)
- Soil as Climate-Critical Infrastructure: From Agricultural Input to Strategic Resilience Asset
- Solution instead of Victim: Integrating Soil Health into NDCs
- COP30: A Turning Point for Climate Action—but Agriculture and Soils Still Left Behind

Executive Summary

While contemporary climate mitigation discourse focuses primarily on carbon sequestration and the reduction of greenhouse gas emissions, this report introduces a critical additional strategy for climate stability: the restoration of Earth’s hydrological cooling system. For over 4 billion years, water has been responsible for approximately 95% of Earth’s heat dynamics through interlinked processes like evapotranspiration and condensation. Central to this system is the soil carbon sponge, a living, porous infrastructure of healthy soil that manages freshwater and enables the cooling processes essential for ecosystem function.

Currently, the planet faces a severe destabilization of this water cycle, with 52% of agricultural land degraded globally and nearly one-third of U.S. soils experiencing erosion rates up to 10 times higher than natural formation. This degradation shifts the surface energy balance away from cooling latent heat flux, which consumes heat through evaporation, and toward sensible heat flux, which directly increases air temperature. In Europe alone, 60-70% of soils are considered unhealthy , contributing to intensified heatwaves and a loss of the "green water" moisture that fuels regional cooling.

The report emphasizes that rebuilding the soil carbon sponge acts as a powerful climate regulator, as every 1% increase in soil organic matter allows a hectare of land to hold an additional 250,000 liters of water. This stored water sustains the vegetation necessary for continuous evapotranspiration, which exports roughly 80 W/m^2 of solar energy back into the atmosphere. Restoring this biological cooling force could potentially offset the 0.9 W/m^2 total energy imbalance causing global warming by re-establishing a cooling effect that is three times larger than the warming caused by human-induced greenhouse gases.

To achieve long-term stability, climate policy must prioritize the regeneration of soil structure across all land types to restore infiltration and water storage. Recommendations include minimizing bare soil exposure through cover cropping and mulching to suppress infrared re-radiation , and protecting forest ecosystems that drive "small water cycles" to return moisture to the soil. By integrating land regeneration with emissions reductions, we can restore the roughly 3.0 W/m^2 of lost natural cooling and enable landscapes to function once again as self-regulating climate stabilizers.

1. Introduction

Globally, 52% of the world's agricultural land is degraded [1]. In Europe alone, an estimated 60–70% of soils are unhealthy, with degradation driven by intensive agriculture, urbanisation, and climate change [22]. In the United States, nearly one-third of soils are severely degraded, with erosion rates exceeding natural soil formation by up to 10 times [23,24]. In addition, Water stress is intensifying rapidly: 30% of European territory and 33% of the population are affected by water stress each year [25]. In the United States, groundwater depletion - largely linked to poor soil water retention - has caused critical declines in major aquifers such as the Ogallala [26].

Over the past 10,000 years, particularly over the last 300, humans have cleared and burned forests, oxidised soils, and created over 5 billion hectares of man-made desert. This has significantly altered the capacity of more than 70% of the global land surface to infiltrate and retain rainwater, negatively impacting the evaporative cooling processes and increasing direct exposure of soils to solar heating [9].

For more than 4 billion years, water has been responsible for approximately 95% of Earth's heat dynamics through a series of interlinked hydrological processes that help regulate the climate [21]. Through evapotranspiration (ET), condensation, and freezing, water transfers heat throughout the Earth system, shaping weather patterns and long-term climate stability [2,3]. Energy is exchanged between the land surface and the atmosphere primarily through two pathways: latent heat flux and sensible heat flux. Latent heat flux occurs when water changes phase from liquid to vapour through evaporation and plant transpiration, a process that consumes large amounts of heat energy from the surrounding environment [21,2]. Because this phase change is endothermic, it cools the land surface while transferring energy into the atmosphere without raising surface temperatures. In contrast, sensible heat flux involves the direct transfer of energy through conduction and convection, increasing air temperature that can be physically sensed [21,2,11]. The balance between these two pathways determines whether incoming solar energy contributes to surface warming or is safely exported into the atmosphere as water vapour. ET returns approximately 60% of annual terrestrial precipitation to the atmosphere and strongly influences regional precipitation patterns and surface temperatures [6]. Disruption of hydrological heat processes has been linked to increasing heatwave intensity, drought, floods, wildfires, and crop failures, particularly in arid and semi-arid regions [4]. These changes indicate a broader destabilisation of the terrestrial water cycle.

Recent data show that soil moisture deficits have intensified across large parts of Europe since 2018, contributing to record-breaking heatwaves and crop losses [27]. In the United States, 2023–2024 drought conditions affected over 40% of agricultural land, significantly reducing productivity and increasing irrigation demand (28). Soil plays a central role in regulating the infiltration, storage, and release of water within the terrestrial system. More than half of the annual precipitation passes through the soil and vegetation. Then it is returned to the atmosphere as evapotranspiration. Whether rainfall infiltrates and recharges groundwater, or becomes surface runoff depends largely on soil structure and carbon content [7]. Biologically active and well-aggregated soils slow down runoff, enhance percolation, and extend water availability to vegetation, sustaining evapotranspiration and contributing to climatic cooling [8].

The capacity to infiltrate and store water below the surface is governed by the soil carbon sponge, a living infrastructure composed of mineral particles, organic matter, and pore space that manages freshwater, supports nutrient cycling, and enables microbial processes essential for ecosystem function [8]. By maintaining this sponge, we safeguard 'green water' - the moisture held in the soil and accessible to plants - which represents a massive but often overlooked reservoir that fuels the terrestrial water cycle. When this structure degrades, soils lose their capacity to infiltrate and store water, shifting surface energy balance away from latent heat dissipation toward sensible heat accumulation, thereby accelerating surface warming [2,10].

Despite the central roles of water and soil in regulating Earth's heat dynamics, modern climate discourse has primarily focused on atmospheric carbon dioxide, omitting the significant contribution made by water-mediated heat fluxes, particularly latent heat fluxes, which dominate planetary heat regulation as water circulates through oceans, soils, vegetation, and the atmosphere [8,9,20].

This report examines how hydrological processes regulate Earth's energy balance, how degradation of the soil carbon sponge weakens these natural cooling mechanisms, and why restoring soil structure and moisture-holding capacity is essential for long-term climate stability.

2. Earth's Energy Budget and Its Natural Hydrological Cooling System

Earth's climate is governed by the balance between incoming solar radiation and outgoing reflected or re-radiated energy. Earth receives approximately 342 W/m² of solar radiation at the top layer of the atmosphere, which must be balanced by an equivalent amount of energy returned to space to maintain climate stability [9,11].

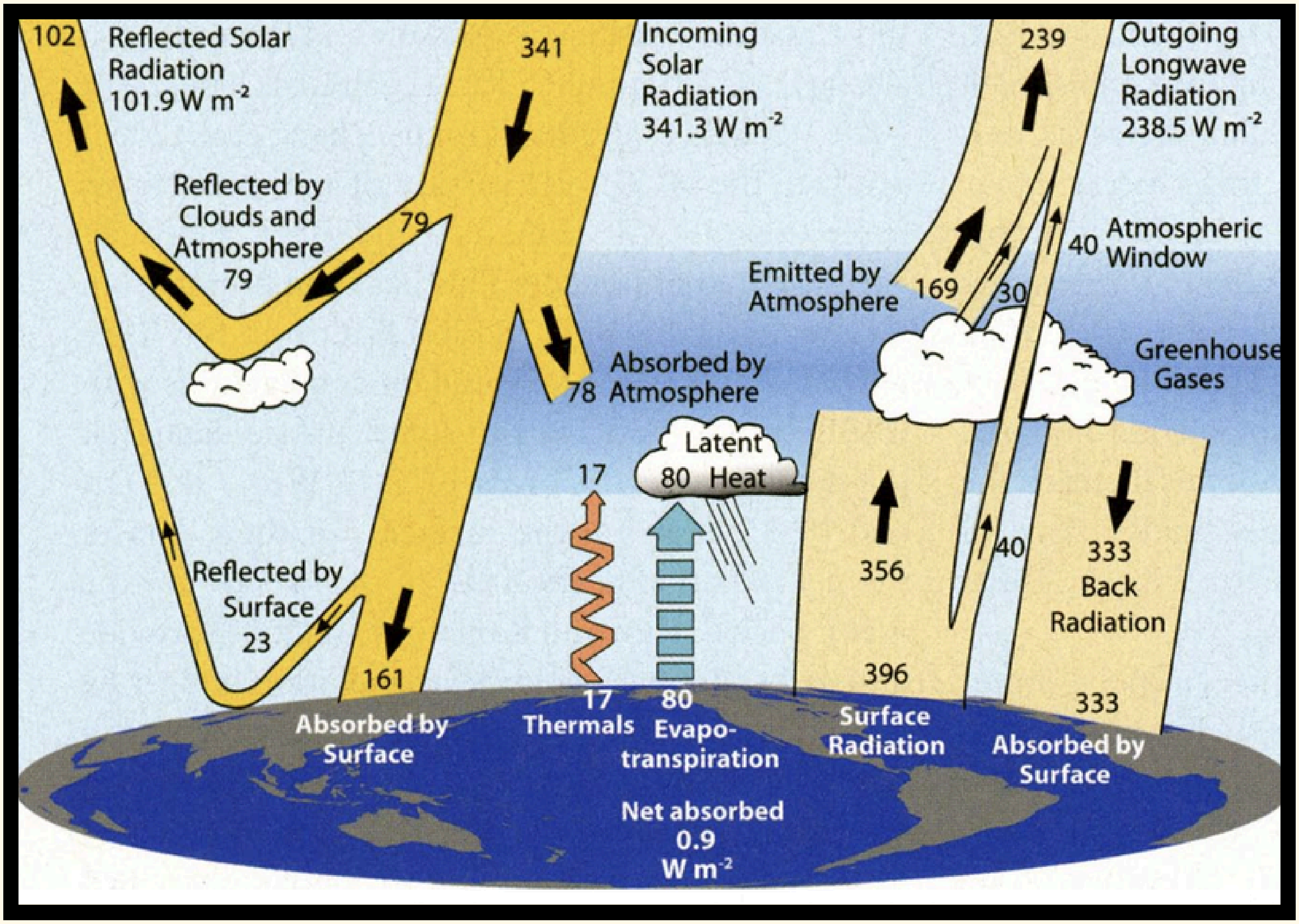


Figure 1: Illustration of Earth's Energy budget [11]

Globally, about 102 W/m² of incoming solar energy is reflected back to space by clouds, aerosols, and surface albedo [2,11]. Evapotranspiration exports roughly 80 W/m², about 24% of incoming solar energy, making it Earth's dominant thermal regulator (Fig. 1) [2,11]. Where water is available, this process efficiently removes heat from the land surface. On dry or degraded land, this energy is instead converted into sensible heat, resulting in a rapid increase in surface temperature [2].

Studies indicate that land surface changes, particularly soil degradation and vegetation loss, can increase local surface temperatures by up to 4°C, independent of greenhouse gas forcing. In Europe, land-use changes alone have contributed significantly to regional warming trends over the past decades [29].

Surface temperature has a significant influence on the amount of infrared radiation emitted back into the atmosphere. According to the Stefan–Boltzmann Law, radiated energy increases with the fourth power of temperature, meaning hotter surfaces emit exponentially more infrared radiation than cooler ones [21,9,11]. This intensifies the greenhouse effect, which is dominated by water vapour and accounts for approximately 80% of the natural greenhouse effect, compared with the relatively smaller contribution of CO_2 [21,9].

Hydrological cooling is further reinforced by cloud formation and the albedo feedback. Water vapour generated by evapotranspiration promotes the formation of low, reflective clouds that return a substantial fraction of incoming solar radiation to space before it reaches the surface [8,9,13]. Forests exemplify this coupling of evaporative cooling and cloud reflectivity, demonstrating how intact ecosystems limit surface heating and stabilise regional climates [21,8,9,13].

3. The Soil Carbon Sponge

The soil carbon sponge is a living porous matrix that absorbs, stores, and filters water while stabilising landscapes and supporting entire food webs that would otherwise collapse into desert or bare rock [14]. It is formed as a living tissue through the activity of soil microorganisms, particularly fungi and bacteria, which bind individual mineral particles together using organic detritus to create stable aggregates. In healthy soils, a single cubic metre can contain up to 25,000 kilometres of fungal hyphae, forming an extensive network that mobilises nutrients and supports soil structure [12].

The effectiveness of the soil carbon sponge largely depends on its structure. Approximately two-thirds of its volume consists of interconnected pore spaces that regulate water movement and storage [12]. Micropores, formed within soil aggregates, retain water through capillary forces and are primarily responsible for storing moisture within the soil matrix for plant use during dry periods [4]. Macropores, including biologically formed biopores created by roots and soil fauna, provide low tortuosity and create preferential flow paths that allow rainfall to infiltrate rapidly into the soil profile, rather than running off the surface [4]. This reduces erosion and flash flooding while enhancing groundwater recharge [4].

In carbon-rich, well-structured soils, organic matter stabilises soil aggregates and maintains pore connectivity, allowing both efficient drainage during intense rainfall and prolonged water availability during dry conditions [4]. This structure enables deep root penetration, often extending several meters below the surface, greatly expanding plant access to water and nutrients [4]. By sustaining green growth for extended periods, even during dry conditions, the soil carbon sponge supports continued evapotranspiration and atmospheric cooling, while simultaneously filtering pollutants as water moves through the soil via physical retention and biologically mediated degradation processes [4].

4. Terrestrial Ecosystems as Regulators of Heat, Water, and Climate

Forest ecosystems cover approximately 42 million km^2, representing about 30% of the global land surface across tropical, temperate, and boreal regions [13]. These forests not only provide ecological, economic, and social services to natural systems and humans, but also have a significant impact on the climate by redistributing heat, driving evapotranspiration, seeding clouds, and shaping regional rainfall patterns [13].

In healthy terrestrial ecosystems, the Earth is cooled through various biophysical processes that occur between the soil and vegetation. Through photosynthesis, plants utilise solar energy to transform atmospheric carbon dioxide and water into organic matter, which is incorporated by soil microorganisms into the soil carbon sponge. In forest areas, large transpiring leaf surfaces convert incoming solar energy into latent heat as water moves from the soil to the atmosphere [12]. The latent heat of vaporisation requires approximately 590 calories per gram of water, allowing ecosystems to dissipate substantial amounts of energy without raising surface temperatures [12]. Forest canopies further moderate surface temperatures by shading the soil, reducing longwave radiation, and limiting extreme surface heating, while also reducing near-surface wind speeds, conserving soil moisture, and allowing evapotranspiration-driven cooling to persist over longer periods [4,13].

Terrestrial ecosystem biology plays a significant role in the formation of rainfall. Vegetated ecosystems release precipitation nuclei, tiny particles in the air on which water vapour condenses, which facilitates precipitation. In regions such as the Amazon, this creates a "small water cycle" where the ecosystem daily transpires moisture and seeds the very thunderstorms that return that water to the soil [12].

When the vegetation and soil structure of these ecosystems are degraded, these cooling mechanisms rapidly collapse. Reduced infiltration and soil water storage limit evapotranspiration, shifting surface energy balance towards sensible heat. As surface temperatures rise, soils dry more rapidly, and hot, dry air masses intensify aridification [2]. These conditions promote the formation of persistent high-pressure heat domes, which suppress moisture inflow and rainfall, thereby reinforcing warming and accelerating landscape desiccation [13]. The increasing loss of healthy ecosystems globally due to human activities has a severe negative impact on the soil carbon sponge.

5. Consequences of a Degraded Soil Carbon Sponge

While humanity has spent 30 years obsessed with the 5% of heat dynamics driven by trace gases like CO2, regulators have almost completely ignored the 95% governed by water when it comes to the mitigation of global climate change. By destroying the Soil Carbon Sponge, we have effectively disabled Earth's primary cooling system. The total energy imbalance causing global warming is approximately 0.9 W/m2 [11]. Walter Jehne argues that by restoring the soil sponge and re-establishing green cover, we could increase evapotranspiration enough to offset this 3.0 W/m2, essentially cooling the planet back to equilibrium via the water cycle rather than focusing solely on CO_2 [21]. Therefore, restoring the soil sponge doesn't just "offset" carbon - it re-activates a cooling force that is three times larger than the total warming effect of human-induced greenhouse gases.

However, currently land and soil degradation further amplify the hydrological stresses the planet is facing today. Over 50% of global agricultural land is already moderately or severely degraded, undermining soil moisture retention and accelerating the transition of drylands toward desertification. Global drought-related damages now exceed US$307 billion annually. The recent UN report on the ‘Global Water Bankruptcy’ emphasizes that these costs are intensified by the loss of soil moisture rather than just a lack of rainfall. In addition, over the last 50 years, the world has "liquidated" 410 million hectares of natural wetlands (an area larger than the European Union). These inland marshes and swamps acted as the planet's primary water buffers and natural shock absorbers; their loss has cost US$5.1 trillion in ecosystem services. Furthermore, approximately 3 billion people and more than half of global food production are now located in regions where total water storage (including soil moisture) is either declining or critically unstable [19].

The encouraging news are that this can still be turned around given the sophistication of the soil eco-system. The world's soils can hold more water than all the world's rivers combined. Every 1% increase in Soil Organic Matter creates a subterranean reservoir capable of holding 250,000 litres of water per hectare which can effectively cool the planet in multiple ways as described in the previous chapters. Rebuilding the Soil Carbon Sponge is the equivalent of building a multitude of 'micro-dams' under our feet which can not only lead to the reversal of both climate change but also effectively lead to increased food- and water security.

6. Drivers of Soil and Ecosystem Degradation

Deforestation and Land Clearing

In 2024, the tropics lost approximately 6.7 million hectares of primary rainforest, the highest loss in at least the last two decades [15]. The historical and ongoing removal of forest cover for agriculture, timber, and settlement has exposed large expanses of soil to direct solar radiation and erosion. As Bonan (2008) documented, the clearing of temperate forests worldwide, including those in the United States, Europe, and China, for agricultural and logging purposes, has significantly altered regional temperature and water balances. [13]. Between 2002 and 2024, China and the United States lost approximately 83,000 and 1.8 million hectares of primary forest, respectively, with logging identified as the dominant driver in both regions. [17,18].

Agricultural Practices

Between 2002 and 2024, Brazil lost 34 million hectares of primary forest, accounting for 47% of its total tree cover loss during the same period [16]. The primary driver of tree cover loss in Brazil is permanent agriculture, which accounts for up to 54 million hectares [16]. Conventional industrial agriculture practices, such as over-tillage, over-reliance on synthetic chemical fertilisers, and extended periods of bare fallow, have disrupted soil structure, reducing microbial activity and exposing organic matter to oxidation [21,8,9]. This degrades the soil carbon sponge, weakening water regulation and transferring carbon from stable soil pools into the atmosphere [4,8,9]. In the European Union, agriculture accounts for over 60% of soil degradation pressures, including compaction, erosion, and organic carbon loss [30]. In the United States, industrial agriculture has led to the loss of up to 50% of original soil organic carbon in many regions [31].

Fire

The widespread burning of forests, grasslands, and agricultural stubble is a huge source of atmospheric carbon and a significant driver of soil degradation. Globally, wildfires burn approximately 300-400 million hectares each year, emitting up to 8 billion tonnes of carbon, while a further 4 billion tonnes is emitted by the burning of agricultural stubble and grasslands [9].

7. Recommendations

Regenerating the soil carbon sponge is a vital nature-based climate solution that shifts the focus from managing harm to rebuilding the systems that regulate Earth's climate. According to Walter Jehne, regeneration requires shifting the global carbon balance away from oxidation and back toward biological sequestration, by maximising carbon capture and stabilising that carbon within living, water-holding soil carbon sponge [21,8,9,11]. Scaling regenerative practices could deliver rapid benefits: studies estimate that improving soil health across global agricultural lands could sequester up to 3–5 gigatonnes of CO_2 annually while significantly enhancing water retention and climate resilience [29].

1. Prioritise Regeneration of the Soil Carbon Sponge
Climate stabilisation strategies should explicitly prioritise rebuilding soil structure and soil carbon stocks across all land types, including croplands, rangelands, forests, and wetlands. Regenerative land management practices, such as reduced tillage, organic matter restoration, agroforestry, wetland restoration, and adaptive grazing, should be expanded to restore infiltration, water storage, and sustained evapotranspiration, thereby shifting the surface energy balance back toward latent heat dissipation.

2. Protect and Expand Transpiring Vegetation
Policies must focus on maintaining continuous, photosynthetically active vegetation cover to maximise evapotranspiration-driven cooling. Forest protection, reforestation, and improved rangeland and pastoral management are crucial, particularly given that rangelands occupy over half of the global land surface and can serve as significant cooling systems when biologically intact.

3. Keep Soils Covered and Cool Year-Round

Bare soil exposure should be minimised through the use of perennial ground cover, cover cropping, mulching, and increased tree and shrub cover. These measures reduce extreme surface temperatures, suppress infrared re-radiation, conserve soil moisture, and stabilise local climates.

4. Reduce Soil Degradation, Dust Emissions, and Atmospheric Hazes

Land management should aim to reduce erosion and dust generation by restoring vegetation cover and soil stability. This will limit the formation of heat-trapping humid hazes, improve atmospheric clarity, and allow more solar radiation to be reflected rather than absorbed.

5. Restore Cloud Formation and Rainfall Cycling

Rehydrated soils and healthy ecosystems should be recognised as essential infrastructure for cloud formation and rainfall generation. Enhancing evapotranspiration and biological aerosol emissions supports high-albedo cloud cover and restores regional rainfall patterns, reinforcing natural cooling feedbacks.

6. Safeguard Night-Time Cooling Processes

Reducing atmospheric haze through ecosystem restoration and emission controls is necessary to reopen night-time radiative cooling windows. This allows stored heat to escape to space, lowers minimum temperatures, and supports dew formation critical for vegetation survival in dry regions.

7. Integrate Land Regeneration with Climate and Development Policy

Climate mitigation and adaptation frameworks should integrate land regeneration as a core strategy alongside emissions reductions. Restored soil–water–vegetation systems enhance food and water security, strengthen rural livelihoods, and build resilience to droughts, floods, and heat extremes for a growing global population.

8. Regeneration with Reduced Fossil Fuel Dependence

While restoring biological cooling systems addresses dominant heat dynamics, it must be accompanied by reductions in fossil fuel use, improved energy efficiency, and lower material throughput to prevent further disruption of atmospheric and hydrological systems.

9. Target Restoration of Lost Natural Cooling Capacity

The overarching goal should be to restore the approximately 3 W/m^2 of lost natural cooling by re-establishing evapotranspiration, cloud formation, rainfall recycling, and night-time heat release. Achieving this would enable landscapes to once again function as self-regulating climate stabilisers.

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