Bauhaus Earth

Sustainable Use of Wood in the Construction Sector

Hans Joachim Schellnhuber

Even if, from spring 2020 onwards, the Corona pandemic has driven man-made global warming from the headlines, all indications show that our civilization has maneuvered itself into a global predicament through unchecked fossil fuel consumption. Many imponderables notwithstanding, science today firmly concludes that the global environment begins to feel ill at 1.5 degrees of "Earth fever" and that the natural foundations of human life are threatened if this fever exceeds the 2-degree mark for an extended period. No one likes to imagine a world 4 or 5 °C warmer than today, even though quite realistic scenarios present global society as staggering toward this very world. There is even a non-negligible danger that anthropogenic climate change could develop its own fatal dynamic through powerful feedback loops (such as the self-reinforcing unlocking of carbon reservoirs in the Arctic and the tropics) (Steffen et al., 2018).

Ahead of Us the Hothouse Earth?

In the summer of 2021, the drumbeat from Lytton, a village in the Canadian province of British Columbia, was heard around the world. At the end of June, temperatures there rose to nearly 50 °C, values never recorded in Canada or indeed north of our planet's 50th latitude, since the beginning of instrumental weather recording. On the evening of 30 June, a forest fire broke out near the village, destroying Lytton within hours. There can hardly be a more macabre illustration of the connection between climate change, extreme weather events, and tragedy. In Germany, the terrible July floods in Rhineland-Palatinate and North Rhine-Westphalia have finally

H. J. Schellnhuber (✉)
Potsdam, Germany

International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
e-mail: schellnhuber@iiasa.ac.at

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roused people from their sweet sleep of climate ignorance. Like a monster crawling out from under our bed after a short sleep, climate change is now beginning to attract attention and dismay once again.

In fact, the average temperature at the Earth's surface in 2020 was already 1.25 degrees above the pre-industrial level. So we are moving unchecked towards the guard rails set by the 2015 Paris Climate Agreement and will break through them in a few decades. The faint planetary fever that the industrial revolution has now produced is already inflicting great suffering on the planet's individual creatures in ever more rapid succession: the Australian bushfires of the 2019/20 fire season destroyed over 20% of the continent's forested area and killed about a billion(!) animals of higher species. On 20 September 2017, Hurricane Maria ripped through the island nation of Puerto Rico with winds of around 250 km per hour. Almost 3000 people fell victim to the extreme event and its aftermath; economists estimate that the region's economic development has been set back by 20 years.

In 2020, a record number of 29 tropical cyclones were recorded over the Atlantic Ocean, which is undoubtedly related to the exceptionally high ocean surface temperatures. One more current example was the Mediterranean storm Daniel in September 2023, which caused havoc in Libya in form of heavy rainfall, flooding and devastation. This storm was referred to as a 'medicane', a Mediterranean hurricane, which seems to be a new phenomenon caused by climate change. Due to the rapidly increasing CO_2 content in the atmosphere, the energy balance of the Earth system is severely disturbed, so that our planet absorbs substantially more energy via solar radiation than it can radiate back into space. The excess is stored as heat in all system components, mainly in the oceans (90%) down to depths of 2000 m and more (von Schuckmann et al., 2020). Growing almost unnoticed, this heat giant will accompany humankind for many centuries to come.

Only 2% of the excess energy is currently warming the Earth's atmosphere, while as much as 4% of it is responsible for melting glaciers and sea ice. This is especially noticeable in the Arctic: in 2019, for example, the Greenland Ice Sheet lost mass at a rate of about one million metric tons per minute! And in two decades, the Arctic Ocean might already be completely ice-free during late summer.

"So what?" is what people in Central Europe might think, without reckoning with the jet stream, the band of strong winds that, at an altitude of 10–12 km, separates the cold polar air from the moderately warm air from the tropics around the Equator.

Since the Arctic is warming about three times faster than most other regions of the Earth and the jet stream is ultimately driven by the temperature difference between regional air masses of the Arctic and the Tropics, the westerly wind band is weakening in the meantime and is experiencing huge bulges ("Rossby waves") ever more frequently. If, by chance, these wave bulges become stationary (because they get stuck on the continental shelves, for example), we will have an extreme weather situation that can manifest itself as a biblical heat wave or even a deluge in Europe, North America, or North Asia (the physics behind this critical phenomenon was already discussed in 2013) (Petoukhov et al., 2013).

The Elephant in the Climate Shop

This brings us to Germany, which endured three consecutive years of drought from 2018 onwards. In 2021, by contrast, we experienced a wet episode with tropical-like rainfall, which in western Germany and Belgium led to one of the worst flood disasters in living memory. These direct experiences reflect in a startling way the above-outlined theoretical insights from the physics of climate change. They make evident that the dry heat will return and cause incalculable damage, especially to our forests. In the 1980s, there was talk of forests dying because of acid rain which, thanks to modern filtration technology in fossil-fuel power plants and refineries, has become insignificant today. The current climate-related forest dieback, in which droughts, fires, storms, and pests fatally interact, is more devastating and very difficult to control in the short term.

The information pages of the German Federal Ministry of Food and Agriculture (BMEL) display a sad statistic: some 285,000 hectares of land currently need reforestation in Germany. Mostly spruce stands are affected, but deciduous trees such as the copper beech also show serious to fatal damage. German forests, “built so high up there,” as Joseph von Eichendorff wrote, must be fundamentally transformed if they are to survive in a changed climate. How can this transformation succeed in terms of forest economy, in a way that achieves profitability? The answer lies in the construction sector in Europe and worldwide—the “elephant in the climate shop” which has long been ignored or at least trivialized in environmental debates.

In fact, nearly 40% of the greenhouse gases currently emitted worldwide (primarily CO_2) are produced during the construction, operation, and demolition of buildings and infrastructure. In western industrialized countries, more than half of all waste mass is generated during construction and demolition. And in Germany, about 45 hectares of near-natural land are converted into settlement and transport infrastructure each day, with serious consequences for flora and fauna. Surprisingly, these facts are not part of society’s basic knowledge, although the sight of construction cranes or cement trucks and the noise of jackhammers or concrete mixers have long been part of everyday life in the modern age. In Bertolt Brecht’s words, this could be explained as stupidity eluding perception once it has reached a certain size.

But we can no longer afford climate stupidity or ignorance today. This is why the built environment must play a central role in society’s sustainability strategies—and not only in Germany: if all housing projects planned in Asia, Africa, and Latin America are implemented with conventional methods and materials, with such “modern” building materials as concrete, steel, aluminum, glass, and plastic, then the Paris Agreement will degenerate into multilateral propaganda (WBGU, 2016). The battle to preserve a civilization-bearing Earth climate will be won or lost outside Europe.

Due to its technological, financial, institutional, and diverse cultural capacities, the EU is probably capable of the fastest transformation of its construction sector, thus able to lead the way toward a circular economy in this critical sector. This can be achieved only with some appropriate humility, because the transformation requires harnessing the best the world has to offer by way of traditional and contemporary building styles.

The Geological Journey of C

The climate history of the Earth is primarily a history of carbon (Schellnhuber, 2015). This is why solving the human-made climate problem largely depends on whether and how we get a grip on "God's element" with the chemical symbol C. Figuratively speaking, we need to coax the most powerful of all genies in our planetary environment back into a safe bottle.

For this, it is worth taking a brief but deep look into the Earth's past. In the late Proterozoic, more precisely in the period between 750 and 580 million years ago, there were probably four large-scale or total glaciations of our planet ("Snowball Earth"). The plate tectonic causes of this do not need to interest us here, but the mechanism by which the Earth was able to free itself from the ice cover does: countless volcanoes, especially at the edges of the continental plates, persistently emitted CO_2 whose steady accumulation in the atmosphere was helped by the fact that the snow and ice cover on the Earth's surface significantly reduced CO_2 sequestration through weathering processes. This continuously intensified the greenhouse effect, the atmosphere heated up, and the great melting finally began.

The subsequent Palaeozoic Era (about 540–250 million years ago) was followed by climatic phases of varying warmth. The most significant for the development of our evolved technical civilization was the Carboniferous period (about 360–300 million years before today). With an atmospheric CO_2 concentration about twice as high as today's (i.e., about 800 parts per million or ppm) and a comparable mean temperature of the Earth's surface (about 14–15 degrees), huge forest and swamp landscapes developed. The flora was dominated by various ferns, especially horsetails 20–40 m tall as well as scale and seal trees. This enormous biomass decayed, partly in the absence of oxygen (anaerobic), in the wetlands and formed the basic substance for thick coal seams, which formed biogeochemically over the course of millions of years. Thus accumulated the fuel for the Industrial Revolution, which began in the eighteenth century in England's north-west and in turn, through various waves of innovation, landed us somewhat casually in today's climate emergency.

Ironically, however, the environmental events in the Carboniferous show an ideal solution out of this predicament, which could lead not only to climate stabilization, but even to partial climate restoration. The lush plant life of the Carboniferous extracted more and more CO_2 from the atmosphere through photosynthesis, which, however, was not completely returned to the air due to wet decay but rather accumulated in fossil deposits (see above). In addition, the deep-rooted plants loosened the soils, creating additional weathering surfaces through which atmospheric CO_2 was also extracted. As a result, the CO_2 concentration in the atmosphere dropped to near 100 ppm, which almost led to another major glaciation (Feulner, 2017). These findings of palaeo research make clear how massively the biosphere can influence the global climate system.

Today, it is our civilization that has thrown this system out of kilter within a geologically extremely short period of a few hundred years. Until recently, the global economy was firmly on course to industrially burn, by 2200 at the latest, almost all the fossil energy resources (coal, oil, gas) that had accumulated naturally over hundreds of millions of years. This artificial oxidation event, unprecedented in the Earth's history, would double or even quadruple atmospheric CO_2, depending on the reactions of the individual elements and processes in the planetary system.

In the meantime, however, in nearly all countries the realization is growing that this unwanted environmental experiment is likely to be punished with devastating climate consequences and must therefore be stopped as fast as possible. On the one hand, this means that global greenhouse gas emissions must be reduced to almost zero by 2050 at the latest; and in highly developed industrialized countries like Germany the phase-out of fossil fuels should be achieved even by 2035. For this we already have coherent roadmaps that take account of the relevant sectors and technologies (e.g., Rockström et al., 2017).

Unfortunately, this is no longer sufficient. Due to human activities, too much CO_2 has already accumulated in the atmosphere, with today's concentration at 420 ppm or about 50% above the pre-industrial level. The associated increase the Earth's mean surface temperature, as already mentioned, is about 1.2 degrees—with the damaging effects described in the first section. A few years ago, the Intergovernmental Panel on Climate Change (IPCC) estimated how these consequences would come to a head beyond the 1.5-degree level and how it might still be possible to hold this forward defense line against global environmental chaos (IPCC, 2018). The result is clear: in addition to the rapid decarbonization of all sectors of the economy we need extensive "negative emissions," that is, processes in which CO_2 is actively removed from the atmosphere.

These processes should be initiated as soon as possible and may have to be sustained for many decades. However, the largely technical approaches discussed so far are rather naive to the point of being scary: the IPCC itself is backing the so-called BECCS process (e.g., IPCC, 2014). In this process, biomass is to be produced on a large scale, the energy stored in it is to be extracted, the remaining carbon is to be captured and deposited somewhere (!) for the long term. A convincing potential-cost analysis for this proposal is still lacking. Even more absurd to my mind are certain geo-engineering processes (Lawrence et al., 2018) in which huge amounts of CO_2 are to be directly removed from the atmosphere by physical-chemical processes. For this, however, a global infrastructure would have to be financed and built from scratch, which would not create any significant value apart from "air washing" and would ultimately degenerate into the biggest technological ruin of all time.

An elaborate synopsis and evaluation of all the existing 1.5-degree scenarios has recently shown that the technical extraction of CO_2 is often sold as an illusory solution to the climate dilemma and that there is generally no single robust strategy for the full implementation of the Paris Agreement (Warszawski et al., 2021). This is precisely where the idea of *turning the built environment into a powerful carbon* *sink* comes in—making a virtue of necessity! For if organic materials were to be used as much as possible as construction materials for future buildings and infrastructure, then one could not merely avert enormous amounts of greenhouse gas emissions that are generated in the production of concrete, steel, etc., but could also additionally capture historic CO_2 emissions from the atmosphere via photosynthesis. In addition, the carbon bound through photosynthesis during plant growth would be safely stored long-term in buildings and products.

The unique advantage over other ways of generating negative emissions lies in the fact that climate protection would here come as a welcome side effect of meaningful and attractive value creation—making this a genuine win-win option.

I discuss the most important aspects of this potentially decisive weapon in the fight against global warming in the next sections. The first systematic assessment of this novel approach has recently been published by an international researcher group that I initiated (Churkina et al., 2020). The almost frighteningly large vision behind it is based on carbon's above-outlined journey through the Earth's ages: a climatically meaningful amount of carbon—the constituent of life on our planet, after all—would be laid to rest for centuries in "built forests" and similar civilizational constructs after passing through many stages (volcanoes, palaeo-atmosphere, biosphere of the Carboniferous Age, fossil deposits, recent atmosphere). In this way, the cooling effect of natural carbon extraction some 300 million years ago could be replayed, as it were, as a large-scale cultural project in time lapse. Figure 1 summarizes the central insights of this section as a planetary infographic.

This could "initially" return the climate to the range of the Holocene—which began about 11,700 years ago and, due to its stable environmental conditions, enabled the explosive development of human culture (Neolithic Revolution). This would probably mean a centuries-long slide, with tenths-of-a-degree steps out of the risk zone. Apart from the climate issue, the move away from fossil-intensive construction also offers a great opportunity to completely rethink modernity in one of its core aspects. More on this in the last two sections of this article.

Bio-Based Architecture

It is clear from the above that a royal road to climate protection should lead directly through the construction sites of the world. As I recently noted in an essay, there has long been a signpost to this effect in my immediate neighborhood, namely in idyllic Caputh near the Schwielowsee (Schellnhuber, 2021a). We are talking about Einstein's summer house, which the architect Wachsmann built out of wood in 1929 at the express wish of the physicist of the century. The main materials used were timber of Californian redwood and Galician fir; peat panels were used to insulate the walls. This place has a magical aura and once again exemplifies Einstein's farsightedness outside the natural sciences: barely 100 years before Greta Thunberg's climate strike, he chose the building materials with which we can contain global warming.

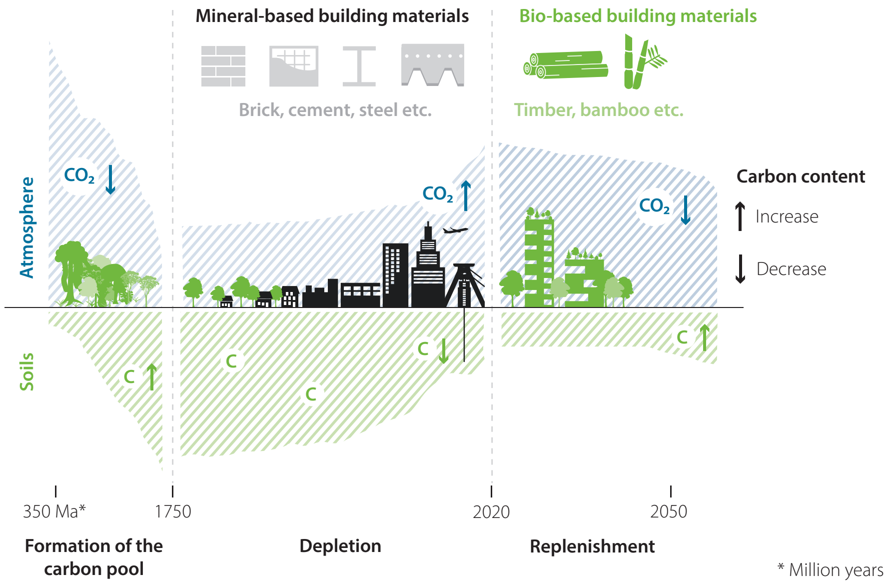

Fig. 1 Over millions of years, the carbon pool formed on land (left). Due to this process and other mechanisms (such as the weathering of rocks), the CO_2 content of the atmosphere slowly decreased. Middle: The urban and industrial growth triggered by the Industrial Revolution gradually depleted the carbon stock on land and increased the CO_2 concentration in the atmosphere again. The towering and load-bearing urban buildings of concrete and steel, made with raw materials and fuels from ever deeper layers of the Earth's crust, consume a lot of energy and cause high greenhouse gas emissions. Right: Settlements built from bio-based materials such as wood and bamboo can serve as artificial carbon sinks. The storage and conservation of carbon in the built environment will help replenish terrestrial C stores, thus reducing current atmospheric CO_2 concentrations or offsetting future emissions (Churkina et al., 2020)

Konrad Ludwig Wachsmann, the architect of Einstein's house, was chief architect of a company specializing in wooden buildings in Upper Lusatia from 1926 onwards. Because of his Jewish origins, he emigrated to the U.S. in 1941, where he met a certain Gropius. Together, the two developed a prefabricated wooden house system (General Panel System) that supposedly enabled five unskilled workers to completely erect a house in just under 9 hours. But Walter Gropius, born in Berlin in 1883, left a broader mark in architectural history. In 1919, he founded the Staatliches Bauhaus in Weimar as a school of art that, through its concept, aspirations, and impact, revolutionized the construction sector of the twentieth century as the New Bauhaus Movement.

Today, the name Bauhaus is usually identified with brutalist reinforced concrete constructions of the post-war period or even with a cheap hardware store chain that has been spreading across Europe's industrial areas since 1960. Wachsmann's masterful use of organic materials has been all but forgotten, and timber construction itself has largely disappeared from the modern cityscape. Even agricultural barns are now hardly ever carpentered but cast and assembled from mineral materials.

This systemic change, especially in commercial and private multi-story construction, took place around 1900 for many different reasons, of which at least three had a decisive joint effect.

First, with the trend in the construction sector toward serial industrial production of elements that are as uniform and homogeneous as possible (see, for example, the famous GDR type WBS 70 board), the particular substance wood quickly fell into disuse. This is because organic substances reflect the evolutionary complexity of life itself: they are depth-structured, anisotropic, and environmentally dynamic—to name just a few characteristic properties. However, these "competitive disadvantages" can be transformed into significant advantages in a highly intelligent building industry, the contours of which are already becoming visible today (see below).

Second, the development of enormous fossil energy resources (especially oil from the Middle East) for the world market from around 1960 onward enabled the comparatively cheap production of concrete, steel, aluminum, glass, plastic, and other non-sustainable building materials. Associated "externalities"—such as the destabilization of the global climate through massive greenhouse gas emissions—were of course not included in the individual cost-benefit calculations of the relevant companies.

Third, the same energy glut forced the historically unprecedented use of heavy machinery in civil engineering. Growing up, I often had to help my father (a master glazier with a penchant for creativity) on building sites after school and experienced how individual physical strength and dexterity were increasingly displaced by diesel-smelling equipment with rough bearings.

And this is how, in the second half of the twentieth century, construction became reliant on rather crude but ubiquitously available and always compliant materials. Expert or even artistic design has retreated almost exclusively to spectacular niche projects for luxury and prestige. To be fair, this has created affordable and hygienic housing for the masses (at least in the Western economies), but should this really be the end of architectural history? Apart from preserving the natural foundations of life, doesn't humanity also need built culture in its environment, that is, a milieu that comforts the soul even in everyday life?

But let us first return to the scientific analysis of the climate problem. As far as building materials are concerned, the all-important difference is expressed in the following three process equations:

$$\text{Iron ore smelting (Davis et al., 2018)} > 2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2 \uparrow \quad (1)$$

$$\text{Lime burning}\, 1000\,^\circ C > CaCO \rightarrow CaO + CO \uparrow Q = 181\, kJ * mol^{-1} \quad (2)$$

$$\text{Photosynthesis} > 6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \quad (3)$$

The laws of chemistry themselves thus dictate CO_2 emissions, which are inextricably linked to the conventional production of reinforced concrete; the laws of biophysics themselves force CO_2 uptake, which is inextricably linked to the growth of biomass! This fundamental asymmetry in greenhouse effect alone justifies the transition from mineral to organic building materials (such as wood, bamboo, jute, flax, hemp, lichen, algae, etc.). Or, to put it casually, if you had the choice between a climate-destroying material and a climate-healing one that tends to have even better properties (see below), which would you choose?

Incidentally, the energy required for the production, transport, processing, and assembly of building materials does not play a fundamental role in such a comparison: we graciously assume that in this respect the mineral-based economy will also quickly switch to the use of renewable energies without direct greenhouse gas emissions. The largely climate-neutral production of steel with "green hydrogen" would play a more systemic role in this context; but thus far this approach is more hype than based on evidence. The promises of the concrete industry and other relevant sectors to offset their CO_2 emissions through reforestation projects in exotic parts of the world are a dead end: why not use sustainably produced wood directly in construction? In general, the conventional construction sector's rhetoric of sustainability is unconvincing (e.g., The Concrete Imitative, 2021), but the economic and political significance of this well-organized industry is enormous.

Not least, stale myths about organic architecture in general and timber construction in particular play into its hand: that timber is much more vulnerable to fire, earthquakes, storms, and insects than reinforced concrete; that timber does not allow large constructions due to its lack of load-bearing capacity and dimensional stability; that wooden houses pose insuperable problems to sound insulation; that the whole thing would be too expensive anyway; and that wood will soon be in short supply worldwide. Many of these bluntly parroted prejudices are as groundless—and as effective—as the slogans that were used for many years to discredit the sustainable transformation of the energy and transport system. As late as the 1990s, people in Germany were still claiming, without good reason, that the local electricity supply from wind and sun would never exceed 4% of total electricity demand. In 2022, this share was already between 37% and 38% (Enerdata, 2023).

The built environment, too, is blighted by a twisted vision of progress, exemplified when ingenious architects and engineers, contracted by autocrats or oligarchs, erect futuristic buildings of concrete, steel, and glass reaching up into the sky. But when bourgeois medium-sized companies dare build an 8-story administration building made of solid wood on behalf of a Rhineland municipality, skepticism abounds: visionary work should be left to California charismatics.

Fortunately, the enlightenment has now arrived even in the world of architecture. Through a mutually accelerating interplay of practical experience and research-led innovation, the myths listed above have been largely debunked. Unfortunately, the relevant information is mostly buried in specialist journals and project reports; but the volume of literature comprehensible to the interested layperson is also growing. Exemplary here are the current books by Pablo van der Lugt, in which almost all critical aspects of bio-based construction are addressed with numerous references to pertinent original works (van der Lugt, 2020).

The greatest reservations about timber construction are related to the latent fear of urban fires, which has become a collective trauma over the centuries, especially in Europe. A case in point is the "Great Fire of London," which destroyed about four fifths of the still largely medieval city within a few days in September 1666. The fire broke out at night in a bakery in Pudding Lane and, due to incompetence on the part of the authorities, quickly developed into an inferno. It doesn't take divine wrath, just a little human stupidity and arrogance to unleash hell on Earth.

With appropriate knowledge and care, on the other hand, bio-based materials can nowadays be installed in a fire-safe manner. Important criteria such as flammability, structural fire stability, fire propagation dynamics, etc., must be assessed and considered in the design. Essential in this context is a holistic examination of the building's core and its casing because modern fire disasters often involve the cladding (the 2017 "Grenfell Tower Fire," also in London, is an example). This is not a technical paper on fire safety, so I refer to the technical literature (such as the website of "Informationsdienst Holz" with articles on "Fire protection in timber construction" etc. (von Winter, 2013)). Here it suffices to point out that, when exposed to fire, solid wood forms a protective surface layer of charcoal which usually slows down or prevents the fire's further advance. This response can be understood as an evolutionary adaptation of tree species to the ubiquitous oxidation risk associated with the equally evolutionary accumulation of oxygen in the atmosphere (Lenton & Watson, 2011).

Of course, active fire protection systems (such as sensor-supported sprinkler systems) can and will also be used in organic construction. Perhaps more important, however, is "passive" fire prevention through appropriate building safety design, adapted to the building's particular purposes and the actually chosen bio-based materials (see below). Similarly for sound insulation: design and composition must consider and exploit the physical building conditions, sometimes down to subtle and seemingly unimportant aspects. At first, this seems to be a disadvantage compared to conventional building, but with advanced digital methods it may well be turned into an advantage (there is more to be said about this, too). Special attention should be paid to the construction of floors and ceilings.

While wood conducts sound well, as can be experienced during a violin concert, its thermal conductivity is very low. The relevant technical parameter in this context is the so-called thermal resistance R which, for building components, should be as low as possible. For comparison: R is 50 for steel, 1.9 for concrete, and only 0.1–0.2 for wood, depending on tree type. This comparative advantage is cleverly used in the design of timber constructions, especially when these are to meet especially demanding requirements. A spectacular example is the Filmarchiv Austria, which was realized in 2004 with organic architecture and whose inside temperature must be kept within a 2-degree range year-round (Thoma, 2016). In everyday construction, wood is used for windows and exterior doors because of their good insulating properties.

But now to the question of all questions: what about gravity? How big and, above all, how high can one safely build with organic materials? Well, certainly bigger and higher than is commonly assumed—and this applies not only to the present and the future. Probably the most impressive historical example is the Sakyamuni wooden pagoda in Shuozhou (China). It was built in 1056, has 9 stories and towers 67 m high (including the base and top)! The European counterpart is the beautiful Heddal

Stave Church (Norway), often referred to as a "Gothic pine cathedral." This church was probably consecrated in 1242 and measures 26 m.

For the reasons outlined above, timber construction has for long been shunned in the modern industrial age. But today we witness a dramatic development to which the invention and spread of new types of wood materials (engineered and modified wood) have contributed decisively. This progress in a rather traditional industry stands in striking contrast to the aversion to innovation that, according to experts and insiders, has pervaded the success-saturated mineral construction industry for decades. The key innovation is simple but compelling: instead of, like in the past, searching for the optimal tree that can be sawn to size and installed directly, today's construction involves the composition of suitable wood elements. Solid wood materials, whose structural elements are joined and fixed together by glues, dowels, nails, etc., are becoming increasingly important. This approach is certainly reminiscent of the "additive manufacturing" of consumer goods (vulgo: 3D printing), in which the desired object is not created by milling off a blank, etc., but by skillfully assembling the necessary ingredients in a material-saving way.

It all began quite humbly in the mid nineteenth century in Thuringia with the serial production of plywood from wood veneer panels that were glued and pressed together perpendicular to the grain direction. This made it possible to largely "lock" the material dynamics through swelling and shrinkage under the influence of environmental fluctuations (in temperature, humidity, etc.) and to achieve a high dimensional stability. The process was simple, and the corresponding products were considered functional but inferior compared to objects made of grown solid wood. Since then, the approach has gained dramatically in importance and reputation, especially with the post-1990 introduction and perfection of cross-laminated timber (Fig. 2) in Germany and Austria (e.g., Schickhofer, 2013). These are suitably dimensioned solid wood panels made of at least three crossed board layers, which can be prefabricated in the factory and used in construction for almost all components

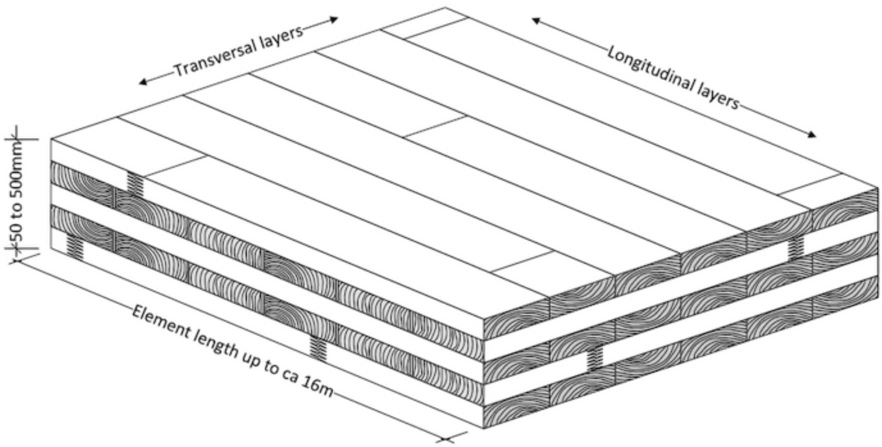

Fig. 2 Schematic representation of cross laminated timber (Schmid et al., 2018)

(exterior and interior walls, roof trusses, ceilings, railings, balconies, façades, etc.). The construction principle, which is as simple as it is ingenious, largely compensates for the natural heterogeneity and anisotropy of raw wood—almost any desired property (stiffness, strength, elasticity, fire resistance, etc.) can be realized through design and choice of material.

In addition to cross-laminated timber, there is today a whole arsenal of solid wood, veneer, chipboard, and wood fiber materials to choose from for almost every application. There is also a whole range of composite materials in which, for example, wood fragments are mixed with concrete or plastic. However, these are practically non-recyclable and therefore unacceptable for sustainable construction.

Ever since the creation of the New York skyline of skyscrapers in 1908, "modern" construction has been associated with high-rise buildings. Today, projects around the world that make use of the approaches just outlined prove that such architectural feats can also be achieved with wood. In Heilbronn, Germany, there is already the "Skaio", a 34-m-tall 10-story residential building made of organic material. In Hamburg's Hafencity, an eco-skyscraper is now rising to a height of 65 m. For Berlin-Schöneberg, the "WoHo" is planned, a 98-m hybrid timber building that will offer 29 floors of commercial and living space for all income levels. In Vienna-Donaustadt, the namesake "HoHo" has been in existence since 2019 and already towers 84 m. This makes it the second tallest wooden building in the world after "Mjostarnet" in Brumunddal, Norway (85.4 metres, 18 stories), which was completed in the same year.

These buildings will soon be overshadowed by a wooden skyscraper (strengthened with reinforced concrete) that, commissioned by software company Atlassian, will rise to 180 m near Sydney's central railway station. In Chicago, the true home of skyscrapers, 228 m is the target for a similar construction. And in Japan, the "PlyscraperW350" is being planned as the 350-m-tall new headquarters of a traditional timber construction company. Apparently, one of the most earthquake-prone countries in the world trusts the fabulous stability properties of cross-laminated timber.

If we look back at the less spectacular, but much more climate-relevant mass residential construction in Germany, we observe a rapid and encouraging development, especially in the area of detached and semi-detached houses. Of the total number of new buildings approved in this category in Germany in 2020 (105,962), 22.2% were prefabricated timber houses—with even much higher proportions in Baden-Württemberg (38.4%) and Hesse (32.4%)! In multi-story buildings, on the other hand, the relative market volume of timber construction is still an order of magnitude smaller. A similar picture emerges in commercial construction, where timber as a material is somewhat on the retreat in agriculture (e.g., barns), but is increasingly used for other commercial buildings.

Timber construction is also continuing to advance in other European countries (especially Austria, Switzerland, and Scandinavia). In North America, the corresponding building materials (mainly sawn timber from conifers) are traditionally popular in family housing. However, solid wood is hardly ever used, which has a negative to catastrophic effect on comfort, safety, durability, and environmental compatibility. Such lightweight construction is evidently due to the desire to keep the costs of a suburban home with a double garage as low as possible. Yet it is already possible to build high-quality timber houses at very competitive prices, as is to be demonstrated on a large scale in the so-called Schumacher Quartier on the former Berlin-Tegel airfield. It is planned to build 5000 flats for 10,000 people there in timber construction over the next 10–12 years—and about 20% cheaper than conventional construction (Tegel Projekt GmbH, 2020, 2021).

In general, the killer argument, that sustainable business is always more expensive than working with fossil fuels and extracted minerals and therefore a doomed elite project, will not save the concrete industry from extinction. In contrast to building with organic materials today, photovoltaic power generation, for example, was still hopelessly uncompetitive with its climate-damaging rivals (especially coal-fired power) 30 years ago. However, targeted political support (such as the legendary German Renewable Energy Sources Act of 2000) and a vibrant innovation dynamic triggered by it have pushed the production costs for solar power at favorable locations into a range that is unattainable for fossil energy sources. And this does not even take account of the "externalities": the enormous losses to the common good (climate damage, illnesses, ecosystem destruction, etc.) caused by electricity generation with coal, oil, or gas! If the learning curve of the sustainable building industry is now steeply bent upwards through improved framework conditions, increased research and development (R&D) activities, and economies of scale, there will no longer be any socio-economic reason to continue building in the dismal post-war style.

This sets in motion a self-reinforcing innovation spiral that will also help overcome the other challenges to "alternative" construction. In addition to resistance to earthquakes, hurricanes, and vibrations, this also involves the less spectacular but enormously important protection against fungal attack, insects, moisture, etc. Whereas before the turn of the millennium, aggressive chemical interventions were still heavily relied on here, ever-improving thermal processes are now being developed which remove, even before the wood is installed, many wood constituents that could later attract pests (such as woodworms). Furthermore, such treatment ensures that the wood moisture content remains permanently below the critical level of 20%, which stops the advance of fungi and microbes. Comparable results with concrete buildings are often only achieved through problematic coatings.

It is noteworthy in this context that innovations in organic construction also aim to avoid as far as possible substances harmful to climate or health. In the past, such substances were used on a massive scale in the gluing of wooden elements. Research, development, and practice have not yet been able to completely overcome this substance problem, but several solutions are already emerging (see, for example, the publications of the Fraunhofer Institute for Wood Research WKI).

Forestry's Transition Toward Sustainability

As explained above, large-scale bio-based architecture is not only technically and operationally possible but could well dominate building in the twenty-first century. However, we must now face an objection that is raised in every relevant discussion right after the allegedly uncontrollable fire problem: there would not be enough organic building material—in Germany, in Europe, worldwide—for the desired transformation. Or rather, the necessary quantities could only be procured through a brutal industrial plantation system. The latter would not only counteract climate protection itself, but also trample on other key sustainability goals such as the preservation of biodiversity.

In 2021, this skeptical attitude has stiffened even further. On the one hand, this is due to price volatility on timber markets, which is related to some mainly temporary special factors: massive shifts in demand due to the COVID-19 pandemic, disruptions in the global supply chain system, reduction in sawing capacity in the wake of the 2008 financial crisis, forest fires and bark beetle infestations in North America, etc.

On the other hand, some activists and nature conservation associations have recently intensified their campaigns for a purist forest policy. Two ideas seem to be central to this. First, that "the forest," in contrast to farmland, is a piece of "pure nature"; and second, that forest ecosystems undisturbed by humans store the most carbon.

Both ideas are romantic misconceptions. If we look at Western Europe, for instance, we find only tiny remnants of post-glacial (or even pre-glacial) primary forests ("primeval forests"). And if we look at the whole continent, it hardly looks any different. Only Finland and the Carpathian arc still have significant original forest areas, dominated by conifers in the former case and deciduous trees (mainly beech) in the latter. According to the WWF, 6000 years ago, 80% of Europe was covered with forest. Today, about 40% of our continent is still forested, and less than 0.2% of this area is primeval forest. Germany has no primary forests left at all; of its 11.4 million hectares of forest area 94% are even actively managed.

As far as the storage capacity of forests is concerned, a fundamental error is often made—consciously or unconsciously—by not considering the entire system cycle. Of course, a tree can only absorb atmospheric CO_2 so long as it forms additional photosynthetic biomass: grows in height, width, or depth. After the plant has matured, the carbon remains stored for decades to millennia, depending on the species, until decay finally sets in. Then the tree falls and rots, the CO_2 returns to the atmosphere, and space is made for the regrowth of the same species or competing species. Without human influence, forest ecosystems mature after 600–2000 years (!) in a dynamic equilibrium, with a natural distribution of species and ages according to site conditions. The carbon content of these systems remains largely constant over long periods through balanced supply and removal of CO_2.

By contrast, through the targeted extraction of biomass by means of sensible management, an autonomous ecosystem can be transformed into a driven one (in the sense of control theory) that can organize a net flow of carbon from the atmosphere into a stock of long-lasting material assets (wooden houses, roof trusses, wood-based materials, furniture, etc.). With the right planting and felling strategy, maximum growth (and thus maximum CO_2 extraction) is ideally achieved on a permanent basis. And the conversion of harvested biomass into useful objects takes the place of rotting—with the crucial difference that the re-release of CO_2 does not occur until several centuries later. The terrestrial dwell time of atmospheric carbon is thus artificially stretched, buying humanity valuable time in the fight against global warming! In the next section, I will explain this approach further with the help of a system diagram.

But of course, the size of the climate protection effect outlined above depends on the extent and nature of the forest area used. After many years in which the challenge of a transformative global land use strategy was often trivialized to a simple call to individual actors ("Let's plant a tree!"), a serious debate on deforestation and reforestation has finally begun. The research group led by Jean-Francois Bastin of ETH Zurich made an important contribution to this with their assessment of the "Earth's tree restoration potential" (Bastin et al., 2019)—although (or perhaps because) the publication attracted massive criticism from specialist colleagues. Based on extensive empirical data sets and with the help of machine algorithms, the scientists developed a model that identifies the potential geographical forestation cells worldwide with relatively high resolution (30 arc seconds). The model even calculates the respective percentage area of tree canopy, which increases from 0% in dry deserts to 100% in dense equatorial forests.

Result of the study: under today's climate conditions, 4.4 billion hectares of the Earth's land surface could be covered by trees. If one subtracts from this the existing canopy area (2.8 billion hectares) as well as the land currently occupied by agriculture and settlement, then an estimated 0.9 billion hectares remain. On this globally scattered area (see Fig. 3), afforestation or reforestation could in principle take place in the sense of a global repair measure. More than half of the potential is concentrated in just six countries (Russia, USA, Canada, Australia, Brazil, and China).

According to the study, if this potential were fully exploited, the added forest areas, when fully grown, would store additional 205 gigatonnes of carbon. If this vegetation were to continue to exist (without the biomass decoupling described above), this alone could compensate for more than two thirds of the CO_2 budget that would still be available to our civilization if the 2-degree guard rail were to be observed. If the newly created forests were mainly used for the regenerative production of raw materials for organic construction, demand could be met on a large scale (see below).

Desertified areas could prove to be a wild card in the great reforestation game, especially dry subtropical areas that once were more or less densely forested. Australian agronomist Tony Rinaudo received the "Alternative Nobel Prize" in 2018 for his conceptual and practical contributions to the revitalization of deserts (especially in West Africa). His work is driven by two critical insights. One is his rediscovery of the "subterranean forest" during the terrible Sahel drought of the 1970s. During an excursion in Niger, he noticed the scattered low bushes sprouting

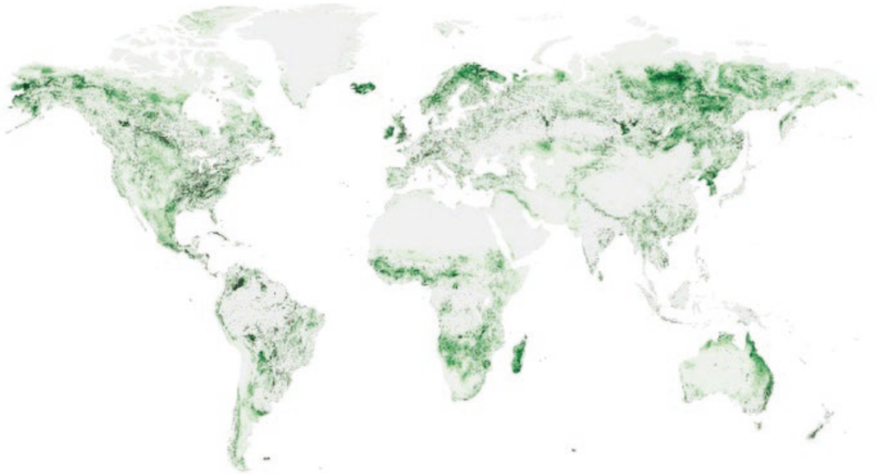

Fig. 3 The global reforestation potential. Today's existing tree cover as well as agricultural and urban areas according to GlobCover were subtracted from the worldwide potential tree cover (Bastin et al., 2019)

from the seemingly sterile desert floor. On closer inspection, these turned out to be branches of living tree roots hidden by the sand. With a simple knife, these roots can be pruned so that young trees sprout from them again. And indeed, there are millions and millions of hidden tree trunks in the Sahel and also in India, Brazil, Australia, etc.

Rinaudo's other critical insight is that reforestation of suitable areas should be realized by and for local farmers (FMNR—*Farmer Managed Natural Regeneration*). Often, large-scale governmental or international reforestation campaigns fail in the Global South because imported tree nursery plants are introduced into the dry soil and then irrigated at enormous expense in people and material. Behind the planting front, which continues to move, a high percentage of the young trees usually die. Rinaudo's double-local approach, however, has been crowned with great success. FMNR has already reclaimed over 20 million hectares of forest in several African countries!

More spectacular, but rather utopian by contrast, is the project of the "Weather Makers," a Dutch company of engineers of a special kind (Rose, 2020). This group around co-founder Van der Hoeven wants to reforest about half of Egypt's Sinai Peninsula, an area of about 3 million hectares. What seems insane at first glance becomes possible on closer inspection. For the now desolate peninsula was still green until a few millennia ago, and satellite images reveal ancient river networks that apparently collected abundant precipitation and transported it to the Mediterranean. Presumably due to unsustainable human practices (excessive use of biomass, overgrazing, etc.), the vegetation disappeared, the soils eroded, and fertile humus was washed away—partly into the large mud lake Bardawil on the north coast. The sediments of this lake, now dozens of meters thick, will be the starting point of the restoration campaign by Van der Hoeven and his fellow campaigners.

Their bold undertaking is inspired by China's remarkably successful attempt to re-vegetate the legendary loess plateau in the center of the country and thereby to stop the soil erosion that has prevailed there for a millennium, giving the mighty Huang He ("Yellow River") its name. With massive support from the World Bank, which provided 300 million US dollars as part of a 12-year project, a breathtaking restoration campaign took place in the former granary of the Middle Kingdom. With relatively simple measures (tree planting, terracing, soil enrichment with organic carbon, water retention, and pasture management), the conversion of almost 1 million hectares of desert into a vital ecosystem was achieved by the end of the campaign in 2009. This gives hope for many degraded areas around the world, which may be transformed back into fertile and site-appropriate forested landscapes sooner than had long been assumed (e.g., Blaustein, 2018).

This is precisely why the United Nations has called for the *Decade of Ecosystem Restoration,* which aims to revegetate around 350 million hectares of degraded land by 2030, thereby removing up to 26 billion tonnes of carbon from the atmosphere.

However, forestry calculations should not be made without the climate economist. Bastin et al. estimate that in the most pessimistic of the common emission scenarios (RCP 8.5), the Earth's tree carrying capacity would shrink by over 200 million hectares compared to today. In this case, large increases in boreal forests (e.g., in Siberia) due to climate change would be offset by even larger losses of tree crowns in the tropical rainforests (e.g., in the Amazon region). However, the authors themselves emphasize that the corresponding model calculations involve enormous uncertainties and do not satisfactorily model a whole slew of processes, disturbances, and feedbacks. Nonetheless, based on this analysis, there does not seem to be a fundamental shortage of forest development options.

On the other hand, in view of the existential importance of the topic, one can by no means be satisfied with the current state of scientific knowledge. As already indicated, the study has provoked numerous responses from colleagues in the field, who point out various shortcomings in terms of content and methodology. Whoever is ultimately right on the individual points, the research has been set in motion. At the Potsdam Institute for Climate Impact Research, we are currently trying to accelerate it by asking how much forest area would actually be needed for timber harvesting in the various scenarios of climate-positive transformation of the building sector. The starting point is the work by Churkina et al., already cited above, which estimates the global carbon sink effect of organic architecture. In the most recent follow-up study (Mishra et al., 2022), a scenario is developed in which 90% of the new residential and commercial buildings constructed by the end of the century are made largely of wood. The background is a plausible socio-economic development of the world society, in which humanity's degree of urbanization rises to 80%.

The quantitative analysis is performed with the integrated model complex MAgPIE which simulates the cost-optimal global production of food, feed, bioenergy, and timber in the twenty-first century. Special attention is paid to the terrestrial biosphere, where the dynamics of managed forest systems and the behavior of natural vegetation (primary and secondary forests, non-forested vegetation areas) must be modelled. The calculations are based on extensive data sets from international organizations (FAO, IUCN, UNESCO, etc.). The latter indicate, among other things, the areas that are highly productive for agriculture and those that should be off-limits to forestry for various reasons (intact natural forests, hotspots of biodiversity, retreat areas of indigenous cultures, etc.).

The most important result of the model calculations is that the renewable raw materials needed for the "wooden cities" can be provided without grossly violating other sustainability goals. However, the productivity of the cultivated areas would have to be increased through appropriate measures and investments, and a considerable expansion of global forest plantations would be needed. Concretely, up to 143 million hectares of such plantations would have to be newly established by 2100 (see Fig. 4 for the optimal geographical distribution).

The necessary areas could be taken primarily from unprotected or degraded forests and non-forested areas with low biodiversity. In addition, our model simulation envisions a shrinking of pasture areas, which would have a twofold emission reduction effect, especially in the beef industry. Timber harvesting in the 90% scenario (90 pc in Fig. 4) could save 122 billion tonnes of CO_2 by the end of the century—this alone would relieve the carbon budget agreed with the 2-degree guard rail by about 11%! Obviously, the share in relation to the 1.5-degree budget would be much

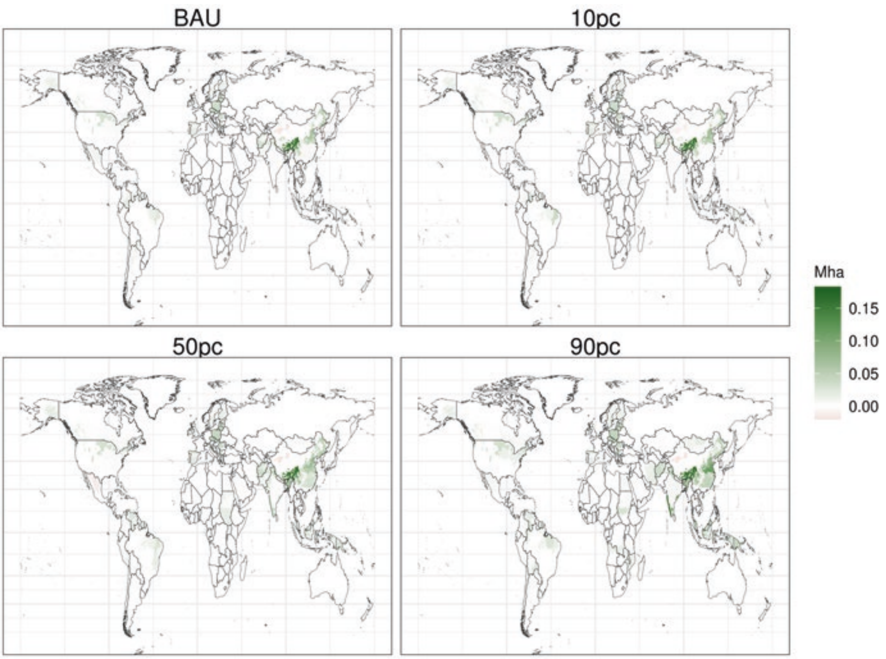

Fig. 4 Difference in forest area in million hectares (Mha) between 2100 and 2020. Shades of green represent the increase in plantation area in 2100 compared to 2020 (Mishra et al., 2022)

larger still. Thus, on a global scale, it becomes clear that bio-based settlements can make a substantial and feasible contribution to climate stabilization and restoration.

Accordingly, more and more studies have recently been devoted to the question of the basic availability of organic building materials, whereby very different aspects are being considered. The relationship between production and suitability of the plant types in question is of special interest. In Germany, for example, under the current climate conditions, 75% of the forest areas would naturally be covered with beech and 17% with oak. Spruce would only occur at altitudes above 700 m. Contemporary forestry turns this distribution upside down, because currently 25% of our forest areas are planted with spruce and 23% with pine! (Richter, 2021) In spite of all the romanticization, the "German forest" is a highly artificial thing whose construction began in early eighteenth century (see the legendary *Sylvicultura oeconomica* by Hans Carl von Carlowitz (2013/22)). The main criteria for management were rapid growth to make up for the forest losses of the previous centuries and good material properties for building and furniture production. The clear winner in this competition was the spruce, whose suitability is still raved about by modern timber architects, but the existence of this tree in the Central European lowlands is seriously threatened by human-made environmental changes.

Is this why the age of the beech is dawning, at least in Germany? This is by no means certain, because climate change seems to be affecting this deciduous tree—in contrast to the oak—more than predicted. Nevertheless, beech will probably play an important role in forestry in the future. So far, however, the construction industry has been reluctant to make friends with this wood, but that could change: since 2014, the Thuringian company Pollmeier has been offering the wood material "BauBuche" (building beech), which is produced by completely peeling open the tree trunks and skillfully smoothing, pressing, cutting, and gluing the resulting thin strips. This technique produces a very homogeneous material with a load-bearing capacity close to that of reinforced concrete. In addition, the approach is extremely resource-efficient, which in turn drives down costs. However, "BauBuche" and its undoubtedly numerous successors in the hardwood industry must be used optimally, which in turn is only possible if architects and engineers learn to handle the new material, and the state building codes no longer block the corresponding innovations.

Besides beech as a renewable raw material, we need to think about other tree species that can withstand global warming, serve the relevant value chains, and provide vital ecosystem services. Oak wood, for instance, is well suited for construction, but difficult to work because of its hardness. New processes and production facilities will probably also have to be created for the increased use of pine. The elastic all-rounder ash has recently been threatened by various pests that have migrated to Central Europe (such as the fungus *Hymenoscyphus pseudoalbidus*, which originated in Japan). Contemporary strategies for the conservation and utilization of native species are therefore needed, but the carefully considered introduction of tree types of non-European origin must not be taboo either if forestry is to keep pace with the enormous global dynamics. In this context, experts often mention the robinia (origin: North America; preferred climate: warm, moderately humid; properties: flexible, resilient, and rot-resistant wood) and the bluebell tree (origin: China; preferred climate: warm-dry; properties: fast-growing, light, stable, and fire-resistant wood).

Twenty-first century forestry faces the unprecedented challenge of composing location-appropriate forest ecosystems from many species and age classes to meet a variety of objectives. This is a veritable paradigm shift: less than one third of European forested land has trees of diverse ages; 30% are plantations with only one tree species, 51% still have two or three species, and only 5% are home to six or more tree species (Science for Environment Policy, 2021)!

But even the fate of the spruce, the conventional bread tree of German forestry, is not sealed. A recently published research paper runs through different variants of a national forestry strategy for Great Britain, which would allow 30,000 hectares of land to be replanted annually in the period from 2020 to 2050 (Foster et al., 2021). This study provides a wealth of interesting insights, but above all shows that newly planted commercial coniferous forests have by far the greatest potential as carbon sinks. This is so because the most important factor in realizing "natural" negative emissions is identified as the growth rate of the ecosystem under consideration. But this takes a long time: the cumulative climate protection effect of stands with continuous logging exceeds that of unused stands only after 120 years. The study is hopefully the prelude to a whole series of analyses that will also map Europe's biogeographical diversity.

So, while there is much to suggest that carefully managed forests in temperate climate zones can contribute significantly to climate restoration, there is a heated scientific-political debate about the tropics and subtropics. The "naturalist" position, which vehemently advocates the permanent non-use of reforested areas, is represented by environmental researchers such as Simon Lewis (Lewis et al., 2019). But the arguments against plantations do not consider the important option of biomass processing into durable products such as building materials. At the same time, this option must evidently be assessed differently in the Global South than, for example, in Europe: tropical hardwood cannot play the same value-added role as softwood from temperate climates due to its ecological properties and economic conditions, as must be discussed in more detail elsewhere.

By contrast, the latitudes near the equator offer a unique plant species that played a formative role in traditional architecture there and is likely to regain similarly prominent importance in future construction: bamboo. This is a family of sweet grasses (more than 12,000 species) whose culms are hollow on the inside and become increasingly stiff on the outside. The stability of the walls derives from the numerous fibers and the high silica content (e.g., Schönauer, 2021). The giant bamboo is the fastest growing plant in the world, gaining half a meter a day and eventually reaching a height of over 40 m. Interestingly, the culms push their final cross-section out of the ground right from the start; so there is no thickness growth as with woody plants. In summary, bamboo is undemanding, highly regenerative, light, and yet resistant to pressure and tension, thus in principle an ideal climate-positive material.

To assess bamboo's potential for modern sustainable construction on a global scale, the questions of geographical availability and further processing in line with demand must be answered with priority. First, it should be said that the species spectrum of this miracle grass covers an altitude range from 0 to 4000 m and a temperature range from −28 to +50 °C. Bamboo species are native to all continents except Europe and Antarctica; some of them can also be planted and cultivated almost anywhere in temperate latitudes. As far as its use as a building material is concerned, several innovative processes and tools are currently being developed that should finally bring bamboo out of its South Seas kitsch niche and directly into the dynamic new world of architecture.

This involves a wide range of aspects, such as the dynamic bonding of various tube geometries, the production of flat components with wood-panel-like properties, or the use of advanced digital methods in individual building design. An up-to-date overview is given, for example, in Chapter 5, "Bamboo Technology," in the aforementioned book by Pablo van der Lugt. In my view, we are witnessing the beginning of a development that could lead to flourishing mid-sized economies based on regional resources in countries such as Ecuador, Ghana, Indonesia, or Vietnam.

At the end of this section, to preempt two potential allegations, it is important to state two self-evident facts. First, intact primary forests absolutely must be protected, if necessary with appropriately designed trade agreements and new types of financial instruments. But, for the sake of the climate, secondary or degraded forests should also be protected from further human intervention and damage. In the tropics especially, such ecosystems have proven to be highly resilient. They can largely regain important forestry properties such as the original growth rate just 20 years after a massive disturbance—if nature is left in charge (Poorter et al., 2021).

Second, there are critical elements of the terrestrial biosphere that have stored enormous amounts of carbon but could lose this storage function in a practically irreversible way due to civilizational interventions (*Irrecoverable Carbon*: IC). A recent paper maps these ecosystems, explains their special importance, and presents remarkable figures: half of the IC is located on just 3.3% of the planet's land surface, 23% of the total is in protected areas, and 33.6% is currently used in a sustainable way by indigenous communities (Noon et al., 2021). This highlights the opportunities but also the risks that must be considered in preserving this important component of the Earth system. The further displacement of indigenous peoples from their traditional habitats alone could cause fatal reservoir losses.

Conclusion: The "reforestation of the world" for the benefit of our biosphere, climate, culture, and economy is possible in principle. But due to the multiple target functions and the heterogeneity of the fields of action, it is probably the most complex challenge in the history of our civilization. It is high time to jettison the simplistic and short-sighted strategies of the post-war era and steer a far-sighted, evidence-based course between brutal forestry and radical environmental protection.

The Forestry Construction Pump

We can now combine the insights and facts of the three previous sections into a "Technical Guide to Climate Restoration." The inverted commas are meant to signal self-irony in view of the fearsome dimension of the claim and to emphasize the provisional nature of the approach: the operationalization of the following basic considerations still requires enormous analytical, empirical, experimental, and social-science efforts. System theories, data collection, simulation models, demonstration projects, instrument discourses, etc. of unprecedented breadth and depth must be carried out on the topic in the coming years. "Horizon Europe," the EU's current research and innovation program, could play an essential role.

The concept itself, however, can be outlined: the built environment must be transformed from a monstrous CO_2 source into a powerful CO_2 sink. This requires (1) bio-based material (especially in the construction phase), (2) sustainable energy (mainly in the operational phase), and (3) cycle-oriented component use (mainly in the demolition phase). While the problem associated with point 2 could be quickly overcome with the brilliant triumph of renewables and dramatically improved energy system thinking, we are still in the early stages with points 1 and 3. However, if land use and settlements are consistently thought and designed together, we can be successful on these two fronts as well. In essence, it is about bringing supply and demand for climate-positive building materials into a sustainable balance at a significantly higher level. How the demand side could be greatly improved was outlined in Section "The Geological Journey of C"; how the supply side could be shaped in harmony with other sustainability goals, in Section "Forestry's Transition Toward Sustainability".

The concrete "TA Climate Restoration" is shown in the following graphic (Fig. 5):

In this illustration, the migration of carbon through different compartments of the Earth system is traced as part of an active surplus strategy. In the final analysis, this strategy transforms atmospheric CO_2 from the burning of fossil fuels into wooden buildings and infrastructure of high utility; in the best case, exhaust gases are transformed into kindergartens made of wood. A better "value proposition" will be hard to find in the sustainability market.

In natural equilibrium, there is a stable atmospheric CO_2 concentration maintained by several biogeochemical processes. In one of the most important of these processes, terrestrial vegetation through photosynthesis removes CO_2 from the atmosphere that is, however, largely returned to the atmosphere via metabolic (respiration, etc.) and transformative (decay, etc.) processes. A small proportion is stored in the soil as organic carbon; the deficit in the air is made up, for example, by CO_2 emissions from volcanoes.

Due to the enormous technical oxidation of fossil fuels, this equilibrium has been greatly disturbed for about 200 years. This has not only resulted in an increase in the global mean temperature, but has also substantially altered the productivity of the biosphere. The latter absorbs a good quarter of anthropogenic CO_2 emissions and

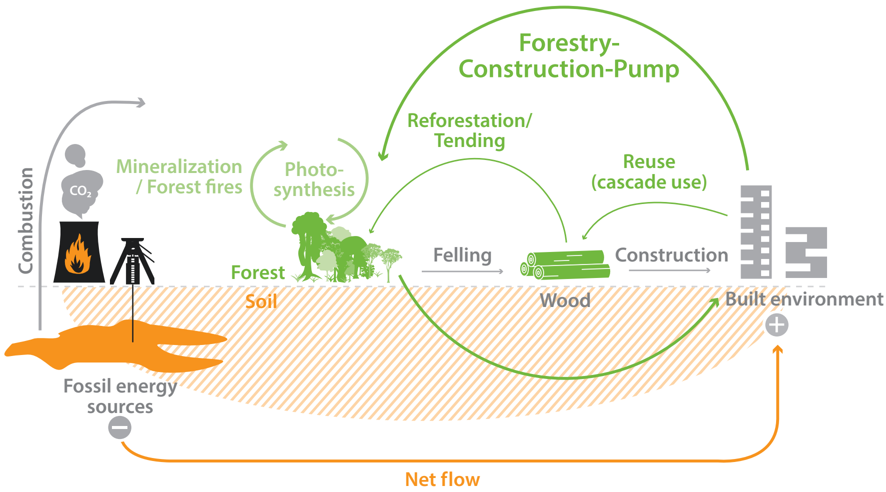

Fig. 5 The forestry construction pump. A cyclical carbon dynamic among terrestrial vegetation, atmosphere, soil, timber, and built environment (Schellnhuber & Köllner, unpublished)

thus tends to increase in mass. Through targeted forestry and construction measures, the atmospheric CO_2 surplus can now be siphoned off again and stored at least in the medium term (centuries to millennia). This is essentially done via two cycle-like processes: via the harvest-plant-tend-harvest cycle for living biomass and via the composition-decomposition-recomposition cycle for processed biomass. In both cases, these are not true closed circular processes, but the repetitive nature is clearly evident. In cycle 1, permanently stimulated growth through decoupling of mature plants is essential, in cycle 2, the most value-preserving and reversible is assembling of the construction components. Through the interaction of the various natural and civilizational processes, a kind of pump is created for the targeted cleaning of the atmosphere from unwanted pollution that was a by-product of the fossil-industrial economy. This organizes a (largely after-care) flow of carbon from the ancient deposits of the Carboniferous into present and future human settlements.

To preempt the undoubtedly numerous objections to this utopian-seeming but, if successful, existentially important project, I would like to state explicitly here that each individual element of the diagram requires strict scientific scrutiny, that the approach must be explored with great care geographically and explicitly for all continents and economic areas, that a dynamic view taking into account different time scales (e.g. how often per century can the “pump” be operated?) is essential and that the envisioned system can ultimately only be developed and planned with the help of quantitative simulation modelling. This also outlines a highly ambitious research agenda.

Finally, whether the political-economic preconditions for the realization of this project can be created for purposeful planetary design is almost impossible to predict. The special strength of this approach—apart from its reliance on largely nature-based solutions and practices—lies in its *technical and social scalability:*

similar to photovoltaics, anyone and everyone in almost any place can make an almost arbitrarily large contribution to the overall solution. On the supply side, this may be planting a single tree or preserving a primary rainforest the size of Germany. On the demand side, this may be the climate-positive addition of a two-family house or the construction of an entire new metropolis from bio-based building materials. Therefore, this humanitarian project can become a project of all humanity.

As a physicist, I am used to subjecting every task first to an elementary order-of-magnitude analysis which, in this case as well, provides interesting insights. Recently, the scientific journal *Nature* published an article by an Israeli research group that was both illuminating and shocking (Elhacham et al., 2020). It demonstrates in a simple and convincing way that mankind has become a force that is massively reshaping the Earth. Following Paul Crutzen, this development is often described with the term "Anthropocene," mostly referring to the change in energy flows on our planet and the resulting amplification of the natural greenhouse effect (Schellnhuber, 2021b). In fact, the interventions of our civilization in the material flows in the Earth system are rather more dramatic (e.g., Smil, 2013). The above-mentioned Nature publication explicitly shows that in 2020, for the first time, the "Anthropomass"—i.e., the total mass of man-made materials (concrete, bricks, asphalt, metals, plastics, etc.) on Earth—exceeds the sum of all living biomasses!

What quantities are we talking about? Well, if we really only want to compare sheer orders of magnitude, then the planetary living biomass before the beginning of human civilization in the Holocene weighed roughly 2 trillion tonnes. About half of this has already been destroyed by economic activities; in its place, an ensemble of artificial masses weighing about 1 trillion tonnes has been created.

Now we can do a lumberjack (rather than milkmaid) calculation: in the last ten millennia, humankind has increased the atmospheric CO_2 concentration from about 280 to about 420 ppm, which corresponds to a weight increase of about 1 trillion tonnes. In the long term, this mass must be removed from the atmosphere to complete the desired climate restoration. Disregarding all natural processes that are taking place anyway, in which, by the way, soils play a critical role, this would be realized mainly through reforestation and organic architecture for settlements and infrastructures. An average wooden house weighs about 100 tonnes and thus binds nearly 200 tonnes of CO_2. If about 2 billion houses were to be constructed from bio-based materials over the next centuries, then some 400 billion tonnes of atmospheric CO_2 would be extracted enduringly removed from the climate system. Another 100 billion tonnes could be stored in infrastructure, so that about half of the restoration rent (500 billion tonnes of cumulative negative CO_2 emissions) would be raised via the built environment. The other half would have to be taken care of by an intelligent sustainable forest strategy (see also Section "Forestry's Transition Toward Sustainability").

The bottom line is that the anthroposphere would also undergo a fundamental material transformation in addition to the energetic one: *The corresponding demineralization processes would largely replace today's trillion tonnes of artificial masses with harvested or living biomass and thus successfully complete a renaturation on a planetary scale.* Whether such a breathtaking plan can really succeed is another matter. But the path and goal have now been relatively clearly outlined. And, as I explained above, implementation can begin at any time with local contributions. Even “realpolitikers” and cynics should find it difficult to refuse here.

The New Bauhaus Movement

The transformation of the built environment is a decisive prerequisite for correcting a climate development that seriously endangers the foundations of human life. But today there are also myriad other reasons to look at the housing system as a whole and to rethink it thoroughly.

For “what if CO_2 did not influence the planetary radiation balance?”—as some confused minds stubbornly claim? Would we then—freed from climate fears—find our existing built environment socially and aesthetically appealing? Must we really surround ourselves with dysfunctional ugliness that literally cements social differences?

Structurally, built modernity has failed in the concentric logic of megacities, which in daily, weekly, and seasonal shuttle movements suck in enormous quantities of living beings, goods, energies, and information, digesting and then discharging them back “into the hinterland.” This principle of operation has a multitude of fatal consequences, of which I mention just a few:

- There are the sprawling scattered settlements on the periphery of the metropolises that have no identity beyond their geometric relationship to the center. The country house kitsch runs riot there in detached houses on tiny plots. You can’t push social atomization much further, but the poisonous current “home ownership debate” shows where the vanishing point of middle-class longing still lies many decades after the destruction of World War II.
- There is the cultural emptying of the so-called provinces, where the meeting places in the villages and small and medium-sized towns are becoming deserted, the traditional places of *joie de vivre* are falling into disrepair and even the most elementary supply facilities are disappearing in the direction of the upper center. If young people must turn the town’s only bus stop into an inhospitable substitute pub, we need not be surprised if, at the next election, resentment and envy of the urban elites steer the pen to the right.
- Then there are the 1–2 billion people (no one knows exactly how many) who live in informal settlements—mostly in slums on the outskirts of big cities, but also under motorway bridges, in disused docks, even on smoldering rubbish tips. Often only a few kilometers away from the glamorous city centers where, for example, the hip penthouse with a view of New York’s Central Park or the mostly empty luxury apartment in one of the “Dark Towers of London costs tens of millions of dollars or pounds (Schellnhuber, 2021a).”

I quote here from the original manuscript of my essay published in the FAZ in 2021, in which I argue that building culture, urban development, and spatial planning have been in the wrong movie for a long time—at least not one set in the twenty-first century. In the right movie, we are at a turning point reminiscent of the great social ruptures that caused the traditional social orders to disintegrate at the end of the First World War. From the ruins, something new quickly emerged, not least the *Staatliches Bauhaus* (State Bauhaus), which Walter Gropius founded as an art school in Weimar in 1919. Through its concept, aspirations, and impact this school revolutionized the twentieth century world of architecture.

"The *Bauhaus* was decidedly contemporary at the time because it chose a holistic approach that brought together all trades from carpenters to painters. It studied and enthusiastically employed the possibilities of its technical epoch (such as modular construction) and saw itself as a social progress project that wanted finally to create decent living space for the masses 'below' the elites. Organic materials were definitely part of the school's fabric canon, but the actual idea of sustainability was understandably as alien to it as the dark side of the moon.

But what if Gropius and his comrades-in-arms (from the architect Mies van der Rohe to the graphic artist Feininger) were suddenly to find themselves in today's world and were to direct their programmatic and creative energies to its dramatically transformed challenges? They would certainly place the planetary ecological crisis at the center of their work (ibid)."

Since these historical personalities are unlikely to be reborn, people of the present must take appropriate action. In this context, the Association of German Architects (BDA) has been playing a lead role in Germany for quite some time, especially with its magnificent manifesto on climate-friendly housing development (BDA, 2019). For some years now, I have been exchanging ideas with leading BDA members.

Independently of this, however, I had long entertained the idea of reviving the basic approach of the Weimar Bauhaus—*striving for a holistic building culture mindful of social responsibility*—in view of the climate emergency. The anniversary year 2019, 100 years after the Bauhaus founding, was an appropriate time to take action.

I succeeded in bringing the *Bauhaus Earth* initiative circle to life, which includes some remarkable personalities and has met for the first time in December 2019 in Caputh near Potsdam, close to Einstein's summer house. Among other things, this resulted in the "Caputh Declaration," which calls for an early transformation of the built environment within planetary boundaries and consciously embraces the holistic approach of the historic Bauhaus. Quote: "If civilization is not merely to survive, but to develop in diversity and solidarity, we must take a new holistic view of the built environment."

But the declaration also clearly expresses that the Bauhaus approach must be transported into the twenty-first century and given a new direction that corresponds to the requirements and possibilities of our time: "*A main goal of all building culture must be the good life of people in harmony with nature.* The guiding concept of the sustainable modernity that is now to be created through architecture, art, design, manufacture, infra-structure, urban development, landscape design and spatial planning could therefore be the organic (or the natural)—in contrast to the mechanical which was the lodestar of the declining industrial modernity."

I will expand on the last sentence in the next and final section. It is worth reporting here that *Bauhaus Earth* is developing excellently, taking on its first institutional forms and setting in motion interesting projects. The initiative is now spreading far and wide. First and foremost in this context is the *New European Bauhaus* (NEB), a major European project that has enormous transformative potential. The NEB was launched by Ursula von der Leyen, President of the European Commission, in her *State of the Union Speech* of 16 September 2020. According to the NEB website, she said: "The new *European Bauhaus* is a creative interdisciplinary initiative to create a meeting place where future ways of living are shaped at the intersection of art, culture, social inclusion, science, and technology. It brings the Green Deal to the center of our lives and is a call to develop and realize together ideas of a sustainable, inclusive, intellectually and emotionally engaging future."

This is necessarily "Commission jargon," which strings together as many positively connoted words as possible to underpin a certain program. Also in my capacity as official advisor to the NEB, I should therefore emphasize the most important terms as they ultimately give direction to the whole: this is about the future of building/the building of the future, in which *sustainability, participation, and beauty* are more important standards than profit, competition, and prestige. This can be dismissed as a noble but unrealistic claim. However, the debates on the NEB that are already being organized across Europe suggest that our civilization is finally ready to break out of the post-war global paradigm to seriously discuss better narratives of modernity.

In order not to go beyond the scope of this article, I would like to highlight only one aspect here. Can there be such a thing as a "mass movement towards beauty"? Is aesthetics and especially building culture not the privilege of the wealthy or educated elites, while the lower strata of society are (must be) politically fobbed off and mentally anaesthetized with a "class movement towards kitsch"? These questions touch on an explosive socio-cultural problematic and must be discussed or answered only with great seriousness.

But I do want to bring one thought into play here: well-preserved small historic towns and villages in Europe can often boast a remarkably valuable functional aesthetic, while in the contemporary provinces, architectural horror usually dwells. The latter settlements have lost almost all connection to the (topographical, climatic, resource-economic, regional-political, art-historical, etc.) conditions of their location, while the former have grown out of a long collective confrontation with these very conditions. Umbrian hill towns such as Spello or Spoleto, for example, are supremely beautiful architectural implementations of the principle of defense against raids by Saracens or Vikings. The "people" can build if they are given sufficient time and resources to do so. In the exhausting battles over reconstruction after the Second World War, the concepts and practices of collective-evolutionary settlement development were unfortunately largely lost. At best, the eccentric constructs of the "star architects" who serve the whims of a wafer-thin global upper class stand out from the desolation of today's commercial and residential ensembles.

Hi-Tech Meets No-Tech: Entering the Cyborganic Age

To conclude this chapter, let me venture a perspective that looks beyond the built environment and attempts to glimpse what might constitute the essence of a post-industrial civilization. I believe this essence will be decisively shaped by the *reconciliation of humans with nature on a cultural plateau that can still be reached in this century.* The essay justifying this in more detail has yet to be written, but I would like to place a few signposts here already.

I quote once again from the FAZ manuscript repeatedly mentioned: We must finally muster the will to "comprehend the exuberant inventiveness of evolution. This requires courageous entry into the comprehensive school of nature. Unfortunately, we have set fires to their most precious libraries (the Amazon, the Congo, Borneo, and Sumatra), and the first thing to do is to put them out. If we are then willing to learn, both the gain in knowledge and the practical benefits will be enormous. Construction and operation in the twentieth century were mainly oriented towards mechanics and thermodynamics, toward the directly calculable, under the dictate of optimization that maintains its stranglehold on economic thinking even today. The built environment in the twenty-first century should instead take inspiration from elements in the Earth's ecosystem that grow, bend, circulate, flourish late or by accident.

Some may regard this as an excessive romanticism about nature. But after some decades of scientific study of non-linear processes and complex systems, I must conclude that the evolutionary creation of a rose bush far outshines the engineering design of a powerful diesel engine. Incidentally, the engineer's brain is itself an outgrowth of nature: for example, millions of years of environmentally controlled selection processes have led to the mounds of certain termite species in South Asia being so cleverly designed in terms of shape and material that the structures achieve optimal ventilation in the diurnal cycle of the outside temperature (King et al., 2015).

The living world is full of such success stories, but they are usually discussed only in the exclusive circles of bionics experts. For the disciples of modernity, progress is still synonymous with detachment from the nature that created us. In *Bauhaus Earth*, this matricidal obsession can be ended by combining high-tech with no-tech to create innovations the likes of which the building industry has never seen (Schellnhuber, 2021a)."

In this context, Marc Weissgerber and I introduced—in a contribution to the catalogue of the exhibition "urbainable—stadthaltig: positions on the European city for the twenty-first century" (Schellnhuber & Weissgerber, 2020)—the concept of cyborganics in settlement design. This term anticipates a possible new architectural epoch oriented towards the following principles:

Cybernetic principle. Buildings, empowered by appropriate artificial intelligence (AI) tools, are self-regulating and learning systems that adapt optimally to their respective environmental conditions and the dynamic needs of their users. "Cybernetic" is essentially understood here as "digitally controlled."

Organic principle. Buildings are developed like ecosystems, using climate-friendly materials, employing and offering important ecosystem services. This principle could be boldly implemented by, for example, creating “living” houses that integrate vital trees or other plants. The constructions would then mature over time and could also be rejuvenated.

This may sound like hyperbolic sci-fi babble, but just a few decades ago even gene therapy would have been dismissed as hype. And really no one would have dreamed that a microbiological method with the cryptic abbreviation CRISPR would play a heroic role. The scientific age has only just begun ...

This is especially true for the construction industry where, for half a century, barely any innovations have been stimulated or productivity increases realized. The industry is overripe for transformation. Interestingly, this is already advancing from the margins into the established center, where the least imagination still promises the greatest profit. This may change soon as many small and medium-sized companies, particularly ones driving wooden architecture, are now beginning to conquer the markets—initially in Central Europe and the Far East, but surely soon in other parts of the world as well. These companies perfectly embody the hi-tech-meets-no-tech paradigm with their value creation: they work with renewable raw materials but use customized AI methods for this purpose, i.e., the most advanced cognitive tools in human history to date. *Forward to nature!*

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