

THE IN A HURRY SERIES

Trees

in a Hurry

Forests, roots, and the lungs of the Earth

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The Whole Thing in One Page

The public image of a tree is a large plant standing still. A trunk, a crown, some roots below, a bird for scale. That picture catches the outline and misses the achievement. A tree is a machine that spends carbon to reach light, pulls most of its water through pipes without a central pump, repairs itself without replacing damaged parts, and may keep the same construction project running for centuries.

There is no single tree family. Oaks, palms, conifers and tree ferns reached it by different roads. Tree is a strategy: stay in one place, build upwards, keep the investment alive and return to the light year after year. Wood must be built, defended and supplied. Height exposes leaves to sun while increasing the distance water must travel. Longevity spreads the cost across time while guaranteeing that drought, wind, fire, fungi, insects and people will eventually arrive.

Among oaks, pines and many trees with vascular cambium, the trunk solves several problems at once. Living cambium adds new wood around old wood. Xylem carries water upwards under tension, drawn by evaporation from leaves. Phloem distributes sugars from sources to places that are growing, storing or repairing. Bark holds the boundary. Much of the visible trunk is dead tissue still doing structural work.

Roots are less like an underground tree than a shifting foraging front. Many nutrient-absorbing roots lie high in the soil, where oxygen and decomposing material are available, though some species reach much deeper. Roots anchor, store and explore. Fungi extend their reach in exchange for carbon. Some fungi link plants, and experiments detect below-ground transfers. The popular forest internet, with wise elders directing help to chosen young trees, runs far ahead of what those experiments establish.

A forest begins when these individual bargains overlap. Crowns divide light into layers. Roots and fungi contest water and nutrients. Leaves and wood pass through decomposers; minerals return to uptake while carbon returns to the air or enters longer-lived stores. Fallen trunks become habitat,

moisture stores and future soil. Gaps opened by death release suppressed seedlings. Fire, wind, flood, browsing and insects do not interrupt a timeless equilibrium. Their frequency and severity help make the forest that follows.

Forests cover about a third of the world's land. They hold carbon, take up more while growing, move enormous quantities of water, cool surfaces through shade and evaporation, alter roughness, cloud and rainfall, and build habitats in three dimensions. Calling them the lungs of the Earth confuses gross production with net effect. Photosynthesis releases oxygen, but respiration, decay and fire consume most of it again within the short biological cycle. Forests matter to climate for better reasons than supplying the next breath.

Human civilisation grew inside this system. Wood became fuel, shelter, ships, mines, paper, railways and cities. Clearance made fields and fortunes. Forestry made trees legible as crops. Plantations can produce timber efficiently, yet a ranked stand of one age cannot replace the history, structure and species of an old forest.

The final difficulty is speed. Trees win by committing to a place for a long time. When conditions move faster than seedlings can establish and populations can shift, that commitment turns against them. A forest may look permanent while its future is already failing at ground level.

That is the book.

Why You Should Care

A coast redwood more than a hundred metres tall has no heart. Water reaching its highest leaves has crossed a vertical distance greater than the length of a football pitch through dead conduits narrower than a drinking straw, in a column held under tension. Pull too hard and the column can break. Pull too little and the crown closes its pores, restricts carbon dioxide entry and stops growing. The tallest organisms on land live close to a plumbing failure.

That is the first reason to care. Trees make the familiar physically strange.

Wood looks passive because its fastest events occur in spring and its largest changes take decades. Beneath the stillness, leaves exchange water loss for carbon gain, stems add conduits, fine roots turn over and proliferate in useful patches, fungi receive carbon, and branches are shed when their upkeep exceeds their return.

The second reason is scale. Forests occupy about 4.14 billion hectares, roughly 32 per cent of the world's land area. They are living infrastructure for climate, water and biodiversity, but no single number captures the job. A tonne of carbon stored in an old trunk is a stock. Carbon added this year is a flow. Shade changes local heat immediately. Water released from leaves can affect clouds and rainfall far beyond the crown. Snow exposed after boreal trees are removed reflects more sunlight. The climatic value of a forest depends on latitude, moisture, age, soil, disturbance and what would replace it. Counting trunks is a poor substitute for understanding the system.

The third reason is architecture. One large tree can offer sun-baked bark, shaded bark, sap, flowers, fruit, leaves, twigs, cavities, rot pockets and dead limbs at different heights. When it falls, the same body becomes damp shelter, food and soil structure. A forest multiplies these changing surfaces across ages and species. Biodiversity is supported by the dimensions and decay of the building, not by green area alone.

A fourth reason is that forests remember. A bent trunk records a vanished opening. A line of stones under beech may mark a field abandoned two centuries ago. Charcoal in soil records fire. Pollen in lake mud records species that no longer grow nearby. Rings can preserve droughts, insect outbreaks and cold summers year by year. The present forest is an archive written by survivors, which means it records both what happened and what managed to remain.

Then there is the human account. Remove wood from history and little remains standing. Fire altered diet and survival. Handles extended force. Beams made roofs. Charcoal smelted metal. Ships joined oceans. Pit props held mines open. Paper carried law, debt, religion and science. Modern societies advertise their steel and silicon while continuing to build, package,

heat and wipe with processed trees. The material became ordinary because it was so useful.

The current danger is easily simplified and therefore easily mishandled. Deforestation still removes nearly 11 million hectares a year, while forest expansion elsewhere reduces the net loss to about 4.12 million hectares a year. Those figures describe different things. A new plantation can offset area on a spreadsheet without replacing a cleared primary forest. A million seedlings can satisfy a press release while most die. Planting trees in a native grassland can damage biodiversity and reduce water. Leaving a damaged site alone can sometimes restore it better than planting, and sometimes produce only scrub, fire or repeated grazing. Forest repair has no universal recipe.

This book will give you a better test. Ask what structure has been built, what flows through it, what history produced it, what disturbance regime maintains it, and whether the next generation can establish under the conditions now arriving.

Once you can answer those questions, a forest stops looking like scenery.

The Core Ideas

A Tree Is a Strategy, Not a Family

Ask a botanist for the branch of the evolutionary tree labelled trees and there is none. A pine is more closely related to a low juniper than to an oak. An oak shares flowering ancestry with herbs that never become woody. Palms stand tall without making a cylinder of wood in the way oaks and pines do. Tree ferns arrived at a trunk by another route again. The form has appeared, disappeared and reappeared across plant lineages because the opportunity keeps returning: rise above competitors, hold leaves in the light and keep the structure for another season.

Tree is therefore a job description. The usual candidate is a perennial plant with an elongated, self-supporting stem, branches and secondary growth,

but every clause produces exceptions. Bananas can look like trees while their apparent trunk is packed leaf bases. Palms are unquestionably trees in ordinary life and awkward in a definition built around a vascular cambium. Some willows alternate between shrub and tree according to site. The boundary is useful and untidy because evolution was solving a problem, not filing a catalogue.

The form is also conditional. A species that grows as a tree in a sheltered valley may remain a twisted shrub at a windy treeline. Human pruning can hold a genetically tall species as a miniature without changing its ancestry. Across flowering plants, woody and herbaceous habits have shifted repeatedly, with some island lineages becoming woody after descending from softer-stemmed ancestors. Tree is what development produces under inherited rules and local limits, not an essence carried by a name.

The shared strategy is expensive. Many herbs can build soft tissue, reproduce and abandon much of the structure when winter or drought arrives. A tree commits carbon to cellulose and lignin, raises leaves where wind and gravity become harder, and maintains transport routes through years in which growth may be poor. In return it avoids starting from ground level each season. Height gains light, a deep crown gains many leaves, and a persistent trunk lets one organism occupy space for decades or centuries.

That persistence is possible because a tree is modular. It has no single growing tip and no central organ whose age sets the age of every part. Meristems at shoot and root tips keep producing new tissue. Buds can sleep, branches can die, roots can be replaced and a wound can be sealed around rather than healed back to an original state. The whole organism can survive while losing large pieces of itself. A mammal losing a third of its body is an emergency. A tree may carry the dead part for another hundred years.

The strategy has been successful on an absurd scale. A global synthesis published in 2022 estimated roughly 73,000 tree species, with thousands probably still undescribed. Most of the missing species are expected to be rare and concentrated in tropical regions, which means they are also among the easiest to lose before they are named. The number is an estimate, not a

census, and the difficulty matters. Trees are large and conspicuous, yet humanity still does not know how many kinds there are.

Keep the definition functional. A tree is a long-term wager that carbon invested in height, wood and persistence will buy repeated access to light. Forests are what happens when millions of those wagers encounter one another, the weather and time.

The Trunk Is a Water Machine

Cut across a young stem of an oak, pine or most other trees that thicken by secondary growth and the arrangement looks almost too neat. Near the outside, phloem carries sugars and other compounds from productive leaves towards growing, storing and repairing tissues. Inside it, a thin ring of vascular cambium divides and lays down new phloem outward and new xylem inward. Most of that xylem will die as it matures. Its empty, reinforced cells then become the pipes and much of the structure we call wood.

Such a trunk is accumulated plumbing. The newest outer sapwood conducts most water. Older inner xylem may be taken out of service, blocked or filled with protective compounds, becoming heartwood. It can no longer transport sap, but it still holds the crown up. Most metabolically active tissue lies near the margins and in living cells threaded through the sapwood. What looks most solid is largely a useful inheritance.

In a tall tree, bulk water transport is not driven by a pump at the base. Evaporation from wet cell walls inside a leaf creates tension. Water molecules cohere to one another and adhere to conduit walls, so loss from the leaf pulls on a connected water pathway extending through twigs, trunk and roots to the soil. Sunlight drives evaporation, stomata regulate the opening, and the xylem transmits the pull. Root pressure can matter in some plants and situations, but it cannot account for water rising through a redwood.

This works because water resists being pulled apart, and fails because water can still break. Drought increases tension. Air entering a conduit can form an embolism that blocks flow. Pits between conduits help route water

around failures, while the size and arrangement of vessels or tracheids trade efficiency against safety. Wide conduits move more water with less resistance but can be vulnerable under freezing or severe drought. Species solve the compromise differently. Ring-porous oaks build conspicuous bands of large spring vessels; many conifers rely on narrower tracheids; diffuse-porous trees spread similarly sized vessels across a growth ring.

Water transport is inseparable from carbon transport. Leaves export sugars through phloem towards cambium, roots, fruits, storage tissues and wounded sites. Those destinations change by season and damage. In spring, stored reserves can support new leaves before the crown earns much current income. During drought, growth may stop while maintenance and defence continue to demand carbon. The hydraulic machine builds the carbon machine, and the carbon machine pays to repair the hydraulics.

Leaves manage the risk through stomata, microscopic pores that admit carbon dioxide and release water vapour. Closing them protects the hydraulic system but restricts photosynthesis. A droughted tree faces a controlled retreat: reduce water loss and starve carbon gain, or keep the pores open and risk hydraulic failure. Prolonged stress can involve both shortages and damage, which is why the old contest between hydraulic failure and carbon starvation does not require one winner in every death.

Height makes every part of this bargain harder. Gravity lowers water potential with each metre, path length adds resistance, upper leaves become smaller or more constrained, and wind loads increase. Work on coast redwoods showed strong hydraulic limitation near their crowns, but the often quoted universal maximum tree height is too tidy. Species, moisture, conduit design, crown shape, mechanics and local climate all matter. Trees do not stop at one ceiling. They approach several limits at once.

The trunk hides these constraints by standing quietly. It is a pressure system operating close enough to failure that each leaf must ration the opening through which the tree feeds.

Roots Forage, Trade and Hold

The child's drawing puts a second tree underground, its roots descending as far as the branches rise. Real root systems are less symmetrical and more opportunistic. Many fine absorbing roots occupy the upper layers of soil, where rain arrives, oxygen diffuses and dead material releases nutrients. Structural roots spread laterally beyond the crown in some settings. Taproots may dominate early and fade in importance. Other species or sites produce roots that reach many metres down. There is no standard underground silhouette because soil is patchy and the useful patch keeps changing.

A root tip advances through pores and fractures, protected by a cap and followed by a zone bearing fine root hairs. These greatly increase contact with water films and mineral surfaces, but much of a tree's effective reach belongs to another organism. Mycorrhizal fungi colonise roots and extend threads through volumes of soil too small or distant for roots to exploit efficiently. Fungal partners can deliver mineral nutrients, often phosphorus or nitrogen, and alter access to water. The tree transfers photosynthetic carbon in return. The outcome ranges from strongly mutual to costly, depending on partners and conditions.

Different partnerships work differently. Arbuscular mycorrhizal fungi enter root cortical cells and form exchange structures within them. Ectomycorrhizal fungi sheath fine roots and grow between cells without entering them, common among many pines, oaks, beeches and birches. Fungal individuals can connect more than one plant, and common networks have been mapped in some forests. Experiments have also detected movement of carbon and other compounds within below-ground systems. From that evidence grew the wood wide web: old trees as hubs, seedlings as beneficiaries, a forest behaving like a purposeful community.

The popular account is ahead of the measurements. Critics writing in 2023 documented repeated overstatement and positive citation bias, and questioned how often transfer through a continuous fungal link has a meaningful net benefit for recipients. Researchers responding in 2025

argued that those critiques discounted evidence for network existence and transfer too broadly. The shared ground is narrower than the story: some fungi link multiple plants and material can move below ground. Route, amount, cost, benefit, donor control and generality remain live questions.

Roots must breathe as well as drink. Their living cells need oxygen, so waterlogged soil can leave roots unable to use the surrounding water because oxygen starvation damages living tissue and transport.

Flood-tolerant trees answer with air spaces, shallow systems, raised roots or specialised structures that improve gas exchange. Dry soils create the opposite geometry, rewarding deeper access where rock and groundwater permit it. The underground design is therefore an aeration problem as much as a water problem.

Roots also move water in ways that complicate the direction of flow. Some deep-rooted plants lift water from moist lower layers and release it into dry upper soil at night; under other gradients, water can move downwards or laterally. Natural root grafts can join neighbouring trees and permit exchange, while also carrying pathogens. Anchorage depends on the spread and strength of the whole plate of roots and soil, not on one heroic taproot. In wind, a tree, its root system and a mass of soil resist overturning together.

Below ground, carbon is allocated to growth, storage, exudates, symbionts and defence. Fine roots turn over. Old roots become channels for water and other organisms. Roots alter soil structure and chemistry while soil conditions redesign the next generation of roots. They are not foundations poured once. They are a changing interface between a stationary organism and patchy soil.

A Forest Is Vertical History

A row of trees can be a plantation, an orchard or a windbreak. A forest requires more than stems close together. It is a volume arranged by light, water, death and inheritance. At the top, the canopy intercepts radiation and wind. Beneath it, smaller trees, shrubs, herbs, climbers, epiphytes, mosses and seedlings occupy declining or shifting light. Below them, litter, roots, fungi, microbes, animals and mineral soil process what falls. Leaves and wood are broken down, mineral nutrients become available again, and carbon returns to the air or remains for a time in wood and soil. The layers are connected, but they do not experience the same climate. A still, damp understorey can sit metres below a hot, turbulent crown.

The canopy is not a roof. It is a contested surface full of holes. When a branch breaks or a tree dies, light reaches leaves that have waited years at low growth. A seedling may spend decades suppressed, adding almost no height, then accelerate when a neighbour falls. Pioneers can colonise large openings quickly. Shade-tolerant species may advance through small gaps. The pattern of deaths, seed sources, browsing and soil determines which response wins. Forest succession is therefore not a ceremonial march towards one final climax. It is recruitment under inherited conditions.

A mature forest also contains an abundance of dead wood. Standing snags offer cavities and hunting posts. Fallen trunks retain moisture, release nutrients slowly, redirect water, shelter seedlings and feed fungi and invertebrates. Rot creates hollows inside living stems. Coarse woody debris may hold carbon for decades while becoming habitat of increasing complexity. Tidying a forest can remove much of the structure on which forest species depend. What looks neglected to a gardener may be doing several jobs.

Edges alter the volume. Sun, wind and dry air penetrate from a clearing or road, changing temperature, humidity, fuels and mortality beyond the line that a map labels forest. Two patches with equal area can therefore provide different interior climates if one is compact and the other narrow or perforated. Fragmentation is not merely less habitat. It changes the

proportion exposed to boundary conditions and can interrupt the movement of seeds, animals and fire.

Age adds irregularity. An old forest tends to contain large living trees, young cohorts, canopy gaps, standing dead stems, fallen wood and soils that have developed under long continuity, but there is no single old-growth template. A wet tropical forest, a boreal spruce stand and an ancient oak pasture differ in disturbance, density and human history. Old growth describes ecological qualities and continuity that must be defined for place, not a calendar birthday shared worldwide.

Disturbance is part of that definition. Some forests are shaped by frequent, low-severity fire. Others experience rare fires that kill most trees over large patches. Windstorms can remove single crowns or flatten landscapes. Floods build and erase riverine forest. Insects and pathogens thin one species and release another. Large herbivores alter regeneration. Across regions, cultural burning, grazing, coppicing and wood harvest have produced forests that are neither untouched nor ecologically empty. Their effects depend on intensity, continuity, objectives and local ecology, not merely on whether people were present. The useful question is what occurred, how often, at what severity, across what area and against which previous history.

A forest is thus a present arrangement of past events. Its tallest trees record old opportunities. Its missing seedlings may record deer today. Its even-aged canopy may record fire, storm or clear-felling. Its deadwood records what managers allowed to remain. Learn to read those clues and the green wall opens into time.

Trees Manufacture Time

A tree makes new body at its edges while carrying old body inside. Buds extend shoots. Root tips explore soil. Cambium adds a sheath of wood around the stem. In strongly seasonal climates, differences between early and late growth create annual rings. The newest ring does not replace the old trunk. It wraps it, turning one year's hydraulic tissue into another layer of structure and record.

This growth pattern changes what ageing means. The organism may be ancient while its leaves are months old, its absorbing roots younger still and its active xylem only a few rings deep. Cells in long-lived meristems keep founding new modules. Trees do show age-related changes in growth, reproduction and vulnerability, but there is no simple plant equivalent of every organ wearing out together. Death usually arrives through size, damage, drought, competition, pathogens, fire or interacting stresses rather than through a scheduled expiry.

Injury is managed by compartmentalisation. A branch tear or fungal infection is not restored to pristine tissue. The tree alters chemistry around the damaged area, restricts spread where it can and grows new wood over the boundary. The wound remains inside. Hollow trunks can therefore support healthy crowns because the outer cylinder bears much of the mechanical load and conducts the active flows. A veteran tree may be structurally reduced, biologically vigorous and full of habitat created by failures it survived.

Time also solves reproduction. A tree can wait through bad years and produce a heavy seed crop when stored resources, weather and pollination align. In mast years, populations of some species fruit heavily and roughly together, swamping seed predators and changing food availability across a forest. Seeds then outsource movement to wind, water, gravity and animals. A fruit is transport payment. A wing is an aerodynamic bid. A nut cached and forgotten by a jay or squirrel has been planted by an animal that intended to eat it.

Long life does not mean slow carbon gain in absolute terms. Large trees often add a smaller percentage to their mass than young trees, yet the starting mass is so great that the annual addition can be large. A 2014 analysis across hundreds of species found that individual-tree carbon accumulation generally increased with size in the observed range. That does not mean every old stand accelerates forever. Mortality, competition, soil and disturbance operate at stand scale. It does mean that the phrase old trees have stopped growing is often wrong in the unit that matters.

The search for the oldest tree exposes another difficulty: what counts as one life. A single stem can be dated by rings. A tree that resprouts from an old root system may have young wood attached to a much older organism. A clonal grove can contain many trunks sharing one genotype, each replacing the last. Stem age, root-system age and genetic age answer different questions. Longevity becomes less a trophy number than a choice of biological boundary.

The rings become evidence. Cross-dating matches narrow and wide patterns among trees, allowing missing or false rings to be detected and timber chronologies to extend beyond any one life. Ring width, density and chemistry can record aspects of temperature, moisture, fire, flooding and atmospheric change, though the signal varies by species and place. Many tropical trees form rings too, but annuality is less reliable where seasons are weak or irregular.

The force of an old tree comes from duration, and duration is not serenity. It is accumulated exposure. Every old tree is a structure that has met more bad years than a young one and continued by containing the damage rather than erasing it.

Forests Move Carbon, Water and Heat

The lungs metaphor begins with a true reaction. Photosynthesis uses light energy to build organic matter from carbon dioxide and water, releasing oxygen. A leaf does this, a crown does more, and a forest's gross production is immense. The error arrives when production is treated as a permanent gift to the atmosphere. Trees, roots, fungi, microbes and animals respire. Dead wood and litter decompose. Fire oxidises stored carbon. Across the fast biological cycle, those processes consume most of the oxygen produced. A durable net addition occurs only when reduced material escapes reoxidation over long periods, often through burial. Your next breath is not dependent on this year's forest growth.

Carbon accounting needs three separate questions. How much carbon is stored now? How much is being added or lost during a period? How secure is the store? Old forests can hold huge stocks in wood and soil even when annual uptake is modest. Young recovering forests may add carbon rapidly while holding little. A drought, fire, harvest or wave of mortality can reverse a sink. Wood products may retain some carbon after harvest, while soil disturbance, processing and substitution effects complicate the balance. One label cannot answer stock, flow and permanence.

Forests sit inside a larger land sink rather than owning it. The Global Carbon Budget 2025 estimated that terrestrial ecosystems took up 2.4 plus or minus 0.8 gigatonnes of carbon per year on average during 2015 to 2024, equal to 21 per cent of total carbon dioxide emissions in that accounting. That sink varies sharply with climate and includes vegetation and soils beyond forests. Warming and climate variability weaken it relative to the gain driven by rising carbon dioxide and other factors. Elevated carbon dioxide can increase photosynthesis and water-use efficiency, but it cannot supply missing water, nutrients or survivable temperatures.

The physical effect depends on structure, not on the word forest. A tall, rough canopy mixes air differently from short vegetation. Deep roots can sustain transpiration into a dry season, while shallow-rooted cover may shut down. Leaf area, colour, seasonality and canopy height affect how radiation

and rainfall are partitioned. Replacing one green cover with another can preserve a satellite colour while changing the route of heat and water through the landscape.

Water reveals the wider machinery. Roots absorb it, xylem lifts it and stomata release most of it as vapour. This transpiration cools leaves and transfers water and latent heat into the atmosphere. Forest canopies also intercept rain, alter infiltration and runoff, roughen the land surface and influence turbulent mixing. Over large tropical regions, recycled moisture contributes to rainfall downwind. Remove enough forest and the effect can extend beyond the cleared ground.

The direction of the climate effect changes with place. Tropical forests usually cool through carbon storage, evaporation and cloud-related processes. At high latitudes, dark evergreen canopies absorb sunlight that snow-covered open ground would reflect, so albedo can oppose the carbon benefit. Locally, shade and evapotranspiration often reduce heat extremes, but water-limited planting can lower streamflow or fail under drought. A tree beside a pavement and a boreal forest across a continent belong to the same subject and not to the same calculation.

Forests cover 4.14 billion hectares, according to the 2025 global assessment. Their influence comes from coupling cycles that accounting systems prefer to separate: carbon, water, energy, nutrients and life. Calling them lungs chooses the one cycle for which the metaphor is weakest. Forests are living parts of the climate system, not interchangeable equipment.

The Strategy That Cannot Leave

An animal can seek shade. A tree can close its stomata. If the heat persists, it can shed leaves, sacrifice branches, deepen or redirect roots and draw on stored carbon. What it cannot do is move its trunk. The strategy that wins by holding a place becomes exposed when the place changes faster than a generation can replace it.

Tree species' ranges move over centuries. Seeds establish beyond the

current range while trees die at the other edge. Pollen carries genes. Populations adapt through variation and selection. The map can shift without any individual travelling. The rate, however, depends on seed dispersal, suitable soils, mutualists, competitors, herbivores, fire, fragmented habitat and the years required to reproduce. Climatic conditions can shift across a landscape faster than forests can follow, leaving mature crowns where seedlings of the same species can no longer establish reliably.

This creates a deceptive interval. A forest may remain green because adult trees are buffered by deep roots and stored resources. Beneath them, regeneration fails. Ecologists call versions of this an extinction debt or regeneration debt: the future loss is built into the age structure before the canopy announces it. The reverse can also occur. Seedlings establish beyond an old range, but a recognisable forest takes decades to assemble. Forest change is delayed in both directions.

Drought makes the hydraulic bargain visible. Warmer air can draw water from leaves more strongly. Soil moisture falls. Stomata close, growth slows and embolism risk rises. Fire weather can intensify at the same time. Insects and pathogens exploit stressed hosts; dead trees alter fuels; severe fire changes soils and seed sources; repeated fire can prevent return. None of these mechanisms acts globally in the same way. Some cold-limited forests gain longer growing seasons. Some dry forests become more open. Species and regions respond at different thresholds. The danger lies in interacting pressures and in assuming that yesterday's forest type is guaranteed to rebuild after disturbance.

Variation within a species matters beside movement between species. Populations carry different tolerances shaped by local climate and history. Moving seed from one provenance to another may improve future fit, erase local adaptation or do both across different years. Gene flow can spread useful variants, but selection needs generations and surviving reproduction. A forest cannot adapt through genes if the adults die before producing a next cohort or if fragments prevent pollen and seed from arriving.

Management can buy options, not immunity. Protecting old carbon and structural complexity avoids losses that seedlings cannot repay soon. Reducing fragmentation can assist movement. Restoring varied ages and species may spread risk. Prescribed or cultural burning can restore a missing process in fire-adapted systems, while fire exclusion remains necessary in forests that rarely burned. Assisted migration may rescue populations or create new ecological problems. There is no climate-proof species list independent of place and time.

This completes the opening wager. Trees commit carbon to height and persistence because light returns to a successful crown. Forests magnify the reward: stable microclimates, deep stocks, repeated water movement, habitat built over centuries. The same commitment produces the limit. The structure is fixed, the replacement rate is slow and much of its value comes from history that cannot be replanted on schedule.

A forest can survive enormous change. It cannot survive every change and remain the same forest. The honest goal is not to freeze its current photograph. It is to preserve enough continuity, diversity and room for the next forest to form.

How It Actually Works

Before the canopy

For most of Earth's history, no plant cast a canopy shadow on land. Early terrestrial plants stayed low because moving water, supporting weight and reproducing away from open water were unsolved problems. Vascular tissue improved transport. Lignified cells resisted collapse. Roots became more than anchors. Branching multiplied the surface exposed to light. Once plants could keep adding height and girth, the land acquired a third dimension.

The earliest forest yet identified lies in rocks on the Devon and Somerset coast. About 390 million years ago, dense stands of Calamophyton grew there, trees only two to four metres high with hollow, constructed trunks and

twig-covered crowns rather than modern leaves. Fallen material accumulated around their bases and their roots helped trap sediment, changing how water moved across the ground. The first forests were already landscape engineers before they looked anything like a modern wood.

A few million years later, *Archaeopteris* combined a large woody trunk, broad branching crown and extensive roots in a more familiar package, though it reproduced by spores rather than seeds. Devonian forests deepened soils, accelerated weathering and redirected carbon and nutrients. By the Carboniferous, swamp forests included giant clubmoss relatives, horsetail relatives, ferns and seed plants. Their buried organic matter contributed to coal formation, though the old claim that coal accumulated because fungi had not yet evolved to decompose lignin is too neat. Waterlogging, burial, plant chemistry and basin history all mattered.

Conifers and other gymnosperms later dominated many forests. Flowering plants diversified during the Cretaceous and eventually supplied most living tree species, while conifers retained the advantage in many cold, dry or nutrient-poor settings. Forest history is not one lineage improving towards the oak. It is repeated competition among designs under changing climates.

The first season

Every forest begins again at ground level. A seed contains an embryo, stored food or access to food, and often a delay mechanism tuned loosely to opportunity. Water enters, metabolism resumes and the first root usually emerges before the shoot. That priority is sensible. A seedling that exposes leaves before securing water has begun carbon gain without the supply needed to sustain it.

The odds are severe. Seeds land in deep shade, dry litter, floodwater or an animal's stomach. Fungi attack them. Rodents and insects eat them. A germinating seed can exhaust its reserves before reaching light. Large seeds buy time and powerful early growth but are expensive for the parent and hard to disperse. Small seeds travel farther and gamble on a favourable

microsite. Pioneers often produce many light seeds able to cross open ground. Shade-tolerant trees tend to invest more in survival beneath a canopy, though no single trade-off covers every species.

Once leaves unfold, the seedling must become carbon-positive. The first carbon income goes into more leaf, more root and enough support to connect them. Allocation shifts with scarcity. Shade can favour leaf area and height extension. Dry soil can favour roots and conservative water use. Browsing may remove the entire year's gain. A sapling bent under a fallen branch can redirect a shoot upwards. The architecture appears planned because selection has retained developmental rules that respond to local signals.

Most seedlings never join the canopy. Dead seedlings become food and organic matter, while their abundance leaves strong selection among sites and traits. The few survivors carry a biased history. What looks like the normal form of a mature tree is the form that passed a long series of filters.

Building a trunk and crown

A young shoot lengthens from buds at its tips. Auxin produced near a leading shoot can suppress buds below, a pattern called apical dominance, while light direction, damage and species-specific branching rules modify the result. Some trees build a strong central leader. Others divide early into spreading axes. Leaves arrange themselves to capture light without paying too much for supporting tissue or shading one another.

The cambium turns extension into permanence. Each growing season it adds xylem inward and phloem outward. New xylem cells enlarge, reinforce their walls and die into service. New phloem remains living but is gradually crushed, shed or incorporated into bark as the circumference expands. Rays running across the stem move and store material laterally. Bark combines inner transport tissues with outer protection against water loss, heat, impacts, insects and infection. Thick bark can insulate living tissue from surface fire. Thin bark is cheaper where that risk is low.

A crown contains leaves working under unequal conditions. Sun leaves are

often smaller and thicker, built for high light and water demand. Shade leaves spread thinner surfaces under a filtered spectrum. Within each leaf, chloroplasts capture light while stomata regulate the carbon dioxide admitted and the water released. Branches that lose the light contest may be starved, shed or sealed off. Trees can alter crown shape around neighbours without any overview of the whole. Local growth responses create the impression of intention.

Mechanical loading helps shape the wood. Wind flexes stems and stimulates changes in growth. Angiosperms can make tension wood, rich in specialised fibres, on one side of a leaning stem or branch; conifers commonly make compression wood on the other side of the problem. Buttresses widen the base of many tropical trees, though their functions and development vary. The trunk is not a standard pole scaled up. It is a record of forces encountered while growing.

Water places a major limit on the construction. As the tree rises, the gravitational and frictional costs increase, leaves regulate their stomata more cautiously, and hydraulic damage becomes harder to avoid. The tree can widen sapwood area, alter conduit size, reduce leaf area or build a flatter crown. Each adjustment has a carbon cost. Height is the outcome of this negotiation, not a simple race to the sun.

Joining the forest

Once crowns overlap, the light environment changes abruptly. The canopy captures most direct radiation, slows wind beneath it and keeps humidity higher. Shade-tolerant leaves use brief sunflecks and diffuse light. Climbers avoid paying for a trunk by borrowing one. Epiphytes place themselves in the crown without rooting in the ground, collecting water and nutrients from rain, dust and trapped litter. In wet forests, whole gardens can occupy branches. In cold forests, the crown is simpler but still divides the atmosphere into levels.

The world's main forest zones express different constraints. Tropical rainforests grow through warm, wet years and support immense tree

diversity, often with many species represented by few individuals. Tropical dry forests shed leaves or reduce activity through a pronounced dry season. Temperate deciduous forests avoid freezing and winter water stress by abandoning leaves, while temperate evergreen forests retain them where conditions favour longer leaf life. Boreal forests run on short summers, cold soils, fire and insects, with conifers often dominant. Montane forests compress climate zones up slopes. Mangroves solve salt, unstable mud and tidal oxygen shortage at the boundary of land and sea.

These labels hide variation, but they prevent one forest from standing for all. A fire that maintains an open pine woodland can erase a rainforest seed source. A gap that fills in months in the tropics may remain open for years near a cold treeline. The same tree strategy runs under different budgets.

Competition continues below ground. Roots proliferate unevenly, overlap and compete; some respond to neighbouring roots, but patterns differ among species and experiments. Fungal partners alter access to nutrients. Large trees influence water and shade while seedlings alter the future composition. Herbivores, seed predators and pathogens can prevent abundant species from turning every successful adult into a local monopoly. Forest diversity emerges from many mechanisms, no one of which amounts to peace.

Sex, seeds and distance

A long-lived organism must reproduce across changing neighbourhoods. Some trees carry male and female flowers or cones on the same individual. Others separate sexes among trees. Wind pollination works through volume and timing, releasing clouds of pollen when leaves or weather do not block the path. Animal-pollinated trees invest in scent, colour, nectar and targeted delivery. In specialised partnerships, losing key pollinators can sharply reduce reproduction.

Fertilisation begins another dispersal problem. Wind-borne seeds use wings, hairs and small mass. Fleshy fruits recruit animals, which carry seeds away and deposit them with fertiliser. Nuts recruit hoarders. Floating fruits

cross rivers or seas. Explosive pods throw offspring beyond the parental shadow. Gravity remains common and underrated, particularly when slopes and floodwater take over.

Distance changes risk. Staying near a parent means landing in a site where the species has already succeeded, but it also means shade, competition, specialist enemies and crowded relatives. Travelling farther increases the chance of unsuitable ground while escaping local hazards. Seed size and dispersal structures alter that trade.

Some trees bypass sex through suckers, sprouts and fragments. After fire or cutting, dormant buds on roots, stems or lignotubers can rebuild a crown using an established below-ground system. Coppicing exploits this capacity by repeatedly cutting stems and harvesting regrowth. A grove may contain many trunks belonging to one genetic individual. Counting stems can therefore overstate individuals, while counting genotypes can understate the ecological reality of thousands of separate crowns.

Reproduction is the only route by which a fixed organism moves through climate and geography. The seed is a small, disposable version of mobility. Everything after establishment is commitment.

Death opens the roof

Trees die standing, fall alive, snap, uproot, burn, rot from within or decline across decades. The cause listed last is often only the final pressure. Drought weakens hydraulic function, bark beetles breach defences, fungi spread through stressed tissue and wind finishes the stem. Forest mortality is frequently a chain rather than a culprit.

The gap begins before the trunk reaches the ground. Light and rain penetrate. Roots of the dead tree stop taking water. Neighbours expand crowns and roots. Seedlings that were waiting accelerate, while pioneers arrive if the opening is large enough. The fallen crown crushes some plants and creates protected microsites for others. A root plate lifts soil and exposes mineral ground. The log stores moisture, then collapses into a ridge. One death rearranges resources for decades.

Fire rearranges forest structure at scales from a scorched bark patch to a landscape. Its effect depends on fuel, weather, season, interval and severity. Some pines protect seeds in cones that open after heating. Thick bark lets mature trees survive surface fires that kill young competitors. Eucalypts can resprout from protected buds. Other forests contain thin-barked species, moist fuels and seeds poorly equipped for repeated burning. Introducing frequent fire there is degradation, not restoration.

Wind, flood, avalanche, insects and disease each leave a signature. A hurricane can create a mosaic of snapped crowns rather than a blank clearing. An insect outbreak can remove one host species and leave the rest. A pathogen introduced beyond its evolved range can transform a continent's forest, as chestnut blight did in eastern North America and Dutch elm disease did across Europe and North America. The forest may remain green while losing a defining tree and many relationships attached to its size or chemistry.

Recovery is not guaranteed. If seed trees are too distant, soils too damaged, grazing too heavy or fires too frequent, a forest can cross into another state. The process called succession requires propagules and tolerable conditions. Time alone is not a treatment.

The human forest

Humans entered the story among trees and have been cutting them ever since. Wood burns before it melts, can be split along the grain, shaped across it and joined without industrial temperatures. It supplied handles, digging sticks, bows, boats, shelters and fuel long before most archaeological wood survived. Stone tools dominate museums partly because stone waits better.

Agriculture changed the scale. Forest was cleared for light, fields and pasture. Wood became charcoal for metal, beams for buildings, wheels for transport, barrels for storage, ships for trade and war, and props for mines. Cities depended on distant wooded catchments even when their monuments celebrated stone. In many historical shortages, the last tree had

not vanished. Usable wood of the right species and dimensions had become scarce or expensive at the place and time required.

Management arose early because many trees regrow predictably after particular cuts. In parts of Europe, coppice woods produced repeated crops of poles, pollarding raised the cut above grazing mouths, standards matured above coppice for larger timber, and wood pasture combined grazing with open-grown trees. Elsewhere, communities enriched useful trees, managed fire, protected groves and combined cultivation with woodland according to local knowledge and tenure. Human influence is ancient and varied. It does not make every intervention benign or every forest equivalent.

Forestry also became a way for states to make wooded land legible. Surveyors divided irregular use into compartments, inventories converted mixed stands into merchantable volume, and rotations placed harvest on an administrative calendar. In many regions, this improved sustained timber supply. It could also erase local rights, seasonal grazing, gathering and cultural burning by treating them as disorder inside a timber estate. Scientific measurement did not choose the objective. It made the chosen objective easier to enforce.

Industrial forestry simplified the problem into yield. Stands could be planted at known spacing, thinned and harvested on rotations. Species were moved around the world for straight growth, pulp or resistance to local conditions. The method supplies large volumes of wood from limited land and can reduce pressure elsewhere, but it also creates concentrated risks: one age, one genotype or species, exposed together to storm, drought, fire and pests. A plantation is an agricultural system made of trees. That does not make it worthless. It makes the word forest insufficient.

Clearance continues. The 2025 global forest assessment estimated deforestation at nearly 11 million hectares per year during 2015 to 2025. Expansion and natural regeneration elsewhere lowered the net loss of forest area to 4.12 million hectares per year. Net change can improve while ecologically irreplaceable forest disappears, because a hectare gained is not necessarily equivalent to a hectare lost. Definitions based on canopy

cover and height can count young plantations while missing degradation under a canopy that remains visible from above.

Restoration begins by asking why trees are absent. Remove grazing, repeated fire or drainage and forest may return from nearby seed sources. Where soil, seed supply or animal dispersers are gone, planting or direct seeding may be necessary. Where forest recovery is the goal, mixtures of locally suitable native species often rebuild more structural and biological variety than one commercial species, but site history, objectives and the previous land use matter. Survival depends on years of care and future climate. The cheapest seedling is the one nature establishes; the most expensive is the one planted for a target and dead before the next audit.

Measuring a moving structure

Foresters began with diameter tapes, height estimates and sample plots. Those remain indispensable because a satellite cannot identify every stem, root or hollow. Repeated censuses reveal growth, recruitment and mortality. Allometric equations convert trunk diameter, height and wood density into biomass estimates, carrying uncertainty each time a local relationship is applied elsewhere.

Tree rings provide dated growth. Dendrometers record tiny changes in stem radius. Sap-flow sensors estimate water movement. Pressure chambers and vulnerability curves test hydraulic stress. Isotopes trace carbon and water. Flux towers measure exchanges of carbon dioxide, water and energy above a canopy. Aircraft and satellites map cover, disturbance and greenness. LiDAR times laser returns to reconstruct canopy height and structure in three dimensions. None sees the whole forest. Agreement among methods matters more than the seduction of one global map.

Even the boundary of forest is a decision. Global assessments need thresholds for canopy cover, potential height, area and land use so countries can report consistently. Those rules are indispensable and blunt. They can classify temporarily unstocked forestry land as forest, separate tree-covered agricultural land from forest, and count plantations alongside

naturally regenerated stands while recording them in different subcategories. A global area total answers a real question, but it cannot answer every ecological one hidden inside the same hectares.

The hardest measurements remain underground and slow. Root turnover, deep soil carbon, fungal networks, rare species and delayed mortality resist easy observation. Forests can change in physiology before cover changes, and national statistics can disagree with atmospheric budgets because they define managed land and fluxes differently. Precision begins with the boundary of the claim.

How we know

Living trees can be instrumented, labelled, scanned and revisited, but no experiment can run for the full life of a redwood. Forest science combines short physiological measurements with long plots, tree rings, natural disturbances, historical records and models. Each observes a different timescale.

Fossil forests preserve trunks, roots, spores and sedimentary effects, rarely the full community. The current earliest known forest changed in 2024 when 390-million-year-old Calamophyton stands were described from Somerset and Devon, displacing the better-known Cairo, New York, site by several million years. The record will change again if older evidence appears.

Global forest area comes largely from national reporting assembled by the Food and Agriculture Organization, while satellites provide independent spatial evidence. Carbon fluxes are estimated through inventories, atmospheric inversions, process models and eddy-covariance measurements, whose system boundaries do not always match. Below-ground transfers remain especially difficult to isolate, which is why claims about fungal networks demand more restraint than their cultural popularity suggests.

The main mechanisms are supported across methods. Their magnitudes, thresholds and future combinations remain unevenly measured.

What People Get Wrong

"Forests are the lungs of the Earth"

The phrase survives because leaves release oxygen and lungs exchange gases. The analogy then encourages a false emergency: lose a rainforest and the planet may run out of breathable air. Photosynthesis does release enormous quantities of oxygen, but trees, animals and microbes respire, dead tissue decomposes, and fire burns stored carbon. As biomass is made and broken down, those processes consume most of the oxygen produced.

Atmospheric oxygen accumulated over geological time when reduced material escaped oxidation, especially through the burial of organic carbon. The present reservoir is vast. Forest loss is dangerous because it releases carbon, removes future uptake, alters water and heat, destroys habitat and damages people who depend on forests, not because tomorrow's oxygen tank is running empty.

Gross oxygen production remains immense. The correction concerns net balance and the existing atmospheric reservoir. The metaphor also hides the stronger story. Lungs do not store centuries of carbon, lift soil water into clouds, roughen the atmosphere, cast continental shade or build living space from ground to canopy. Forests deserve protection without being given the wrong job.

"A tree's roots mirror its crown"

The neat mirror appears in school diagrams because it makes a balanced object and fits the page. It also reassures builders that roots occupy a predictable cone. Real systems follow water, oxygen, nutrients, cracks, drains, soil depth and neighbours. In many trees, much of the fine absorbing system is concentrated relatively near the surface and spreads laterally. Structural roots taper and branch. Some species form deep roots, especially where water and geology allow it, but depth varies too much for a universal silhouette.

The correction matters above and below ground. Soil compaction, trenching

and paving well beyond the trunk can damage major roots. Adding soil can suffocate them. A large root cut on one side may alter anchorage rather than merely remove a distant feeder. Conversely, the presence of a tree does not prove that one giant taproot descends beneath it.

Root grafts, old channels and fungal partners can extend the functional system further, while foundations, pipes and compacted verges redirect it. The relevant map is made by soil conditions and time, not by crown geometry.

Think of roots as a responsive network occupying opportunity, not an underground sculpture designed to balance the crown.

"Trees talk through a wood wide web"

Fungi form mycorrhizas with tree roots, and one fungal mycelium may colonise roots of different plants. Experiments have detected movement of isotopically labelled carbon and other compounds within below-ground systems. Those findings do not establish a forest internet in which elder trees identify relatives, direct aid and coordinate a cooperative community.

The stronger story became persuasive because it gives forests human virtues and turns invisible biology into a familiar network diagram. It also benefited from citation chains in which cautious findings grew more certain as they were repeated. Critical reviews in 2023 found evidence for important net carbon transfer benefiting recipient seedlings to be limited and alternative routes hard to exclude. A 2025 reply argued that this sceptical reading underweighted evidence for physical links and transfer. The live dispute concerns route, magnitude, cost, benefit, mechanism and generality.

Experimental separation is difficult because roots, fungi, microbes, dissolved compounds and shared air all offer possible routes. Detecting a labelled atom in another plant is easier than proving who moved it, through which path, at what net cost and with what consequence.

Use precise verbs. Fungi connect. Materials can move. Trees and fungi

exchange resources. Communication, intention and care require evidence of a different kind. Removing the social fable does not make the underground world less interesting. It returns the surprise to the organisms themselves.

"Old forests stop taking up carbon"

The myth begins with a valid growth curve. Young even-aged stands often gain biomass rapidly, then slow as competition and mortality increase. From this came the idea that a mature forest is carbon-neutral and climatically expendable, while a harvested and replanted stand keeps working harder.

Scale breaks the argument. Measurements from many unmanaged old forests show net uptake, while other stands are near balance or become sources. Large individual trees can add more carbon in a year than small trees because a modest percentage applied to an enormous trunk and crown is still a large amount. More important, an old forest already holds a stock that took centuries to assemble. Harvest releases part of it quickly and can disturb soils; regrowth repays that carbon debt over time, if the stand survives and if the wood is not rapidly oxidised.

The counterfactual matters. A managed forest supplying long-lived wood differs from one cleared for short-lived products or from an old stand left intact. Product claims cannot be settled by growth alone.

This does not make every old stand an ever-accelerating sink or every harvest harmful. It means uptake rate cannot replace stored carbon in the decision. Protecting a full reservoir and filling an empty one are different climate services.

"Fire is always bad for forests"

A blackened landscape looks like pure destruction, and near homes it may be a catastrophe. Ecologically, fire has no single meaning. Some forests evolved with frequent surface burns that recycle nutrients, maintain open structure and spare thick-barked adults. Some trees resprout after burning or release seeds in response to heat. Excluding fire for long periods can increase fuels and shift species, making later fires harder to control.

Other forests burned rarely. Repeated fire can kill seed sources, dry edges and prevent recovery, especially where human ignition and climate change create a regime with no historical equivalent. Even within one region, severity and patchiness decide whether surviving trees remain, soils are protected and animals can recolonise.

Cultural burning adds a further correction. In some landscapes, Indigenous peoples maintained particular fire patterns for generations, so removing people and suppressing their burning changed the forest rather than returning it to an untouched baseline.

The correction is not that fire is good. It is that the unit of judgement is the fire regime: frequency, season, intensity, severity, extent and the interval since the previous burn. Suppression, prescribed burning and non-intervention can each be right in different forests. Slogans make poor fire plans.

"Planting trees is always good for the climate"

A seedling offers a visible action, an easy count and a future carbon claim. The missing questions concern place, survival, time and substitution. Planting on land that would naturally support forest can restore cover, especially where seed sources are absent. Planting on native grassland, savanna or peat can damage biodiversity, disturb stored carbon and alter water. Dark trees over snowy ground can reduce reflectivity. Fast-growing plantations in dry catchments can lower streamflow.

Poor planting also consumes money, land and attention that could protect

existing ecosystems, remove grazing pressure or cut emissions. A visible intervention can displace a quieter one that would have done more.

Then comes permanence. A planted tree stores little carbon at first. It must survive heat, browsing, fire, disease and changing climate for decades before fulfilling a large promise. Credits calculated from expected growth can be sold before that growth exists. A plantation harvested for short-lived products may cycle carbon rapidly. None of this cancels sound reforestation. It makes design and monitoring part of the claim.

The order matters: avoid fossil emissions, protect existing forests and other carbon-rich ecosystems, remove the pressure that caused loss, allow natural regeneration where it works, and plant where intervention is needed. Planting a tree in the wrong ecosystem is not automatically a climate benefit.

"A plantation replaces a forest"

Area statistics can place a naturally regenerated forest and a single-species plantation in the same column if both meet thresholds for height and canopy cover. From above, green is green. At ground level, age structure, deadwood, hollows, soils, understorey and species interactions may differ.

Plantations perform real jobs. They supply timber, pulp and fuel efficiently. Mixed or native plantings can support substantial biodiversity, and a plantation on degraded farmland may offer more habitat than the land use it replaces. The error is using those gains to cancel the loss of an old natural forest. Continuity cannot be transferred between hectares. A cavity that takes decades or centuries to form is not present in a five-year-old stand because both contain trunks.

Rotation length changes the result too. A stand cut before cavities, large deadwood and varied cohorts develop is repeatedly reset before many forest features appear. Longer rotations and retained legacies can narrow some gaps without abolishing the distinction.

Judge the replacement against the function being claimed. For wood yield, a

plantation may outperform. For rapid erosion control, it may help. For old-forest species, large carbon stocks and historical structure, it cannot provide an immediate substitute. Equal area is an accounting result, not ecological equivalence.

Use It

Separate stock, flow and permanence

Whenever someone claims that a forest stores carbon, ask which quantity is being described. The carbon already held in trunks, roots, deadwood and soil is a stock. The change during a year is a flow. The chance that the stock remains out of the atmosphere is permanence. These can point in different directions.

An old forest may add carbon slowly while protecting an enormous inherited stock. A young stand may add it quickly from a low base. A plantation may grow fast and then be harvested into paper that decays soon. A burned forest may emit carbon now and recover some later. A project can report an impressive annual flow while ignoring the stock destroyed to create it, or sell a century of expected permanence from trees exposed to fire in year ten.

Use the same discipline beyond carbon. Forest area is a stock; annual loss and gain are flows; legal and ecological protection affect permanence. Number of seedlings is an input; surviving canopy is an outcome. The three-column test prevents a lively rate from hiding an empty reservoir and a large reservoir from being treated as immortal.

Follow the water before counting the trees

A tree-planting proposal usually arrives with species, hectares and carbon. Ask for the water budget. Where will roots obtain water through the driest season? What happens to groundwater, streamflow and downstream users? Will trees cool a wet landscape through evapotranspiration, or intensify scarcity in a dry one? Does the site naturally support closed forest, open woodland, grassland or peatland?

The question also improves diagnosis of a living tree. Browning leaves can reflect root damage, compacted soil, blocked drainage, drought, heat or hydraulic failure rather than a problem in the leaf itself. A paved surface may send rain away from roots while increasing heat around the crown. Irrigation at the trunk may miss most absorbing roots. Water connects crown symptoms to soil causes.

At larger scale, following water reveals why forest loss is more than a carbon event. Canopy removal changes interception, shade, evaporation, infiltration, runoff and atmospheric moisture. The consequences depend on rainfall and latitude, but the mechanism begins with the route of a water molecule from soil to leaf to air. Count trees after tracing that route, not before.

Read a forest vertically and historically

Do not stop at the green ceiling. Look for layers, openings and ages. Is there an understorey, or has browsing removed everything within reach? Are young trees present? Do they belong to the canopy species or to a different future forest? Are large trunks accompanied by saplings, or are they a final generation standing above grass? A healthy-looking crown can conceal failed recruitment beneath it.

Then look for history. Multi-stemmed stools suggest coppicing. Pollards carry repeated cuts above browsing height. A uniform cohort may follow fire, storm, planting or clear-felling. Pits and mounds can mark uprooted trees long after the wood has rotted. Charcoal, old banks, drainage ditches and straight boundaries expose earlier land use. Large spreading crowns inside dense woodland may have grown when the site was open.

Dead material belongs in the reading. Standing snags, broken limbs, hollows and fallen trunks indicate habitat and continuity, not failed housekeeping. Their absence can reveal intensive removal even where living trees are abundant. The forest in front of you is a temporary cross-section through a longer sequence. Ask what event produced this structure and what structure is now being produced.

Judge disturbance by the regime

A photograph taken after fire, logging, windthrow or insect attack invites a verdict from appearance. Replace the verdict with six questions: what happened, how often, how severely, in which season, across what area and after what previous disturbance? The same label can describe renewal or collapse.

A low surface fire passing through a fire-adapted woodland may preserve adult trees and create seedbeds. Repeated high-severity burns before new trees reproduce can remove the forest. Selective harvest that retains old trees, deadwood and varied structure differs from clearing a whole catchment. An insect outbreak in one host species differs from broad mortality during drought. Scale and interval control recovery.

This lens also catches management mistakes. Suppressing every fire can remove a necessary process and accumulate fuel. Prescribing fire in a historically moist forest can introduce a new pressure. Salvage logging after disturbance may recover timber while removing biological legacies needed for recovery. No action is neutral either. The correct comparison is among future regimes, including the one created by leaving current pressures alone.

Count the next generation

Planting day is photogenic. Recruitment is the biological result. For any restoration programme, ask how many seedlings are alive after the first dry season, after five years and after the first fire or grazing event. Ask whether roots established, whether seed sources remain, whether species match future rather than past climate, and whether young trees can reproduce. For illustration, a million planted stems with one per cent survival is a different project from ten thousand that form a self-renewing population.

Natural regeneration deserves the same scrutiny. It can be cheaper, locally adapted and diverse where nearby forest, dispersers and tolerable soils remain. It can also fail under repeated browsing, weeds, fire, isolation or changed hydrology. Leaving land alone is a method only when the main

limits on recovery have been identified and reduced.

The strongest measure is not trees planted or even trees standing. It is a trajectory: canopy, understorey, soil, deadwood, species and regeneration moving towards a system able to persist without indefinite rescue. That standard is slower and less marketable. It is also the one biological recovery requires.

The limits

Trees are powerful and fashionable, a combination that attracts impossible assignments. Forests cannot cancel continued fossil emissions at the required scale. They cannot restore extinct species, recover ancient soil immediately or guarantee stored carbon against every future drought and fire. Urban trees can reduce heat and improve streets without solving regional climate. A plantation can supply renewable material without becoming old growth. One intervention cannot maximise timber, biodiversity, carbon, water and fire safety everywhere at once.

The hydraulic model also has limits. Carbon and water explain much, but nutrients, genetics, herbivores, microbes, institutions and human rights can decide outcomes. A technically sound restoration that excludes people with customary claims is not sound in the world where it must persist. Global figures hide regional gains and losses. Satellite greenness can hide degradation. A single forest plot can be measured beautifully and generalised badly.

Trees reward patience, but patience is not an excuse for delay. Some losses are effectively irreversible on human timescales. The honest position lies between botanical salvation and fatalism: protect what cannot be rebuilt soon, restore what can recover, and measure what happens after the ceremony.

The one thing to keep

Keep the wager.

Every tree has taken carbon from air and spent it on a fixed structure in the

expectation that light, water and tolerable weather will return. The trunk records the investment. The crown gathers the return. The roots search. The forest is what happens when those long bets overlap, fail, regenerate and alter the conditions under which the next bets are made.

This changes what you see. A giant tree is not a finished monument but an operating water column near physical limits. A hollow is not emptiness but contained injury and habitat. A fallen trunk is not waste but structure moving into another phase. A green plantation is not equivalent to an old forest because equal colour does not contain equal time. A bare restoration site is not measured by how many hands held seedlings on the first morning, but by whether a self-renewing forest occupies it decades later.

And the lungs phrase falls away. Forests need no borrowed organ to matter. They hold history in wood and soil, move water into air, soften heat, shelter much of terrestrial life and give human societies a material they have never outgrown. Their power comes from staying. Their danger comes from having to stay.

The next time you enter a forest, look down before looking up. The future is smaller than the canopy, and it is waiting in the shade.

Terms

Tree. A perennial, self-supporting plant that builds a persistent elevated stem and crown. The category is functional rather than one evolutionary lineage, so palms, conifers, flowering trees and tree ferns reached it differently.

Meristem. A region of dividing cells that produces new plant tissue. Shoot tips, root tips and lateral meristems let a tree renew young parts while carrying an old structure.

Vascular cambium. The thin cylinder of dividing tissue that adds secondary xylem inward and secondary phloem outward. Its continued work allows woody stems and roots to increase in girth.

Secondary growth. Increase in stem or root thickness after primary extension. In most woody trees it is driven by cambium and creates the expanding cylinder of wood and bark.

Xylem. Tissue that transports water and dissolved minerals from roots towards leaves. Mature conducting cells are usually dead, reinforced tubes whose arrangement also provides much of a tree's mechanical support.

Phloem. Living transport tissue that distributes sugars and other compounds from sources, usually mature leaves, towards growing, storing, reproducing or repairing tissues. Flow can run in different directions in different tubes.

Sapwood. Relatively young outer xylem that still conducts water and may store reserves. Its depth differs among species and with tree age, health and crown demand.

Heartwood. Older inner xylem withdrawn from water transport and often filled with resins, gums or other compounds. It contributes support and sometimes decay resistance, though its cells are no longer alive.

Bark. All tissues outside the vascular cambium, including living inner phloem and protective outer layers. Bark limits water loss, cushions damage and can insulate living tissue from heat and fire.

Stoma. A microscopic adjustable pore, plural stomata, in a leaf or green stem. Opening admits carbon dioxide for photosynthesis while allowing water vapour to escape, tying carbon gain to hydraulic risk.

Transpiration. Loss of water vapour from plants, chiefly through stomata. It cools leaves and helps pull water through xylem from soil to crown, while linking forests to atmospheric moisture and heat.

Cavitation. Formation of a vapour cavity within water under tension in xylem. It can create an embolism and reduce the conducting capacity of a stem, root or leaf.

Embolism. An air or vapour blockage in a water-conducting conduit. Trees

can isolate embolism, and some refill conduits under particular conditions, but widespread failure can leave the crown unable to meet its water demand.

Root hair. A fine extension of a root epidermal cell that increases contact with soil water and mineral surfaces. Root hairs are short-lived and operate near growing root tips.

Mycorrhiza. A partnership between a fungus and plant root. Fungal hyphae extend access to soil resources, while the plant supplies carbon. Costs, gains and outcomes vary with partners and conditions.

Arbuscular mycorrhiza. A common mycorrhizal form in which fungal structures enter root cortical cells and create branched exchange surfaces. It occurs across many plant groups and is especially important for phosphorus acquisition.

Ectomycorrhiza. A partnership in which fungi sheath fine roots and grow between root cells without entering them. It is frequent among pines, oaks, beeches, birches and many other forest trees.

Common mycorrhizal network. A physically continuous mycorrhizal mycelium linked to more than one plant. Movement of carbon and other compounds has been detected in linked systems, but route, net effects and ecological importance require case-specific evidence.

Hydraulic redistribution. Passive movement of water through roots from wetter soil layers towards drier ones as water-potential gradients change. Flow may be upward, downward or sideways and can affect neighbouring organisms.

Canopy. The upper layer formed by overlapping crowns. It intercepts most incoming light, exchanges water and heat with the atmosphere, and creates the shaded microclimate beneath it.

Understorey. Vegetation growing below the main canopy, including smaller trees, shrubs, herbs and seedlings. Its composition reveals light conditions, browsing pressure and part of the forest's possible future.

Gap dynamics. Change caused when branch or tree death opens the canopy. The size, timing and location of gaps influence which suppressed seedlings, pioneers or surviving trees gain light and space.

Succession. Directional change in ecological composition and structure through time after new substrate or disturbance. Forest succession follows inherited soils, survivors and seed sources rather than one guaranteed final stage.

Disturbance regime. The characteristic type, frequency, severity, season and spatial pattern of events such as fire, wind, flood, insects or harvest. The regime matters more than the label alone.

Old growth. Forest with substantial ecological continuity and structures associated with long development, often including large trees, varied ages, deadwood and complex soils. Definitions must be fitted to region and forest type.

Snag. A standing dead tree or broken standing stem. Snags provide cavities, perches, food and slowly changing habitat, so removing them can impoverish an otherwise wooded site.

Coarse woody debris. Large fallen branches, trunks and roots in a forest. They store carbon and water, alter microsites, release nutrients slowly and support organisms throughout decomposition.

Dendrochronology. Dating and interpreting tree rings by matching growth patterns among samples. Cross-dating can assign exact calendar years and expose missing rings, false rings and environmental signals.

Mast seeding. Intermittent, broadly synchronised production of unusually large seed crops by a population. Masting can overwhelm seed predators and create pulses of food that travel through forest communities.

Carbon stock, sink and source. A stock is carbon held at a moment; a sink gains carbon over a period; a source loses it. Confusing these measures produces much bad forest accounting.

Go Deeper

The working tree. Peter A. Thomas, *Trees: Their Natural History*, second edition (Cambridge University Press, 2014). This is the best next step for the machinery: wood, roots, water transport, architecture, reproduction, ageing, damage and death. Thomas writes for readers who can tolerate scientific terms but do not want a specialist monograph. The book is broader and more systematic than this one, with enough comparative biology to show where convenient rules fail. Read it when the hydraulic and structural model has made you curious about the exceptions. Keep a pencil nearby: its diagrams and examples repay returning to after seeing the same feature on a living tree.

The forest as evidence. Tom Wessels, *Reading the Forested Landscape: A Natural History of New England* (Countryman Press, 1997). Wessels teaches the reader to infer abandoned fields, wind, fire, logging, grazing and other past events from trunks, stones, pits, mounds and species patterns. Its limitation is geographic: New England's land-use history and trees cannot stand for tropical, boreal or African forests. Its method travels well. It is the most practical of these recommendations because a walk after reading it becomes an investigation rather than a view. The illustrations by Brian D. Cohen help turn subtle clues into recognisable forms.

The inhabited square metre. David George Haskell, *The Forest Unseen: A Year's Watch in Nature* (Viking, 2012). Haskell returns through one year to a small circle of old-growth forest in Tennessee and uses close observation to connect weather, microbes, plants, animals and time. This is not a tree manual and does not attempt global coverage. It shows what scientific attention feels like when held on one place long enough for events normally dismissed as background to become the story. Read it for lived scale and patience, and for a model of how to move from one observable detail to a larger process without reducing the place to an inventory.

The human material. Roland Ennos, *The Wood Age: How Wood Shaped the Whole of Human History* (William Collins, 2020). Ennos follows wood

through primate evolution, fire, tools, buildings, ships, mines, paper and industrial society. The argument is deliberately expansive, and some readers will want more weight given to other materials and institutions. That is also why it is useful. It corrects histories that leap from stone to bronze to iron while treating the material that supplied handles, fuel, roofs, vessels and supports as scenery. Pair it with Thomas when you want to move between the mechanics that make wood useful and the historical systems that consumed it.

Notes and Sources

Sources were checked on 4 September 2026. The notes follow the order of the book and identify the main support for claims that are numerical, contested, memorable or easy to overstate. Routine botanical anatomy and terminology are drawn chiefly from Thomas, *Trees: Their Natural History*, and Venturas, Sperry and Hacke on xylem hydraulics.

The Whole Thing in One Page and Why You Should Care

Global forest area and change. The Food and Agriculture Organization's *Global Forest Resources Assessment 2025* reports 4.14 billion hectares of forest in 2025, equal to 32 per cent of global land area. It estimates gross deforestation during 2015 to 2025 at nearly 10.9 million hectares per year and net forest-area loss at 4.12 million hectares per year. Gross deforestation and net change answer different questions because forest expansion elsewhere offsets part of the loss. FAO figures are assembled mainly from national reports under common definitions; they should not be read as a measure of ecological equivalence among primary forest, naturally regenerated forest and plantation.

Height and plumbing. The description of a coast redwood's hydraulic difficulty follows Koch and colleagues and the wider synthesis by Venturas and colleagues. Koch's study found strong leaf-level and hydraulic limitation near the tops of exceptionally tall redwoods. The book does not repeat its

estimated maximum as a universal ceiling because species, site, mechanics and climate alter the limit.

The Core Ideas

Tree as a strategy. Klimeš and colleagues reconstructed repeated transitions between woody and herbaceous growth forms among flowering plants, supporting the treatment of tree form as an evolved strategy rather than a single lineage. Cazzolla Gatti and a large international team estimated about 73,300 tree species globally, roughly 14 per cent more than the number then known. The estimate depends on statistical extrapolation from unevenly sampled databases, so the book describes it as an estimate rather than a census.

Wood, xylem and phloem. Thomas supplies the main comparative account of cambium, secondary growth, sapwood, heartwood, bark, crown architecture and reproduction. Venturas, Sperry and Hacke review cohesion-tension transport, vulnerability to cavitation, conduit trade-offs and drought mortality. The current literature does not support one mechanism as the cause of every drought death; hydraulic failure, carbon limitation, heat, pathogens and their interactions vary among species and events.

Root form and depth. Jackson and colleagues synthesised root distributions across terrestrial biomes. Their results support the claim that a large share of fine-root biomass commonly occurs in upper soil while also documenting deep rooting and strong biome variation. The book therefore rejects both a universal shallow plate and the schoolbook mirror of crown and roots. Local geology, oxygen, water, nutrients, species and age remain decisive.

Mycorrhizal networks. Simard and colleagues demonstrated movement of labelled carbon between ectomycorrhizal tree species in a field experiment. Karst, Jones and Hoeksema later found positive citation bias and overinterpretation in claims about common mycorrhizal networks. Henriksson and colleagues concluded that evidence for ecologically significant net carbon transfer through such networks that benefits recipients

remained lacking. Simard, Ryan and Perry replied in 2025 that these critiques discounted evidence for the existence and function of common networks. The manuscript retains the shared ground and the dispute: mycorrhizal partnerships exist; fungal individuals can connect plants; some movement has been measured; continuity of route, net benefit, donor control, prevalence and generality require case-specific evidence.

Forest structure, edges and deadwood. Harmon and colleagues established coarse woody debris as a major structural and biogeochemical component of forest ecosystems. Ewers and colleagues showed that fragmentation can impair a forest's buffering of microclimate, supporting the distinction between equal area and equal interior conditions. Old growth has no single global age threshold; definitions depend on regional disturbance regimes, tree longevity, structure and continuity.

Damage and age. Shigo and Marx's compartmentalisation model remains the foundation for understanding how trees restrict dysfunction and build new tissue around damage rather than restoring wounded wood. The model has been refined, and it is not a promise that every boundary succeeds. Stephenson and colleagues analysed 403 tropical and temperate species and found that absolute mass growth for most species increased with tree size across the observed ranges. The book narrows this to individual-tree carbon accumulation and does not convert it into a claim about every old stand.

Old forests and carbon. Luyssaert and colleagues found that many old forests continued to show positive net ecosystem productivity, challenging the assumption that all ageing forests become carbon-neutral. Their synthesis has prompted methodological criticism and should not be read as one fixed global rate. The retained point is the weaker and well-supported one: old forests can continue to take up carbon while already holding large stocks.

Oxygen, carbon, water and heat. The oxygen correction follows ecosystem carbon balance and the atmospheric reservoir described by the Scripps O₂ Program. Photosynthesis releases oxygen while respiration,

decomposition and combustion consume it; gross production should not be confused with a durable net addition. Bonan reviews the combined climate effects of carbon, evapotranspiration, albedo and surface roughness. Lawrence and colleagues show that biophysical effects vary by latitude and that tropical deforestation causes strong warming through carbon and non-carbon routes. The *Global Carbon Budget 2025*, published in 2026, estimates the terrestrial sink excluding land-use change at 2.4 plus or minus 0.8 gigatonnes of carbon per year during 2015 to 2024, equal to 21 per cent of total emissions in that accounting. It also reports a weaker sink in 2024. The manuscript uses the completed decadal value and makes clear that land includes ecosystems beyond forests.

Slow movement under rapid change. The final Core Idea distinguishes movement by seeds and genes from movement by an adult tree. It deliberately avoids a universal rate comparison between climate velocity and tree migration because dispersal, topography, soils, fragmentation and generation time vary widely. Assisted migration and seed-provenance choices remain active management questions with benefits and ecological risks rather than settled global prescriptions.

How It Actually Works

The earliest forest. Davies, McMahon and Berry described in-situ Calamophyton stands in the Middle Devonian Hangman Sandstone Formation of Somerset and Devon, about 390 million years old. Their 2024 paper identifies the site as the earliest forest then known, several million years older than the Gilboa fossil forest in New York. The trees were roughly two to four metres high and altered sedimentary processes. Earliest means earliest currently documented, not first that ever existed.

Coal and decay. Nelsen and colleagues tested the popular hypothesis that Carboniferous coal peaked because lignin-degrading fungi had not evolved. They found evidence inconsistent with delayed fungal evolution as the primary explanation and emphasised climate and tectonic setting. The manuscript retains multiple causes and does not claim one universal route to coal formation.

Forest zones and disturbance. The biome sequence is a compressed organising scheme, not a claim that forests divide into clean global boxes. McLauchlan and colleagues review fire as an ecological and evolutionary process shaped by climate, organisms and people. The text therefore evaluates frequency, severity, season and interval rather than treating the presence of fire as inherently restorative or destructive.

Human use and forestry. Ennos provides the principal synthesis for wood in tools, fire, buildings, ships, mines, paper and industrial society. The account of coppice, pollarding and the conversion of irregular woodland into measured timber production is also supported by Thomas and Wessels and is labelled as regionally European. Ellis and colleagues support the broader point that people have shaped much terrestrial nature for millennia. Practices, rights and ecological outcomes varied sharply. The manuscript does not present European scientific forestry as the origin of forest management or treat ancient human influence as permission for industrial conversion.

Measurement. FAO definitions require thresholds for area, canopy cover and potential tree height while also considering land use. These allow international aggregation but cannot express all differences in age, composition, condition or history. The carbon-budget warning follows Friedlingstein and colleagues: national inventories, dynamic vegetation models, atmospheric inversions and land-use bookkeeping use different boundaries and are revised as methods improve.

What People Get Wrong and Use It

The seven corrections. The lungs correction separates gross oxygen production from net atmospheric change and the size of the existing reservoir. The root correction rests on Jackson and colleagues. The common-network correction retains Simard's field result, the 2023 critical reviews and the 2025 response. The old-forest correction separates individual growth, stand flux and stored stock. The fire correction follows McLauchlan and colleagues. The planting and plantation corrections follow Holl and Brancalion, Williams and colleagues, and Wang and colleagues.

Tree planting and natural regeneration. Holl and Brancalion argue that planting trees is not a universal environmental solution and place protection of existing ecosystems first. Williams and colleagues mapped substantial biophysical potential for natural regeneration across deforested tropical regions, while stressing social and implementation constraints. Their map is potential, not a forecast and not permission to allocate occupied land without local consent. Wang and colleagues found lower biodiversity in intensively managed plantations than in restoration-oriented plantations, with mixed and native approaches generally performing better. No global average decides a local project.

Stock, flow and permanence. These are accounting distinctions rather than three scores that can be added. Stock describes a quantity at a time, flow its change during a period, and permanence the durability of a claimed store. The framework is applied to carbon, forest area and restoration survival because each can be misrepresented by reporting only the most favourable dimension.

Go Deeper

Publication details for the four recommendations were checked against Cambridge University Press, William Collins, the publisher record for Wessels and David George Haskell's publication record. Wessels is explicitly regional. Haskell is close observation rather than a systematic tree text. Ennos advances a broad material-history argument. Thomas is the strongest technical continuation of this book's model.

Bibliography

Assessments, institutional sources and original research

Bonan, Gordon B. "Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests." *Science* 320 (2008): 1444-1449.

Cazzolla Gatti, Roberto, Peter B. Reich, Javier G. P. Gamarra, et al. "The

Number of Tree Species on Earth." *Proceedings of the National Academy of Sciences* 119, no. 6 (2022): e2115329119.

Davies, Neil S., William J. McMahon, and Christopher M. Berry. "Earth's Earliest Forest: Fossilized Trees and Vegetation-Induced Sedimentary Structures from the Middle Devonian Hangman Sandstone Formation, Somerset and Devon, SW England." *Journal of the Geological Society* 181, no. 4 (2024): jgs2023-204.

Ewers, Robert M., and Cristina Banks-Leite. "Fragmentation Impairs the Microclimate Buffering Effect of Tropical Forests." *PLOS ONE* 8, no. 3 (2013): e58093.

Ellis, Erle C., Nicolas Gauthier, Kees Klein Goldewijk, et al. "People Have Shaped Most of Terrestrial Nature for at Least 12,000 Years." *Proceedings of the National Academy of Sciences* 118, no. 17 (2021): e2023483118.

Food and Agriculture Organization of the United Nations. *Global Forest Resources Assessment 2025*. Rome: FAO, 2025.

Friedlingstein, Pierre, Michael O'Sullivan, Matthew W. Jones, et al. "Global Carbon Budget 2025." *Earth System Science Data* 18 (2026): 3211-3288.

Harmon, Mark E., Jerry F. Franklin, Frank J. Swanson, et al. "Ecology of Coarse Woody Debris in Temperate Ecosystems." *Advances in Ecological Research* 15 (1986): 133-302.

Henriksson, Nils, Jim Marshall, Mona N. Högborg, Peter Högborg, Andrea Polle, Oskar Franklin, and Torgny Näsholm. "Re-examining the Evidence for the Mother Tree Hypothesis: Resource Sharing among Trees via Ectomycorrhizal Networks." *New Phytologist* 239, no. 1 (2023): 19-28.

Holl, Karen D., and Pedro H. S. Brancalion. "Tree Planting Is Not a Simple Solution." *Science* 368 (2020): 580-581.

Jackson, Robert B., Josep Canadell, James R. Ehleringer, Harold A. Mooney, Osvaldo E. Sala, and Ernst-Detlef Schulze. "A Global Analysis of Root Distributions for Terrestrial Biomes." *Oecologia* 108 (1996): 389-411.

Karst, Justine, Melanie D. Jones, and Jason D. Hoeksema. "Positive Citation Bias and Overinterpreted Results Lead to Misinformation on Common Mycorrhizal Networks in Forests." *Nature Ecology & Evolution* 7 (2023): 501-511.

Klímeš, Adam, Irena Šímová, Alexander Zizka, Alexandre Antonelli, and Tomáš Herben. "The Ecological Drivers of Growth Form Evolution in Flowering Plants." *Journal of Ecology* 110 (2022): 1525-1536.

Koch, George W., Stephen C. Sillett, Gregory M. Jennings, and Stephen D. Davis. "The Limits to Tree Height." *Nature* 428 (2004): 851-854.

Lawrence, Deborah, Michael Coe, Wayne Walker, Louis Verchot, and Karen Vandecar. "The Unseen Effects of Deforestation: Biophysical Effects on Climate." *Frontiers in Forests and Global Change* 5 (2022): 756115.

Luyssaert, Sebastiaan, Ernst-Detlef Schulze, Annett Börner, et al. "Old-Growth Forests as Global Carbon Sinks." *Nature* 455 (2008): 213-215.

McLauchlan, Kendra K., Philip E. Higuera, Jessica Miesel, et al. "Fire as a Fundamental Ecological Process: Research Advances and Frontiers." *Journal of Ecology* 108 (2020): 2047-2069.

Nelsen, Matthew P., William A. DiMichele, Shanan E. Peters, and C. Kevin Boyce. "Delayed Fungal Evolution Did Not Cause the Paleozoic Peak in Coal Production." *Proceedings of the National Academy of Sciences* 113 (2016): 2442-2447.

Shigo, Alex L., and Harold G. Marx. *Compartmentalization of Decay in Trees*. Agriculture Information Bulletin 405. Washington, DC: United States Department of Agriculture Forest Service, 1977.

Simard, Suzanne W., David A. Perry, Melanie D. Jones, David D. Myrold, Daniel M. Durall, and Randy Molina. "Net Transfer of Carbon between Ectomycorrhizal Tree Species in the Field." *Nature* 388 (1997): 579-582.

Simard, Suzanne W., Teresa (Sm'hayetsk) L. Ryan, and David A. Perry. "Opinion: Response to Questions about Common Mycorrhizal Networks."

Frontiers in Forests and Global Change 7 (2025): 1512518.

Scripps Institution of Oceanography. "Frequently Asked Questions About Atmospheric Oxygen." Scripps O2 Program. Accessed 4 September 2026.

Stephenson, Nathan L., Adrian J. Das, Richard Condit, et al. "Rate of Tree Carbon Accumulation Increases Continuously with Tree Size." *Nature* 507 (2014): 90-93.

Venturas, Martin D., John S. Sperry, and Uwe G. Hacke. "Plant Xylem Hydraulics: What We Understand, Current Research, and Future Challenges." *Journal of Integrative Plant Biology* 59 (2017): 356-389.

Wang, Chao, Weiwei Zhang, Xiaona Li, and Juying Wu. "A Global Meta-analysis of the Impacts of Tree Plantations on Biodiversity." *Global Ecology and Biogeography* 31 (2022): 576-587.

Williams, Brooke A., Hawthorne L. Beyer, Matthew E. Fagan, et al. "Global Potential for Natural Regeneration in Deforested Tropical Regions." *Nature* 636 (2024): 131-137.

Books

Ennos, Roland. *The Wood Age: How Wood Shaped the Whole of Human History*. London: William Collins, 2020.

Haskell, David George. *The Forest Unseen: A Year's Watch in Nature*. New York: Viking, 2012.

Thomas, Peter A. *Trees: Their Natural History*. 2nd ed. Cambridge: Cambridge University Press, 2014.

Wessels, Tom. *Reading the Forested Landscape: A Natural History of New England*. Woodstock, VT: Countryman Press, 1997.