Trees to store carbon

A chapter in: *Trees of the People*, by Alan R. Walker
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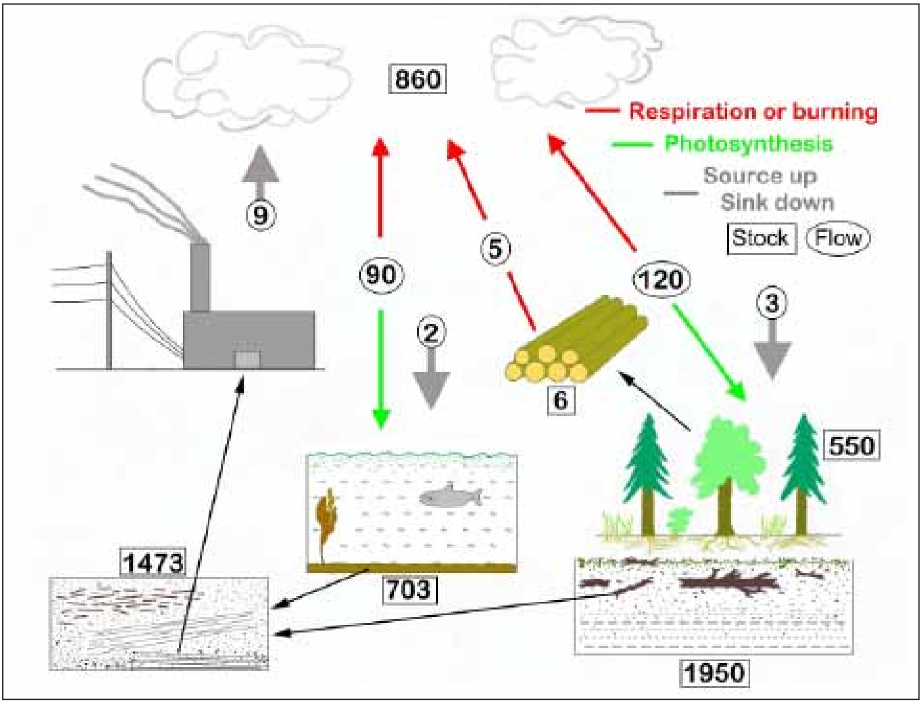
Long before plants came to inhabit Earth the forces of geology had produced an atmosphere of mostly nitrogen, carbon dioxide and water vapour. These last two compounds in the air reflected back down rays of infra-red frequency coming up from the warm ground. This trapped heat into the atmosphere. More energy from sunlight continued to pour into this atmosphere that was becoming like a greenhouse. During the Cambrian Period of five hundred million years ago conditions on Earth improved for the evolution of new microorganisms of many kinds. Since more than a billion years ago microbes had been thriving and were spread across seas and land. Nevertheless they were constrained tightly by the central problem for all forms of life: how to obtain energy.

Managed mixed forest soaking up photons and carbon dioxide.

One solution, the evolution of photosynthesis, shot out in all directions – the Big Bang of life. Microbes of a type called cyanobacteria found a way to divert the energy of sunlight into an intricate pathway of molecules that catalysed the splitting of water into oxygen molecules and hydrogen ions. The oxygen diffused away whilst the hydrogen ions powered further complex energy transfer and enzymic actions that split carbon dioxide into carbon and left the oxygen to combine with the hydrogen ions to form water (see 'Photosynthesis' for diagram). The carbon atoms were incorporated into the structures of the bacterium. Molecule by molecule, and for years by the million, oxygen seeped from these bacteria into the atmosphere. Eventually the oxygen reached a concentration where it verged on being a danger to life through fire and the toxicity of highly reactive types of oxygen. As the cyanobacteria consumed the carbon from the atmosphere the concentration of carbon dioxide dropped from four thousand parts per million to several hundred parts per million.

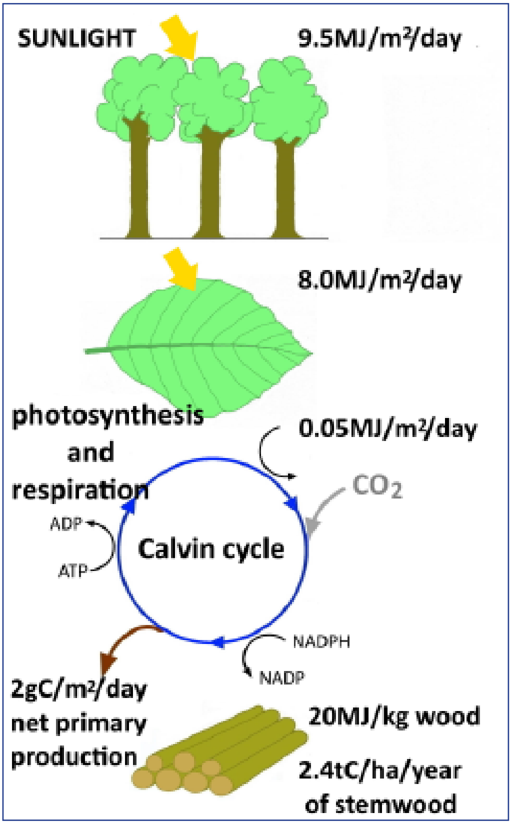


Global biological carbon cycle. Stocks and flows of carbon as billions of tonnes (GtC) at 2018. Carbon in the atmosphere as CO_2, and various stocks of carbon as complex compounds in live and dead organisms. This is not presented as a carbon budget, data are composites from several sources for comparisons of scale of categories and movements of carbon.

This new way of making a living, this photosynthesis, was a ripe opportunity for any other form of life that could somehow combine with cyanobacteria without consuming and destroying them. A mutually beneficial symbiosis, a mutualism, came about, with the cyanobacteria alive within the cell of another organism. Some types of cell that lived by engulfment of other cells continued to thrive with cyanobacteria living within them. As these now mutualistic cyanobacteria continued to photosynthesize they evolved into chloroplasts with typical green chlorophyll. The host cells of the cyanobacteria could not only engulf other cells, they possessed both a true nucleus for efficient genetic control and mitochondria for efficient use of oxygen to energize the cell. This combination of a new source of carbon via photosynthesis and efficient respiration with oxygen allowed these newly complex cells to combine with each other. They became new multicellular organisms. Not just to become larger but to be an organism possessing separate specialist parts: organs such as root, shoot and leaf.

Plants expanded in complexity and range during many more millions of years, all the while consuming carbon dioxide and excreting oxygen. Plants converted the atmosphere of the Earth into a place of ample potential habitats where the temperature ranged from a few degrees above freezing to the level of 20-25^{o}C at which photosynthesis is most effective. Plants grew and spread so much that their basic food resource, carbon dioxide, became of limiting low concentration at about 280 parts per million. Plants thrived so well during the Carboniferous Period, approximately 360 to 300 million years ago, that enormous quantities of their dead remains sank down into soft wet soil where they fossilized as geological formations: methane gas and petroleum oil trapped in porous rock, or seams of lignite and coal layered between rock strata.

Long after their burial these remains of ancient plants were dug up and pumped up by our ancestors to fuel our new machines and energetic lives. Now our waste carbon dioxide rises steadily in concentration, increasing by forty eight percent since the simple days of our early civilizations. The greenhouse effect became stronger, glaciers and ice-sheets melted out into the sea faster than they would have simply from the steady progression of ice-ages. Recently a group of climate researchers unveiled a bronze plaque next to the remains of *Okjökull*, a glacier in Iceland. One hundred years ago *Okjökull* was fifteen square kilometres wide and fifty metres deep. Now, covering one square kilometre as static patches fifteen metres thick this relic is diminished to *Ok*, no longer a glacier. The final words of the plaque read: “This monument is to acknowledge that we know what is happening and what needs to be done. Only you know if we did it. Ágúst 2019, 415ppm CO2”



Photosynthesis to stored carbon. Of the energy of sunlight only 0.53% becomes incorporated as energy content of woody material during photosynthesis. Despite this, much carbon becomes stored in stem wood that grows each year and long beyond the stage of reproductive maturity.

Turn carbon dioxide into tree wood.
A conifer seedling burrowed roots into the soft rich soil of the commercial nursery. Its shoot reached straight up toward the sunlit sky to expose its cotyledon leaves to incoming photons. Both root and shoot needed flexible stiffness for these tasks: a pair of properties difficult to combine. Woody tissues evolving in some plants enabled them to exploit the empty space above the level occupied by mosses, herbs and grasses. Here these new forms of plant life were able to be first to trap photons with their leaves raised high by a central stem and spread wide by branches. The Calvin cycle of photosynthesis provided simple sugars as its output:

glucose made of carbon, hydrogen and oxygen in the formula $C_6H_{12}O_6$ (see 'Photosynthesis'). This carbohydrate powered the respiration of the mitochondria needed for photosynthesis whilst providing the first molecular building block of cellulose. Cellulose polymer formed into micro-fibrils and these built up the bulk of the secondary cell walls of the seedling's stem.

Cellulose has its atomic components making up units each of formula $(C_6H_{10}O_5)n$, a molecule of water is lost from each unit as they link up into a chain of glucose anhydride. Cellulose makes up sixty percent of the mass of dry wood and the rest comprises mostly lignin with small amounts of hemicellulose, pectin and proteins. Lignin is what toughens plant tissues into woody material.

> The carbon content of trees is measured in units of mass, starting with one gram, the weight of a bank note. Gram is central point for the scale of mass which goes in steps of 10^3 so one thousand grams = one kilogram. Research papers mostly refer to grams, leading to measurements of carbon content of forests in petagrams, Pg; that is one quadrillion grams, or 10^{15}g. Or a more modest gigagram, Gg may be used; that is one billion grams, or 10^9g. Weighing forests by the quadrillion grams works for some, but others prefer to use workaday kilograms, 10^3g, and tonnes, 10^6g. The non-metric *ton* is close enough to this metric *tonne* to be not converted here.

In one of those counter intuitive quirks of nature the softwood of needle-leaf trees, gymnosperm plants, has a higher content of lignin than the hardwood of broad-leaf trees. So generally needle-leaf trees have slightly higher carbon content on a weight for weight basis. The term softwood is deceptive in this context of carbon content despite the fact that a plank of spruce is softer than a plank of oak – try sawing or planing them! The close packing of the vascular tubes, the xylem tissue, in a typical genus of hardwood, *Quercus*, gives the hardness. However, much overlap occurs between species of trees. Balsa tree, *Ochroma pyramidalis*, with the least dense stem wood is a broad-leaf species, an angiosperm plant.

A generalization is that softwoods are about 525 kilograms per cubic metre and hardwoods are about 850 kg/m^3. On the working timescale of a forester this makes little difference. Needle-leaf and broad-leaf species contain carbon to the same amount per bulk of wood or area of forest, but the broad-leaf trees take twice as long to grow that bulk. Foresters and timber merchants deal mostly in volumes of timber, cubic metres, rather than its mass in tonnes.

Harvested hard-wood from a plantation of beech, *Fagus sylvatica*.

Mature birch trees *Betula pendula*, in a nature reserve.

How fast can a needle-leaf tree store carbon?

Foresters study needle-leaf species of trees intensively for their ability to soak up carbon from air and turn into stemwood timber, into lumber. They started these studies about one hundred years ago for the attractive opportunity of growing and selling more wood of trees that are fast growing and adaptable to habitats found in many parts of the world. We have available: Sitka spruce, *Picea sitchensis*, originally from Alaska; Norway spruce, *Picea abies,* originally from Scandinavia; Western red cedar, *Thuja plicata*, from British Columbia to Oregon; Radiata pine, *Pinus radiata*, from California; and so on. In its tiny indigenous range *P. radiata*, known there as Monterey pine, has been classed by biologists as endangered, but elsewhere in the world foresters grow it more than any other species of plantation tree.

When reared as seedlings from stocks of seed then planted at densities of up to one every two square metres on prepared ground, these trees grow into a plantation of surviving mature trees at about 2200 per hectare. Estimated by the hectare, they store each year between 2 to 7 tonnes of carbon (this storage is often called sequestration and is presented as say: 5.2 tC/hectare/year, or 5.2tCha^{-1}a^{-1}). Such growth rates are for above ground woody material of entire trees, branches and leaves included, but not the roots. The roots however are significant. One example from the 1980s of a plantation of Sitka spruce trees in northern Europe on good soil and after seventeen years of being densely planted was, as tonnes of carbon per hectare:

stem + bark	branches	foliage	roots
56.6	25.0	26.6	25.0

Clearly it is important to make use of, or take account of, these non-timber components. Branches, as brash (or slash) as loppings and toppings can be converted into biofuel, usually formed into pellets (see ‘Fuelwood’).

Researchers estimate such mass of roots by soil coring but find it difficult to separate even the main roots from soil let alone to include accurately the fine roots and their root hairs. More modern estimates of the relative amounts of carbon stored in soil come later in this chapter.

Conifer plantation landscape. Larch (light green) and Sitka spruce at two stages of growth and some self-seeded spruces on uppermost slopes. Below: harvested logs from the same plantation.

Mixed species woods and forests that are not commercially run plantations for timber and carbon sequestration are, by their wide distribution and continuing growth into the future, an important part of how carbon is stored as woody biomass. Old trees continue to grow and take up significant amounts of carbon long after their peak of reproductive activity.

Needle-leaf and broad-leaf trees are, in their separate ways, equally effective at storing carbon. Maintaining the health, and increasing the area of such woodlands is important and an enterprise that operates in a realm mostly separate from commercial forestry. Trees growing by natural regeneration in their indigenous habitat have the advantage of wide spreading branches on short thick stems. Nobody forced them to grow tall and straight in a close-packed plantation. Seeds of other trees landing too close to such mature trees will have to compete for light and nutrients against both the tree and established grass and herbs. Such big trees store plenty of carbon per tree, they look beautiful and are often easy to walk amongst, but they need a future chapter on amenity trees (see 'Regeneration').

How fast can a broad-leaf tree store carbon?

If needle-leaf trees typically store, very approximately five tonnes of carbon per hectare per year, how much do broad-leaf tree store? A typical set of comparisons of plantation trees, at tonnes per hectare per year is:

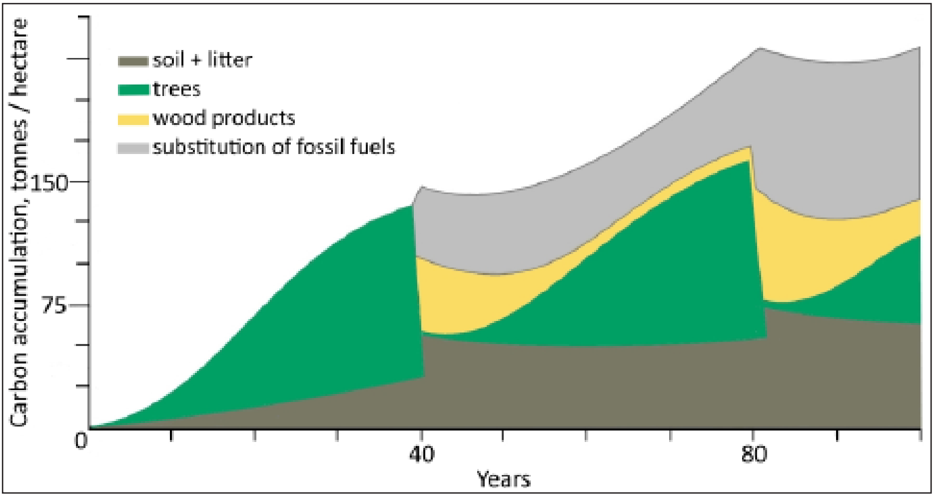
radiata pine	western red cedar	beech	oak
6.2	3.5	2.4	1.1

Given sufficient time the genera of broad-leaf trees that grow well in plantations (beech, *Fagus*; oak, *Quercus*; chestnut, *Castanea*; gum trees, *Eucalyptus*) will store as much carbon as needle-leaf trees. The time needed for forestry plantations to achieve this is typically eighty years for broad-leaf trees, compared to forty years for needle-leaf trees. For natural broad-leaf woodlands a well studied example is a small wood in an agricultural experimental station in England. Before 1883 researchers used this area to test arable crops, then they left it uncultivated and unmanaged whilst they observed it closely. By natural spread from nearby sources of seed a wood developed spontaneously, dominated by oak, *Quercus robur*. This wood has gained two tonnes of carbon per hectare per year averaged over its entire time of development. The stocks of carbon in the above ground trees were 180 tC/ha after 86 years, and 296 tC/ha after 118 years of growth. Clearly natural woodlands and forests have their part to play in storage of carbon dioxide from the atmosphere. Foresters planting for the main or subsidiary function of sequestering carbon consider speed more important for both the economics of the forest and because the faster carbon can be drawn down from the atmosphere the better for our planet.

> Carbon dioxide as gas in the air is the focus of climatologists. This gas is measured by the gram or tonne. But one unit of carbon has an atomic mass of 12, whilst one unit of carbon dioxide has a molecular mass of 44 (12 for the carbon atom plus two oxygen atoms at 16 each). So carbon dioxide weighs 44/12 times more than carbon. When a price in monetary units is specified for tonnes of carbon dioxide, as in: 'US$30 per tonne of CO_2' it is essential to know that price is about x**3.7 less** than the price if stated as dollars per tonne of carbon. This price could alternatively be stated as 'US$110 per tonne of carbon'. Another complication is the term carbon dioxide equivalent, 'CO_2e'. This is a collective measure of greenhouse gases including others such as methane. This is important but not needed here. The abbreviation '[CO_2]' means concentration of atmospheric carbon dioxide.

How much carbon can be stored in one place?

Plantation forestry is a large-scale business and the scale of natural forests that steadily store carbon includes most of the vast areas of: boreal North America, Northern Europe plus Russia; the temperate forests of Eastern USA plus a band stretching from Western Europe to China; and the tropical and sub-tropical forests of South America, Africa plus South-east Asia plus Australia. The total adds up to about four billion hectares, equal to thirty percent of the wold's land surface. The trees on these wooded lands sequester each year about five hundred million tonnes of carbon per year. Of these wooded lands five hundred million hectares are managed forest as plantations. To make decisions for storing carbon in plantations the stocks of carbon of different sites need to be known. A stock of carbon is tonnage in a stated area at one fixed time. If the carbon is moving into the site faster than it is wasted out into the atmosphere, then that stock acts as a sink of carbon. Conversely if carbon is moving out of a site by decay processes faster than it accumulates by growth then that stock is a source of carbon into the atmosphere.



Accumulation of carbon as tonnes per hectare in a conifer plantation during two rotations of planting and felling at 40 years growth. This is **additional** to carbon already in soil before first planting. Soil component includes litter. Wood products component includes material to landfill. Substitution component is an estimate of fossil-fuels displaced by wood used for construction and fuel. Composite data from several sources.

Typical, greatly generalized, tonnage for stocks per hectare of mature plantation trees is 185 tonnes of carbon per hectare. This is for the above ground whole trees, and the same stock quantity applies to both needle-leaf and broad-leaf species of tree. An exception tests the rule: the Tasmanian oak, or mountain ash, *Eucalyptus regnans,* in its indigenous habitat of warm and wet south eastern Australia is the tallest flowering plant in the world, growing up to 100 metres. When growing in its natural fairly dense stands it has been weighed at 1867 tonnes to the hectare. Not merely a magnificent tree to look up at, also it provides much good quality timber as a plantation crop.

> A wider perspective is useful here: woody material from forests continues to be a long-term store for carbon that came from atmosphere. A study in the USA by K.E. Skog and G.A. Nicholson showed that, in the eighty plus years from 1910, the accumulated stocks of carbon in just those wood products such as lumber, sheet wood, card and paper that remained in use was 2.7 billion tonnes. (See 'Wooden buildings' for more on carbon stored in wooden structures.)

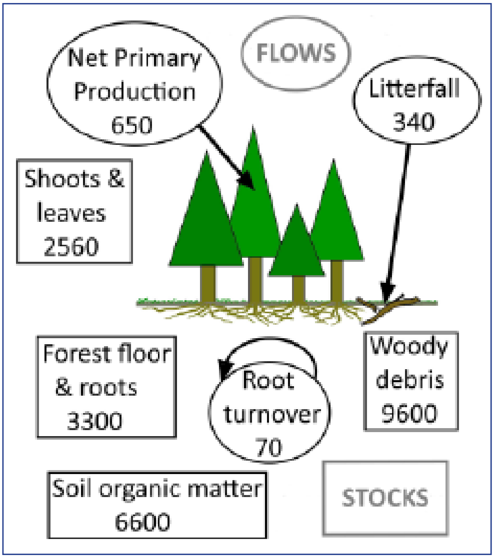
Recently harvested conifer plantation on steep ground. Stumps and brash (slash) of insufficient value to remove and process off-site will store carbon on this ground. This area was being re-planted with conifer seedlings.

Roots and dead trees in the soil.

The seedling of a needle-leaf tree species of plantation tree will add very little carbon to the soil of its nursery. Then out in the plantation its roots immediately become part of the stock of carbon in the soil. Crucial to the tree's survival, these sparse young roots are needed to absorb water and mineral nutrients. If mycorrhizal fungi rapidly colonize the roots they will survive better (see 'Roots'). The network of fine roots combined with the potentially far spreading network of hyphal threads of the mycorrhizas both place carbon into the soil. Fungal hyphae can accumulate to between 100 to 600 kilograms beneath one hectare of forest floor. The carbon content of these threads is much lower than for plant remains in the soil, nevertheless the carbon within these fungi derived mostly from the trees that drew it down from the atmosphere. First the carbon was stored as photosynthate in the leaves, then these sugars were supplied to the mycorrhizal fungi in exchange for mineral nutrients. The fine roots are short lived but their structural carbon and root tip exudates adds continually to the stock of organic carbon in soil. Main roots spread as far as the area under the canopy of each tree and although mostly no more than one metre deep they create a dense network in the soil.

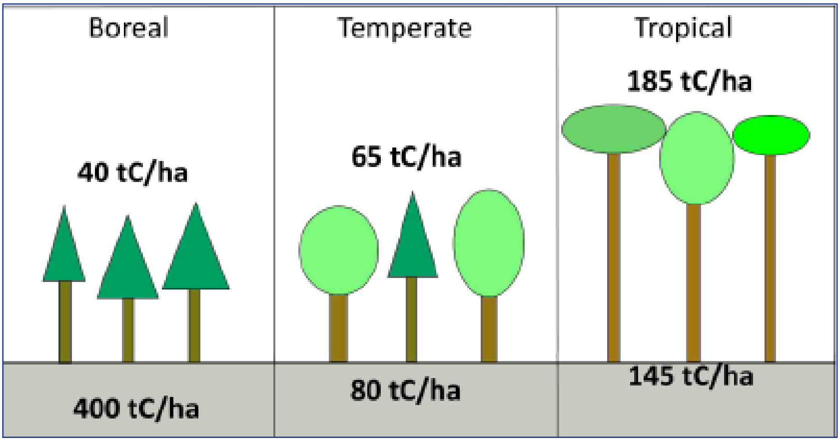
Bog-wood in peat, exposed by stream erosion. Roots and stems of Scots pine in peat 2.5m deep, stored for several thousand years.

A broadscale study in the United Kingdom, sponsored by the national forestry agency, of carbon content of soils (to depth of 1 metre) revealed that within woods and forests the proportion of carbon stored in the soil was seventy five percent of the total of above and below ground stored carbon. This figure varies depending on species of trees grown, soil types and general climate, but studies from other regions demonstrate the importance for carbon storage of litter-fall as broad and needle leaves, fallen branches, whole trees, exudates from roots and the combination of fine roots of trees with mycorrhizal fungi. The latter exchange large quantities relative to the size of root hairs and fungal hyphae, of carbon from the tree in exchange for mineral nutrients from the fungus.



Flows (fluxes) as grams of carbon per square metre per year, and **stocks** as grams of carbon per square metre. Typified by data from two forests in USA: a natural conifer forest and a plantation of pines. Note how much more carbon is stored in soil rather than standing trees. Combined data adapted from Fahey, 2010.

From a seedling to mature tree, eventually all its roots die whilst many of its small roots died each year. Some of that woody material decayed, was consumed by saprophytic fungi of wood rotting species; some was eaten by small animals of the soil. Thus a large proportion of the tree's carbon initially stored in the soil could be released by the respiration, the biological burning, of fungi, bacteria, and animals, if the conditions in the soil were good for these organisms, such as in a well drained sandy loam. If that tree had managed to grow in a boggy soil of low pH then it could end up preserved in the acidic wetness, like vegetables soaked in vinegar in a jar of pickles. Some regions of northern Eurasia have large areas of soil that contain the well preserved remains of stems and roots of needle-leaf trees. Specimens of bog-wood as mature Scots pine, have been dated as thousands of years old using tree-ring analysis, dendrochronology methods. Erosion by streams occasionally expose these bog-woods from the peat formed by accumulated mosses and herbs whilst more remain buried for many years to come. Not just the roots – stems and branches fall to the ground, needle-leaves and broad-leaves fall like rain. All forms the litter layer that incorporates into soil.

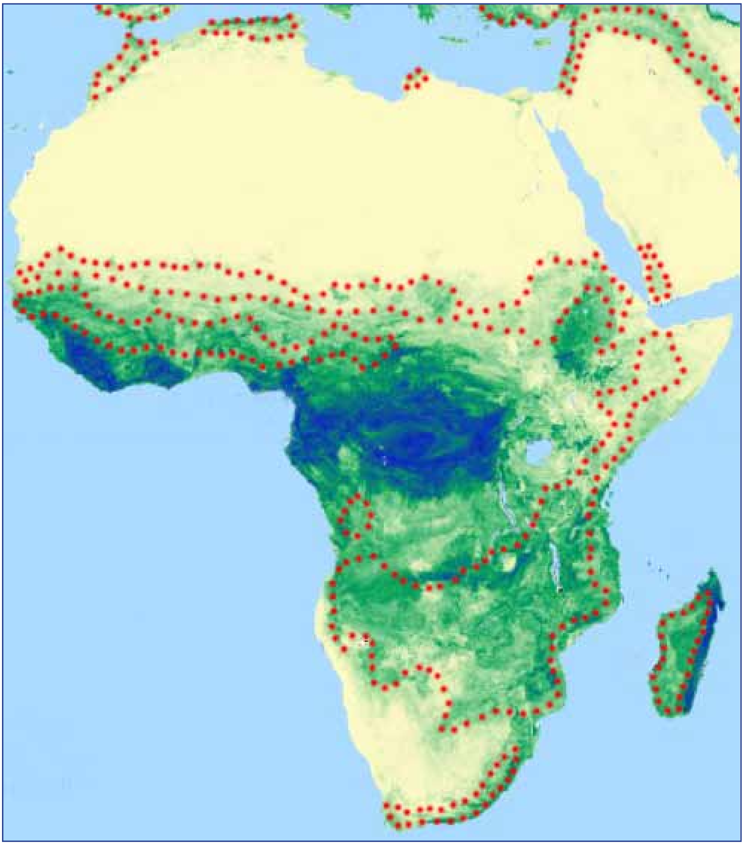


The three principal biomes for tree growth showing stocks of carbon as tonnes per hectare in the trees and soil. Composite data from many sources, to nearest 5 tonnes.

Typically 0.05 to 1 tonne of carbon is added per hectare per year to this sink of carbon in the soil under a forest. Conifer forests in temperate biomes can accumulate a stock of carbon stored in the soil to 400 tonnes of carbon per hectare of forest floor. This is more than twice the typical above-ground stock in the living trees. Despite the difficulty researchers have to measure anything in soil, and despite the wide range of soil organic carbon to be expected in soil under dry cool boreal forests or wet warm topical rain forests, a general phenomenon is clear. Soils worldwide hold a massive stock of carbon, about three times as much as in the vegetation that stands above the soil. Soils have been this large store-house of carbon since the aptly named Carboniferous Period of geology.

Forests storing carbon globally.

The largest forest biomes are in the boreal taiga areas in the far north, the temperate areas north and south of the equator, and the tropical rain forests. The tonnage of carbon in the trees of boreal forests per unit area seem meagre, 40 tC/ha, with their generally thin sparse trees compared with the huge densely packed trees of tropical rain forests that store 185 tC/ha. Again, the obscurity of soil confuses our perceptions. At a combined 440 tC/ha in trees plus soil of the boreal forests covering 1.3 billion hectares compared with a combined 330 tC/ha of the tropical rain forests covering 1.7 billion hectares, the entire bleakly cold and wet boreal forests, store slightly more, **x1.02**, than the exuberantly hot and steamy tropical rain forests. The northern soils are more important than they appear at first sight and footfall. Moreover, beyond that biome lies the expanse of tundra with its peaty bogs and permafrost, storing yet more carbon.



Forest restoration potential: from online source: in Bastin *et al*. 2019, centred here on Africa. Derived from a model of ecological potential for natural forest using data from satellite images; high potential as dark blue to low as pale green. Areas modeled as suitable for forest regeneration, whilst maintaining existing agricultural land, have been outlined in red for this book only.

Foresters catalogue information on forests from satellites, they measure growth rates of trees compared to archived data and dendrochronology studies, they reveal a greening of vegetation in general and of forests in particular. Areas of land covered by forests that regenerate on abandoned farmland are obvious (see 'History' for example of natural regeneration of forests of north eastern USA). This newly reported greening of the land seems more than an expansion of areas of forests. Increase in yearly mean temperature could alter the seasonal timing of leaf bud break and leaf fall, known as phenological events. These lengthen the season of photosynthetic activity of needle-leaves and the appearance and fall of deciduous broad-leaves. Researchers struggle with the interrelated complexities and confounding factors of these ecological observations. They ask what exerts the strongest effect on growth and greening: higher temperature; more carbon dioxide; empty land on which to spread; increased deposition of nitrogenous compounds from the air?

Agro-forestry: managed pasture for livestock with mixed commercial forest in Vosges region of France.

Carbon dioxide in the atmosphere is so often stated to be a severe problem that is easy to forget that for plants it is both scarce and their fundamental nutrient. Increasing concentration of CO_2 in the air is likely to act as a fertilizer for growth of trees, in combination with increase in atmospheric temperatures. However, there is a possibility that any such increase in rate of growth of trees could be taken as a signal that there is less need to expand the number of trees being planted, nurtured to commercial size, harvested and used as timber, lumber, and related purposes. This book emphasizes throughout the business of increasing the woodland and forest cover of the world by many means.

Rapid seasonal growth of leader shoots of conifer saplings in Britain. LEFT: Scots pine, *Pinus sylvestris*, regenerating naturally. RIGHT: Sitka spruce, *Picea sitchensis* regenerating naturally from plantation beyond.

These questions are important enough to release funds sufficient for large-scale and long-term field experiments. A typical set-up is a plot in the grounds of a research station where stands of young trees are grown in many circular patches of 25-30 metres diameter. Around the perimeter of these stands are arrayed many tall pipes from which strong currents of CO_2 are pumped onto the trees. The concentration of CO_2 is increased from the natural level up to 550 parts per million that simulates the level that might occur by 2050. Free Air CO_2 Enrichment studies include measurement of the Net Primary Production of the trees. Comparisons of numerous FACE studies locations in the world reveal an increase in NPP of twenty percent. The added CO_2 acted as a fertilizer.

Increased temperature is not necessarily a favourable condition for increased carbon storage. Tropical rainforests becoming warmer are likely to release more CO_2 from their soils due to increased activity of decay organisms and soil chemistry. This could be greater than any compensating amount of CO_2 stored away by the trees. Despite these conflicting processes, fertilization effects and improved physical conditions in some forests can produce a positive net productivity. That is, the net primary productivity of the forest's trees minus the activity of the decaying organic parts of the forest (its heterotrophic respiration) gives a positive figure. The forest as a whole grows faster than it decays.

> Care is needed with the significance of the amount of carbon contained within trees and the potential for that carbon to be stored (sequestered). The net primary production of a growing tree or forest is the increase in mass of the whole tree per area per time. About half of that mass is **water**. If only fully seasoned wood is considered (about 10% of water remaining) then the carbon content of wood useful for construction or fuel is about half of the mass of the dried wood. Carbon content of stems of softwood needle-leaf trees varies between species at 47% to 55% weight for weight, and hardwood broad-leaf trees between 46% and 50%. Thus a simple rule of **halving** applies to these three following transitions of any type of tree: whole trees to wet stem-wood; wet wood to dry wood; dry wood to carbon content. An entire tree contains much carbon but there is less than appears without thought for tree's structure or whether the stored carbon is held in a growing forest or a stack of dry construction timber. As stated earlier, foresters and timber merchants deal mostly in volumes of wood not weight or mass.

People who grow trees.

Woods and forests spontaneously and rapidly occupy abandoned farmland where that farmland had been cut out of former forests. Farmers move away to areas that are easier or more profitable to cultivate, as long as such areas are available to occupy. In more crowded regions of the world, Europe for example, the uplands have long been occupied by pastoralist farmers, usually those raising cattle that produce milk suitable for specialist cheeses, or raising sheep for their meat rather their wool.

This pastoralism is often reliant on subsidy from government agencies because it makes insufficient profit to encourage farmers to continue with it, particularly younger people with broad education. At least in many of these uplands the remaining forests grow well and usually there is an effective agro-forestry combination of trees and livestock. This is communally managed with selective felling and use of fencing combined with shooting of deer to reduce damage by those herbivores that eat tree seedlings and de-bark saplings.

Conifer plantation being felled for timber, using the harvester at left, and the forwarder at right which carries logs to transport trucks.

The expansion of forested areas to sequester carbon has been described as another example of the tragedy of the commons. That is, reducing CO_2 levels in the atmosphere is crucial for humanity and other life on Earth in the long term but the people who own the land or have access to it for agriculture and other purposes have priorities needing immediate attention. Conflict of interests are likely to be acute, particularly in countries where there is high level of dependence on agriculture as the basic way of making a living

People who grow trees or crops, people who own and manage livestock, often have deeply emotional but complexly calculating relationships with the land they inhabit. Globally these relationships derive from an ancient form of communal use of the resources of grazing land, woodland or cropland at a level where the number of people keeps in balance with the natural regeneration of grass, trees and soil fertility. As populations grow in density then people invent and enforce more distinct codes of behaviour and formal laws. People tenaciously guard codes about their ability to use land and to own land. In some cultures, to plant trees on an area of apparently empty land is to claim that land for exclusive use. The mechanics of how to grow more trees to store carbon are simple and regular compared with their social context of people who making a living directly from what the land can provide. From the perspective of millions of people who need to harvest wood as their only fuel for cooking daily food, the potential for conflict with the aspirations of foresters is great. Demand for fuel-wood is steadily increasing globally in various ways, ranging from collection of wood for a simple cook-stove, to processing forestry waste as loppings, toppings, or brash (slash) into biofuel in sufficient quantities to substitute for coal in a conventional furnace generator of electricity. Estimates have been made that by year 2100 there could be 500 million more hectares of forest planted to meet this demand for biofuel. (see ‘Fuelwood’.)

When a forester evaluates a plantation for tonnage of carbon it stores, the system’s components can be categorized as firstly: seedlings growing until harvest at about forty or eighty years for softwood or hardwood species respectively. Further categories include: stems, branches and leaves that accumulate in the litter layer and eventually within the soil. When areas of the forest are harvested there follows a flush of timber for construction, board, card and paper-making and even waste wood disposed into land-fill pits. A more variable category is the use of wood for fuel that will genuinely substitute for the use of an equivalent amount of energy, the same number of joules, from fossil fuels. Wood, soft or hard and suitably dry, contains at best 20 megajoules per kilogram of potential chemical energy (other fuels for cooking stoves include: charcoal at 30 MJ/kg and kerosene at 46 MJ/kg). The same general forest can bear areas of softwood and hardwood trees. The ages of harvesting schedules can be staggered over a relatively small scale so that the whole forest resembles more closely a natural forest. The potentially higher ecological integrity of such a forest could offset the higher costs of more complex planting, thinning and harvesting.

An example of this trend toward more complex structures of plantations is in Britain. Regulations around felling and replanting now include specified proportions of needle-leaf species (maximum sixty percent) with the remaining area planted with broad-leaf species and with open patches for increasing the diversity of species of plants and animals within the new plantation. Typically there will be opportunities for improving water flow off the land to reduce risk of floods, and provisions made for access to the forest by local people for recreation.

How many tonnes of stored carbon at what cost?
Estimates vary of how well forests, globally, are taking in and storing carbon. These are for forests of the boreal, temperate and tropical regions of the world made during three decades of 1990s to 2000s. This sink, this store of carbon away from our atmosphere, is estimated to be approximately 3.6 billion tonnes of carbon per year. For a sense of scale this should be compared with the source of carbon emissions into out atmosphere from our burning of coal, oil and gas, releasing 7.8 billion tonnes of carbon per year. Clearly trees cannot do all the work of mitigating climate change, but returning carbon back into woody material

is a major contribution and it has scope for forests to store even more. However, this level of storage is calculated to have declined in the 2010s to 3.5 billion tonnes. This is despite increases in area of some temperate and tropical forests. This reduction in the global size of the carbon sink has been caused by disturbances such as forest fires in boreal forests and deforestation in tropical forests.

Tasmanian oak, or mountain ash trees, *Eucalyptus regnans*, in southern Australia. Often grown in plantations for hardwood timber. Credit: Wikimedia, Bob Beale.

There remains much scope for expansion of forested area and the efficiency of the trees within to grow and take up carbon, followed by harvesting and long term use of the wood from the trees. The way that plantation forests are managed is open to innovations aimed specifically at carbon storage. Natural regeneration, reduction of deforestation and the damage of storms and fires all have a contribution to increasing the size of this sink for carbon. Directly organised expansion of forests costs money, lots of it. So there needs to be well developed and financially rewarding markets for the wood as it is harvested from these expanding forests and then used for construction of buildings. These are what economists describe in general terms as *ecosystem services*. Such services are a *public good* in the sense that everyone benefits regardless of whether they paid for the service or not. So economists can put a price on them. An estimate of global size and prices of this market published in 2022, for the 1 to 2 billion tonnes of carbon per year that could be harvested at a cost of US$150 to 200 per tonne of carbon. This is the cost of using forests specifically to sequester carbon. Other methods exist, machines to trap and store carbon dioxide underground, but growing and harvesting trees is likely to remain always the cheapest.

The 3.5 billion tonnes of carbon being taken up and stored as trees is easy for many people to think of as coming from the vast boreal forests of Canada, Scandinavia, Russia, where much of the originally natural forests are now managed for provision timber by harvesting from selected clear-cuts followed by natural or planted regeneration. There are however many other regions of the world where scope for forest expansion has been identified.

Conifer logs from plantations enter a sawmill and will leave as fully processed wooden construction materials for building trades.

Vietnam is a distinct example. Here there are plans, made in 2023 for forests in this country to sequester about 1.4 billion tonnes per year. The plans include the financial value of international trading in carbon-credits. The estimate for this, yearly, to the economy of Vietnam is approximately US$25 billion. Carbon trading is very important for reaching net-zero targets but a topic with a poor reputation: full of economics jargon, open to illegal manipulation … It is beyond the scope of this chapter. Other countries identified for their opportunities for increasing forested areas, afforestation, include some near to Vietnam: such as Laos, Cambodia, Myanmar, Thailand and India. In the Americas such scope for increased forest areas include: Argentina, Brazil, Colombia, Paraguay and Mexico.

China is an example of a country with greatly varied regional scope for increasing forests and much research on the scope for afforestation. The province of Shaanxi in north-central China has recently been evaluated for the potential of carbon sequestration based on forest inventory records from years 2005 to 2025. During that time carbon stored in the forests of that region increased from 207 million tonnes to 285 million tonnes. The prediction was made that from years 2015 to 2060 there would be an increased rate of carbon sequestration from 33.5 tonnes to 46.9 tonnes per hectare of forest. The date of 2060 is significant here: the year in which China has committed to reach net-zero for carbon emission. This is the balance between unavoidable production of greenhouse gases from industrial and domestic life, and the combination of reduced use of fossil fuels and storage of carbon by forests and all other means.

Artificial intelligence methods, machine learning, are now being used to calculate how forest area and rate of carbon sequestration can be increased. Survey data from many thousands of sampling sites in forests can be used predict likely expansion of forest area, the amount of carbon that will be sequestered in the future and the amount of wood, measured as cubic metres of timber that will be harvested for use in construction. Many of these forests, needle-leaf or broad-leaf, that started as natural long ago or started as new plantations, need active management for much of the life of the trees. Conifer species, softwoods, typically need forty to fifty years to mature to suitable size for felling and transport from the forest to a sawmill, there to be transformed into beams, planks, laminated sheet and chip-board. Even the bark of the trees can be stripped off and sold for horticultural uses. Broad-leaf species, the hardwoods, take longer to mature but with time do the same job of storing carbon. They have, per volume of wood, higher commercial value for uses such as furniture making. All this processed wood will continue as a store of carbon for the working life of the wood – another fifty years is an average figure.

Plantation forests are managed from planting to harvest to provide this wood. Access roads need to be created and maintained. Herbivores such as deer and possibly infestations of insects need control. The saplings used to re-stock a clear-felled area, a coupe, are typically set at two metre intervals. Most grow toward the light and form part of the canopy of photosynthetic leaves. Trees that fail to flourish need to be thinned out at repeated stages of growth. At harvest the stumps are left in the ground, contributing to the large stock of carbon that is natural to any fertile soil. The brash or slash of trimmed branches can be gathered and processed into pellets of wood-fuel if machinery is available. This requires work done by machines fuelled with diesel oil. Fully natural forests of the world, far northerly boreal, or deep within tropical rain forests, will continue to do all this work by themselves. For the rest, this balance between the costs and benefits of forestry management depends greatly on the open market for construction timber from a sawmill.

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