Article

Trees—Protectors against a Changing Climate

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ABSTRACT: There are estimated to be about 3 trillion trees on Earth, or about half the number that existed before the dawn of human civilization. Trees are vital to at least four major biogeochemical cycles, namely, the carbon, water, nitrogen and oxygen cycles. In addition to absorbing carbon, and releasing oxygen through photosynthesis, trees are critical for maintaining biodiversity, providing habitat for 80% of land based wildlife, feeding the soil, generating clouds and increasing albedo (thus causing global cooling), influencing rainfall and weather patterns. The loss of trees, therefore, weakens our chances of reaching climate and biodiversity targets, and so proforestation and other practices to stringently preserve the functionality of and holistically restore forest ecosystems, must be adopted as a matter of urgency, paying due attention to soil, and species diversity including mycorrhizae; not being limited to insouciant "tree planting" solutions. Indeed, due to the tardiness of our actions to repair the Earth and its climate, severe restrictions to the cutting of mature trees must actually be enabled globally. However, this alone is not enough, and must be integrated with other forms of land, wetland, grassland and agricultural protection and restoration. Such Nature Based Solutions could provide over one-third of the climate mitigation needed by 2030 to keep within the 2 °C global heating limit. Nonetheless, it is also critical to curb greenhouse gas emissions at source, not only by implementing low-carbon, renewable energy, but also energy demand reduction strategies, such as insulating buildings, societal relocalisation, and local food growing.

Keywords: Proforestation; Deforestation; Climate change; Biodiversity loss; Natural regeneration; Nature based solutions; Overshoot; Behavioural crisis

"*Trees are poems that the earth writes upon the sky. We fell them down and turn them into paper that we may record our own emptiness.*"—Kahlil Gibran (1883–1931).

1. Tree Huggers

Although the term "tree hugger" is used, generally pejoratively, to describe someone acutely concerned with protecting the natural environment, its true origin marks the brutal slaughter in 1730, of 294 men and 69 women, members of the Bishnoi Hindu community, who were trying to defend the sacred khejri trees (*Prosopis cineraria)* in their village from being cut down by soldiers, to provide timber and charcoal to build a new royal palace. By literally hugging the trees, they paid the ultimate price, but this action resulted in a royal decree that no trees could be felled in any Bishnoi village. Accordingly, virtual wooded oases are scattered over an otherwise barren landscape [1].

The word Chipko means "to cling" in Hindi, and the Chipko movement [2] arose in the 1970s, when a group of Himalayan mountain dwellers in northern India similarly placed their arms around trees that had been authorised to be cut down, as an act of non-violent resistance (satyagraha) [1] against state-led commercial forestry and deforestation policies. From their living experience, the protesters were viscerally aware of the link between deforestation, landslides, severe floods, and land subsidence [2]. Also known as tree satyagraha, this strategy became widespread throughout India, impelling reforms in forest management and a moratorium on tree felling in regions of the Himalayas [1].

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It is through this lens that environmentalism and social justice might best be viewed, with trees serving not only as powerful symbols of the current ecological crisis, but as real and essential protectors against a changing climate, and all other symptoms of the current condition of human ecological overshoot [3].

2. Trees and Forests

There are estimated to be about 3 trillion trees on Earth, or about half the number that existed before the dawn of human civilization [4]. Trees are vital to at least four major biogeochemical cycles, namely, the carbon, water (hydrological), nitrogen and oxygen cycles, and hence their significant presence or loss impacts dramatically upon the global climate [5]. The so named “Small Water Cycle” is another critical determinant of local climate and water availability [6]. Since the end of the last ice age, the overall extent of forested land has been reduced from 6 billion to 4 billion hectares, principally from the expansion of agriculture [7]. The majority of trees are present in forests, which now cover about a third of the Earth’s habitable land surface [7], and provide habitat for 80% of land based wildlife [8].

Forests provide 75% of the gross primary production of the Earth’s biosphere, and contain 80% of the Earth’s plant biomass. Net annual primary production for tropical forests is estimated at 21.9 gigatonnes (Gt) of biomass, 8.1 Gt for temperate forests, and 2.6 Gt for boreal forests [9]. Tropical forests are responsible for around 34% of photosynthesis occurring on land [10]. As much as 45 percent of the carbon stored on land is contained in forests [11], and around half of this may be present belowground in soil [12]. In a study of sub-tropical forests in China, it was shown that species-rich stands had higher stocks and fluxes of carbon than low-richness stands, and that the total C stock increased by 6.4% for each additional tree species present. Moreover, older stands were found to have higher C stocks than their younger counterparts. [12].

Forests affect the climate, not only in terms of capturing carbon, as is mostly focussed upon by policymakers, but in maintaining biodiversity, generating clouds and increasing albedo (thus causing cooling), influencing rainfall and weather patterns, and other factors [13,14]. Worldwide, trees require a large amount of energy (in line with latitude) to produce dense wood and seeds, while leaves with large surface to weight ratios are concentrated in temperate forests. Nonetheless, patterns of functional composition within-biome are shown to differ from global patterns due to such biome specificities as the presence of conifers or unique combinations of climate and soil properties [15].

3. Forest Loss—Deforestation and Forest Degradation

Forest loss represents the sum of deforestation and forest degradation: *deforestation* is where trees are removed completely for changes in land-use, such as for agriculture, mining, or urbanisation, and are not expected to re-grow; while *forest degradation* is a more general “thinning” of trees, e.g., from logging, shifting agriculture, or wildfires, and which can be expected to recover eventually [7]. However, it cannot be overstated that, in parts of the globe, particularly the tropics, the deterioration of forests is severe, as a result of a confluence of different human impacts, which vary from region to region in their relative proportion and scale [16]. Globally, around one quarter of annual forest loss is from deforestation: in Latin America, the major driver of deforestation is clearing forest to graze cattle [16], mainly by corporations, while in Southeast Asia it is “freeing-up” land to grow crops, for example, tree plantations to produce palm oil [16].

Tropical rainforests appear to be particularly susceptible to, and hard hit by, the effects of climate change [17]. Thus, since the 1980s, trees in Australia’s old-growth tropical rainforests are dying at double the previous rate [17], while the Brazilian Amazon is found to have been a net emitter of CO_2 for the past two decades [18]. Although the Amazon as a whole, which extends across 9 different nations, has absorbed a net 1.7 billion tonnes of CO_2 equivalent in the past 20 years, the Brazilian portion alone has emitted a net 3.6 billion tonnes during the same period [18]. On the basis of satellite monitoring data, it is concluded that the best chance for preserving the Amazon, and its ability to buffer against climate change, lies in placing formally protected areas and lands in the charge of indigenous peoples [18].

According to a recent study, there has been a *net* global forest loss of 82 million hectares over the 60-year period, 1960-2019. A loss of 437.3 million ha outweighs a gain of 355.6 million ha, and which, along with a population increase of 4.68 billion, means that the *per capita* global forest area has declined by over 60%, from 1.4 ha in 1960 to 0.5 ha in 2019. It is of interest that the spatiotemporal pattern of forest change is found to support the forest transition theory, since forest losses are predominantly a feature of lower income countries in the tropics, while the gains have occurred mainly in the higher income, extratropical nations [19]. The matter of assessing forest loss is complex, in part because different methodologies and models have been used in different studies and over time, thus making it difficult or unreliable to compare reported data over longer timescales [7,20].

Global Forest Watch (GFW) have reported that a high rate of forest loss occurred in 2022, despite political resolutions to curb this [21]. GFW have also released a "Targets Tracker" tool, which enables a coarse resolution proxy for deforestation. By only including certain drivers, losses are identified that are considered most likely to represent deforestation, both in tropical and extratropical regions. Thus, the expansion of small-scale agriculture into humid tropical primary forests is included, along with all losses from commodity-driven deforestation and urbanization. However, more temporary losses are excluded, for example, from forest fires and forestry activities [22].

Net changes in forest area measure forest expansion (either through planting or natural regeneration) minus deforestation, and on this basis, some regions of the world are losing tree cover, while others appear to be gaining it [7]. However, the latter may provide misleading optimism, since some of the "new" trees represent industrial timber plantations, mature oil palm estates and artificially planted forests, none of which have the same degree of biodiversity as primary tropical forests, which contain a breadth and depth of flora and fauna that is erased when their areas are cleared [23]. The possibility has been raised that a warming effect may arise from increased tree cover, particularly at northern altitudes, but this depends on the interplay of various factors, for example the replacement of snowy landscapes, which reflect solar radiation, by darker tree canopies that more readily absorb it [24].

To aid assessment of the overall status of forest management, a globally consistent map has been created with a high spatial detail and which focuses on the following major categories: intact forests, managed forests with natural regeneration, planted forests, plantation forest (up to 15 years of rotation), oil palm plantations, and agroforestry [25]. Nonetheless, it is important to note that intactness is not only determined by spatial extent, but there is also an age component of forest integrity. In tropical forests, the vertical nature of forests can be masked by the rapid regreening of cleared landscapes, while it is well established that more mature and old growth forests harbour more wildlife, carbon etc. It is therefore of relevance that a new "ecosystem integrity index" (EII) has been devised to evaluate the overall health of a forest, thus quantifying the degree of deterioration from intact forest, via disturbed/degraded forest, down to a completely deforested area [26]. Elsewhere, it is noted that while deforestation is well recognised as a major environmental problem, the degree of anthropogenic modification of remaining forests should also be paid due attention, since it may reduce the integrity of ecosystems, and impair forests in delivering many of the benefits that they provide; thus, it has been found that only 40% of the world's forests have a high ecosystem landscape integrity [27].

It has been estimated that, currently, forests keep Earth around half a degree (Celsius) cooler than without them, and help to stabilise the climate. This is due to a combination of effects, including carbon dioxide uptake, but also the release of volatile organic compounds (VOCs) from trees, which create aerosols and aid cloud formation, with a consequent increase in albedo [14]. Thus, we can neither reach "net-zero" emissions targets, nor keep global heating to within the limit of 1.5 °C above pre-industrial levels, if deforestation is allowed to continue. In fact, according to the Special Report on Global Warming of 1.5 °C of the Intergovernmental Panel on Climate Change, an increase in the global forest area of 10 million square kilometres (equal to the land area of the United States) by 2050 is necessary to avoid exceeding 1.5 °C [28].

The renowned American biologist, Edward Osborne Wilson (generally known as E.O. Wilson) regarded mass extinction as the greatest threat to Earth's future, and once said that "destroying a rainforest for economic gain was like burning a Renaissance painting to cook a meal" [29]. He also remarked [30]: "Now when you cut a forest, an ancient forest in particular, you are not just removing a lot of big trees and a few birds fluttering around in the canopy. You are drastically imperiling a vast array of species within a few square miles of you. The number of these species may go to tens of thousands. Many of them are still unknown to science, and science has not yet discovered the key role undoubtedly played in the maintenance of that ecosystem, as in the case of fungi, microorganisms, and many of the insects."

In 2014, Wilson called for setting aside 50% of the Earth's surface, for other species to thrive in, as the only possible ("Half Earth") strategy to solve the extinction crisis [31].

4. Should We Simply Plant Trees, on a Colossal Scale, to Offset Deforestation and Avert Climate Change?

Since forest eco-systems are far more complex than mere assemblies of trees, simply establishing new tree plantations might prove an incomplete, and potentially counterproductive, strategy in regard to stabilising climate and promoting biodiversity [32]. The global area of near natural peatland (over 3 million km^2) sequesters an annual 0.37 Gt of CO_2, while peat soils contain over 600 Gt of carbon, which is as much as 44% of all soil carbon on Earth, and more than the amount of carbon stored in all other vegetation types, including the world's forests [33]. The need to preserve grasslands has been emphasised, and it was noted that savannahs are not "inferior forests" but store large amounts of carbon in their soils [34]. Indeed, savannahs hold more carbon belowground than do forests [35]. Thus, planting trees on peatlands and grasslands can lead to an overall release of carbon into the atmosphere [36].

Clearing established forests for tree plantations is especially detrimental, not only in respect of carbon storage but also biodiversity loss [37]. Moreover, many tree planting projects have failed, in part from a tendency to target the numbers of trees planted, with insufficient regard for environmental impacts such as water demand, and a lack of follow up monitoring and legal protection, to ensure that the trees survive [38]. Thus, if planting is to be done, judicious choices must be made at each stage of the process [39]. This is aptly summarised in the context of the European Commission and European Environment Agency's "Map My Tree" platform [40], aimed to assist with planting 3 billion new trees, which acknowledges the need for: "Planting the right trees in the right place and for the right purpose."

Thus, a paper on the potential for global tree restoration sparked controversy, in regard to the prospect of planting trees over the 0.9 billion hectares that might be available globally, without encroaching on existing forests, or urban and agricultural areas [41]. While it was inferred that thus planting close to one trillion trees over such a large area would absorb two thirds of anthropogenic carbon dioxide emissions, this met with strong dissent on various grounds [42–44], to which the original authors responded [45], and then issued an erratum [46], in which they revised down the amount of carbon that might be removed by global forest and woodland areas. Furthermore, they emphasised that overall tree restoration is not more important than all other methods of environmental conservation, but that "climate change is an extremely complex problem with no simple fix and that it will require a full combination of approaches."

In November 2023, a more tightly focussed paper was published [47], which assessed the global carbon potential of natural forests. They estimated that 61% (139 Gt C) of this potential lies in existing forests, if they are protected to reach maturity, while the next greatest prospect, 39% (87 Gt C), is from areas where forests have been removed or fragmented, further emphasising that while such strategies are no substitute for emissions reductions, valuable contributions to meeting both emissions and biodiversity targets can be made through the conservation, restoration and sustainable management of diverse forests. Hence, this is in accord with the topics of proforestation and natural regeneration, which are addressed in later sections of this article.

The whole matter of tree planting is complex and, to some degree, contentious, but it is fair to stress not only planting trees, but the broader aim to *grow tree-based ecosystems*, as the more complete strategy. However, while natural regeneration is preferable, there remains scope for tree planting [48], especially in areas that will not regenerate on their own [49]. Planting may be integrated with other strategies for restoring highly degraded landscapes, over a range of scales, e.g., the Chikukwa Project in Zimbabwe [50], which is based on principles of permaculture design [51].

5. Proforestation

Proforestation [52,53] is the primary strategy of protecting existing forests from human disturbance, so that they can continue to grow naturally to reach their full ecological potential, thus maximising the absorption and storage of carbon, while increasing biodiversity and structural complexity, including soil, mycorrhizal fungi, insects, plants, lichens etc. [54]. The critical factor of timescale also applies, since active reforestation, or even natural regeneration strategies, assisted or otherwise, will take time to grow new biomass, whereas proforestation builds on what is already there, particularly the larger trees. In one forest, these number only 3% of the total trees present, but account for 42% of its carbon storage [55]; hence, preserving them exerts an immediate, positive impact. Indeed, due to the tardiness of our actions to repair the Earth and its climate, severe restrictions to the cutting of mature trees must actually be enabled globally. There is some controversy over whether an intact standing forest continues to absorb carbon once it has become fully established, or reaches a kind of "saturation" state, but there are strong indications that the accumulation process remains ongoing on a scale from decades to centuries [53]. Intact forests also may accumulate half or more of their carbon content as soil organic carbon or in standing and fallen trees which eventually decay and contribute more soil carbon [56]. Some older forests are found to continue accumulating soil organic carbon [57], while soil organic matter is bound more tightly in older, rather than younger, forests [58]. During the period 2001–2019, global forests were found to have sequestered about twice as much CO_2 as they emitted, and to provide a "carbon sink" that absorbs a net annual 7.6 billion tonnes of CO_2. This is 1.5 times more carbon than is emitted by the United States each year [59]. However, keeping forests intact offers far more than just carbon sequestration and accumulation, but also contributes to maintaining biodiversity, ecosystem services, and building forest and community resilience.

5.1. Biodiversity

In the context of proforestation, we may include forests that are part of wilderness areas, which overall are indicated to halve the extinction risk for terrestrial biodiversity [60]. A meta-analysis was undertaken of 138 studies of tropical forest ecosystems, from which it was concluded that the majority of different kinds of forest degradation affect tropical biodiversity in an overwhelmingly detrimental way, and that primary forests are irreplaceable for maintaining this biodiversity [61]. A greater cumulative carbon storage and structural complexity was found for National parks in the eastern United States, as compared with surrounding forests that are actively managed [62]. Structural complexity may also be enhanced as a result of natural dynamic processes and disturbances which often yield a larger abundance and diversity of flora and fauna [61–64].

5.2. Ecosystem Services

A broad range of "ecosystem services" is provided by forests [65], a term that usually encapsulates the benefits conferred from nature to humans. In a report published by the United Nations, "The Millennium Ecosystem Assessment", which surveys the overall status and prognosis for the world's ecosystems, ecosystem services are categorised as [66]:

(1) *Provisioning Services*, such as food, clean water, fuel, timber, and other goods;
(2) *Regulating Services*, such as climate, water, and disease regulation as well as pollination;
(3) *Supporting Services*, such as soil formation and nutrient cycling; and
(4) *Cultural Services*, such as educational, aesthetic, and cultural heritage values, recreation, and tourism.

Forests provide food, fuel and fibre, but also remove pollutants from the air, filter water, control flooding and erosion, preserve biodiversity and genetic resources, and provide areas for cultural enrichment, recreation and education. Climate regulation by forests and grasslands can also be considered as an ecosystem service, as a result of carbon accumulation or release, and other impacts upon the biosphere [13,14], particular aspects of which depend upon the detailed structure, composition, and also management of a given ecosystem [65].

The matter of scale is important, since ecosystem services can act locally, regionally, or globally. Thus, to provide clean water is typically a regional service, and most beneficial to those living within the boundaries of a watershed. In contrast, there are local and global dimensions of climate regulation: ecosystems regulate the global climate by removing and releasing carbon dioxide and other gases, while changes in land-use can affect local micro-climates by influencing such factors as temperature and precipitation [65].

5.3. Improved Forest and Community Resilience

Globally, 1.6 billion people's livelihoods are dependent on forests [67]. This number includes some 300–350 million who live close to or within "dense forests", half of whom are Indigenous peoples and whose survival depends almost exclusively on these forest ecosystems [67]. In Latin America, Africa, and Asia, close to one quarter of the overall incomes of rural households depends on forests, around half of which is provided from energy, food, animal feed, building materials and medicine [67]. In further support of proforestation, it has been shown that complex and old growth forests are more resilient to climate change [68]. One report showed that taller trees had a greater resistance to drought, and can more effectively capture and retain water, as a result of their larger biomass and deeper root system, indicating that, even in dry conditions, such trees maintain a higher rate of photosynthesis than do smaller trees [68]. A greater resistance to fires has been demonstrated for old-growth forests, as compared to younger forests, whose trees have thinner barks and where there is more fuel available to drive elevated temperatures and fire damage [69]. Thus, proforestation can help mitigate risks from fires to forests and their neighbouring communities, and also help to prevent those communities from flooding, due to increased water absorption by the forests [67]. Hence, there are many benefits provided by complex forests and their ecosystem services, in supporting the resilience of neighbouring communities.

6. Natural Regeneration

In contrast to proforestation, in which existing forests are preserved intact to reach their full ecological potential, natural regeneration is the natural re-growing of forest on land from which trees have been removed (e.g., through logging or agriculture), or the expansion of current forest area. Thus, woodlands are restocked by trees that develop from seeds that fall and germinate in situ [70]. The prospects, and also challenges for using natural regeneration as a means for large scale reforestation in the tropics—where deforestation is particularly severe [7]—have been surveyed in detail. This is particularly important, since to achieve necessarily challenging forest and landscape restoration goals will require cost-effective natural regeneration at the global scale [71]. A study has been presented of the principles for using Natural Regeneration as a means for restoring tropical dry forests. The latter are characterized by a fairly large number of tree species, with small, dry, wind-dispersed seeds, that, over small scales, are able to colonize degraded areas more effectively than plants that rely on vertebrates to distribute them [72]. A study has been made [73] of the natural regeneration potential for a deforested region of the Brazilian Atlantic Forest. From 34.1 M ha of current forest cover, 2.7 M ha had regenerated naturally during the period 1996–2015, and it is estimated that a further 2.8 M ha could similarly regenerate by 2035. Nonetheless, another 18.8 M ha could be restored using assisted regeneration methods, which would be cheaper by (US) $90.6 billion than using tree planting. By restoring these forests, an additional 2.3 $GtCO_2$ of carbon could be sequestered, along with reductions both in species extinction risks and the degree of fragmentation (by 44%), as compared with current levels [73].

Chazdon, has surveyed the particular features and benefits for different modalities of natural regeneration, as emphasised by several large scale case studies [74]. It is concluded that proper incentives for landowners and local communities would encourage the natural regeneration of forests on farms. Furthermore, by identifying those areas whose natural regeneration prospects are optimal, the overall costs for implementing restoration on local, regional, and national scales could be significantly reduced, thus facilitating the restoration of larger areas, with increasingly important roles in climate change mitigation and biodiversity conservation [74]. From a study of natural regeneration on agricultural landscapes, it was determined that the intensification of agriculture tended to impede the occurrence of regeneration, and in the particular study area, fully *Intensive agriculture* is found to be incompatible with natural regeneration. This incompatibility can only be resolved through a strategic division of land sparing and land sharing to balance land-use needs [75]. In a study of natural regeneration in urban versus rural forests, greater early-establishment barriers to recruitment were indicated in urban than in rural forest sites. Once established, however, the transition from seedling to advance regeneration stages may actually be similar in both environments, and in certain cases, advance regeneration may be more viable in urban forested natural areas [76].

Practical Aspects of Natural Regeneration

In regard to natural regeneration, Rewilding Britain propose the following strategy [77]:

Step 1. Let nature lead: Allow natural regeneration as a default approach unless a natural mix of trees and shrubs are unable to establish or would take too long to arrive.
Step 2. Give nature a hand: Kick-start the process by assisting natural regeneration if needed.
Step 3. Plant trees: Plant locally sourced tree saplings only where still considered necessary.

In UK uplands, large tracts of non-native conifer plantations have been established on poor quality agricultural land, and it is desirable to convert some of these to a more natural woodland comprised of native tree species. Where local native seed sources exist, it has been shown that clear felling upland conifer plantation sites to allow natural regeneration is potentially an effective method of establishing native woodland [78]. From a study, whose lead authors are from Kew Gardens in the UK, are offered: "Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits" [79]:

(1) Protect existing forest first; (2) Work together (involving all stakeholders); (3) Aim to maximize biodiversity recovery to meet multiple goals; (4) Select appropriate areas for restoration; (5) Use natural regeneration wherever possible; (6) Select species to maximize biodiversity; (7) Use resilient plant material (with appropriate genetic variability and provenance); (8) Plan ahead for infrastructure, capacity and seed supply; (9) Learn by doing (using an adaptive management approach); and (10) Make it pay (ensuring the economic sustainability of the project).

Further support for natural regeneration is provided by a study published in Nature [80], which concludes that: "Plans to triple the area of plantations to remove atmospheric CO_2 will not meet 1.5 °C climate goals. New natural forests can."

7. Assisted Natural Regeneration

Assisted natural regeneration (ANR), sometimes termed "managed regrowth", can provide a cost-effective method for forest restoration, regenerating biodiversity and ecosystem services, in areas at intermediate degrees of degradation, while simultaneously generating income for rural livelihoods [81–85]. The approach utilises either residual seeds and plants, already available at the specific site to be restored, or as dispersed from neighbouring vegetation. Low-cost methods are employed, to assist in the natural re-growth of vegetation, for example: providing fences to keep cattle, deer and other animals from grazing on new growth, selectively removing vegetation that can threaten the survival of resprouting saplings; avoiding practices, such as mechanical disturbance, logging and burning; thinning of competing vegetation, as required, to promote the growth of tree saplings; and, if and where necessary, planting seedlings [86]. ANR has most often been used to enhance tropical forests [87,88], but is now being used, more widely, to restore forests across a range of ecosystems [81,88,89].

A greater preservation of biodiversity is obtained when vegetation is encouraged to regenerate naturally, even more than when native species are planted. Thus, those native species grown using ANR tend to be adapted to local conditions, and more resilient to local variations in climate and disturbance. A high diversity of species, which include trees, shrubs, forbs and grasses, is obtained through natural regeneration. ANR also tends to create better habitat for local fauna, due to the greater number of plant types, and also more structural diversity [90–93]. There are also cost implications, since it is much cheaper to establish vegetation using ANR, than by active planting [94,95]. The greatest potential for ANR is in locations that have not been intensively cropped or irrigated, or with a relatively short history of intensive land use [96,97]. A connection has been made between deep ecology and the ethical dimension of ANR, in regard to the latter's use for regenerating Lithuanian hemiboreal forest ecosystems [98]. In a critical review, the use of common gorse (*Ulex europaeus*) as a nursery plant to protect the growth of natural forest has been highlighted, although this may spread invasively, with negative impacts on native fauna [99]. A practical manual is also available for restoring forest landscapes through ANR [100].

The following summary has been given, to gauge the appropriateness of ANR for a given situation [83]: "Assisted natural regeneration doesn't work for every landscape; it's critical to assess the local context. For example, ANR works best in areas that are not highly degraded but are surrounded by forest remnants and where seeds are living in the soil. Where intensive farming and overgrazing have heavily degraded or compacted the soil, tree planting/seeding usually makes more sense."

Farmer Managed Natural Regeneration

Farmer-managed natural regeneration (FMNR) is a low-cost, sustainable land restoration technique comprising a set of practices used by farmers to encourage the growth of native trees on agricultural land, with a systematic regeneration and management of trees and shrubs from tree stumps, roots and seeds [101–103]. The degradation of vast tracts of farmland, grazing lands and forests, across the developing world, has advanced to a level that has rendered them unproductive, with deforestation as a worsening feature [7]. Thus, up to 65% of productive land in Africa, including 132 million ha of cropland, is degraded, exacerbating poverty, insecurity over food and nutrition, biodiversity loss, and conflict [103]. Seventy four percent of rangelands and 61 percent of rain-fed croplands, in the drier regions of Africa, are degraded by moderate to very severe desertification. Subsistence farmers, who typically comprise 70–80 per cent of the population in these regions, depend on this land for their livelihoods, and to feed their families. Thus, their lives are made much harsher as a result of its degradation, being subject to frequent hunger, malnutrition and even famine [104]. The restoration of land can potentially increase carbon sequestration, reverse biodiversity loss, recharge groundwater supplies, and increase food and nutritional security [101–103]. The existence of living tree stumps or roots in crop fields, grazing pastures, woodlands or forests, is a critical feature of FMNR [104]. The bushy growth that sprouts from the stumps or roots (often with the appearance of small shrubs) tends not to grow fully to mature trees, being subject to uninterrupted grazing by livestock, regular harvesting of wood for fuel, or burning. Farmers have tended to slash this regrowth in preparation for planting crops; however, by some changes in practice, it can actually be used to provide a valuable resource, and with no reduction in crop yields [105].

The tallest and straightest stems are selected to grow, while the others are cut back. The method is particularly effective if the farmer undertakes a regular pruning of unwanted new stems and side branches, as they first emerge. Other crops can be grown among and around the trees, and wood can be harvested by cutting some stems, while leaving the others to continue growing. Thus, the remaining stems will improve their size and value by the year, and continue to confer environmental benefits. When a stem is harvested, a younger one is chosen to replace it. In addition to its application on croplands, FMNR is being employed on grazing land and to restore degraded communal forests. In the absence of living stumps, seeds from native species are used, and indeed, there is considerable flexibility in how FMNR is practiced, in terms the choice of tree species to be left, the tree density, and timing and methods for the pruning activities [104,105].

In total, 7 million hectares of land in Niger have thus been restored using FMNR, containing 200 million trees, at a density of 60 trees per ha. 2.5 million people now benefit from this improved use of land, across 25 different African countries [106]. Nonetheless, although acknowledging that where FMNR is done, benefits accrue, it has been proposed that further research is necessary to substantiate some of the claims made for the method and the underlying scientific basis for its efficacy [107,108]. In the context of trees and a changing climate, it seems appropriate to mention agroforestry, and as a lead-in to the next section, we note that FMNR has been demonstrated as a useful methodology for scaling-up the benefits of agroforestry systems [109].

8. Agroforestry

Agroforestry, also known as agro-sylviculture, is a system of land use management in which trees or shrubs are grown around or among crops, or on pastureland [110]. Among the advantages of agroforestry are improvements to the profitability of a farm, while contributing to the preservation and protection of natural resources, for example mitigating soil erosion, improving soil structure and health, managing animal waste, creating wildlife habitat, and sequestering carbon [111]. The trees may themselves also provide useful products, including fruits and nuts, and also wood [111]. Agroforestry has been used mainly in tropical regions, especially in sub-Saharan Africa, but is now becoming more widely adopted in Europe and the USA, where it may aid in the cycling of nutrients, and in mitigating droughts [111]. There are commonalities between agroforestry and polyculture, in regard to intercropping practices, although far more complex, multilayered agroforests can be designed which contain hundreds of species. In certain respects, there are similarities with the creation of forest gardens and food forests [51]. Nitrogen-fixing plants such as legumes can be introduced to build soil nitrogen, and may be planted simultaneously or sequentially. Nitrogen fixing trees can also be integrated, e.g.: Italian Alder (*Alnus cordata*), Black Locust (*Robinia pseudoacacia*), Sea Buckthorn (*Hippophae rhamnoides*) [112].

Two scenarios have been evaluated to gauge the potential for increasing tree cover on agricultural land to sequester carbon, described as (1) incremental change, and (2) a systemic change, and it is concluded that both offer substantial carbon storage prospects: 4−6 PgC for incremental change, and 12−19 PgC for systemic change. Furthermore, it is estimated that >18 PgC could be sequestered by increasing global tree cover on agricultural land by 10% [113]. A determination has been made, which is thought to be more realistic than previous estimates, of the total potential C sequestration in the US by forests at 995 $Tg·yr^{-1}$ (776 $Tg·yr^{-1}$) and agroforests (219 $Tg·yr^{-1}$) which represents approximately 15% of the US CO_2 emissions [114]. It has been shown that both food security and income variability are improved in semi-arid tropical regions of southern India, where agroforestry is employed [115]. Knowledge gaps have been identified in regard to utilising agroforestry methods for climate change adaptation, and where improvements could be made [116]. These include the absence of a geographically even distribution of global research, the need to identify specific cases where agroforestry could be applied beneficially for adapting to particular climate hazards combined with longitudinal research approaches, and a dearth of integrated biophysical–socioeconomic information [116]. It is proposed that addressing these deficiencies, along with a broader dissemination of recent knowledge, would help to better place agroforestry within planning and policy considerations for climate change adaptation [116], and in accord with a recent IPCC report [117]. Potential issues of water scarcity have also been considered in regard to implementing agroforestry systems [118]. Interestingly, from a meta-analysis of agroforestry systems in Mediterranean countries, it was deduced that the overall effect of trees on crop yields was negative, and that this might be due to competition for light. However, the authors conclude that, for extreme climate events, benefits could still be accrued if appropriate agricultural methods are employed to achieve synergies among tree cover, tree species, crop species, and management practices. The study identifies a need to investigate the utility of agroforestry at both field and landscape scales, in the Mediterranean region, along with a full lifecycle evaluation both of these systems and other choices and designs for companion planting [119].

9. Forest Fires

Data recorded, over the period 2001–2019, conform that forest fires are becoming more widespread, burning nearly twice as much tree cover today as they did two decades ago [120]. Thus, an additional 3 million hectares of tree cover is lost to fires, annually, than was the case in 2001, and more than a quarter of all tree cover loss over the past 20 years has been caused by forest fires [120]. It is widely held that the severity and scale of forest fires are driven by the fuels that have accumulated in the understory, due to the suspension of forest management to reduce these fuels (i.e., pulping, masticating, thinning, raking, and prescribed burning), along with extensive fire suppression practices [53]. In addition, species migration due to climate change results in pests attacking and killing trees in Canada and the US, which generates far more fuel, along with longer dry periods and increased temperatures [121].

Fire suppression involves extinguishing fires immediately that they begin, to prevent them from destroying people's homes, which are increasingly built near to or within forests [122]. Although wildfire suppression serves human safety and protection of property, it is thought that the lack of natural fires can change ecosystems, and increase the scale of fires when they do occur. Hence, fire ecology is more complex than is often assumed. Controlled burns have been proposed as a means for reducing the amount of fuel in forests [123], while in California, native Americans have been invited to revive their cultural burning practices [124], and it is proposed that similar indigenous knowledge could be used to prevent bushfires in Australia [125]. In the US, the Nature Conservancy is working with the United States Forestry Service to manage forests ecologically, and by deliberately thinning the forest understory, it is thought that fire can be deliberately reintroduced as a restorative agent [126]. Another study has emphasised that the high intensity of forest fires can impair the regrowth of seedlings, but that by controlled burning with forest thinning, or cultural burning by indigenous groups, the chances of forests recovering from them are improved [127].

Although, as noted, the intensity and scale of recent fires are thought to be strongly correlated with the accumulation of fuel materials in the understory, there is some evidence suggesting that proforestation should actually reduce the risk of fires [53]. It is important to note that fires are essential features of forest dynamics in the Western US, and also, even with fuel removal treatments, they are not entirely preventable [128]. It has been stressed that the area of forest burned is, in fact, currently smaller than in the first half of the twentieth century, when there was more intensive timber harvesting, but no active suppression of fires [129,130]. Indeed, it has been found that, during the past 30 years, in the Western US, intact forests burned at appreciably lower intensities than did their managed counterparts [131,132]. It may be that the increased potential fuel in intact forests is counterbalanced by the drier conditions, increased wind-speeds, smaller trees, and residual and more combustible fuels that are a feature of managed areas [128,132]. Hence, instead of trying to extinguish wildfires wherever they occur, it might be more effective to restrict development in fire-prone areas, while creating and protecting zones around existing developments, and introducing the construction of fire-resistant buildings [128,133].

10. Urban Trees and Wet-Bulb Temperature

The presence of trees and shrubs in streets, parks, woodlands and other urban spaces confers many benefits in towns and cities (where more than half of the world's population lives). Such plants help to ameliorate some of the negative impacts of climate change, especially as a result of sequestering carbon, and providing local cooling through evapotranspiration and shading [134]. They also provide habitat for biodiversity, and help to connect people and nature, with improvements to both physical and mental health. However, the choice of trees and shrubs for a particular location should not include species that may not survive and thrive in an expectedly warmer future climate, with predictably more severe and more frequent periods of heatwave and drought [134]. One study has indicated that by increasing tree cover in Europe, from its average of 14.9% to 30%, could reduce city temperatures by 0.4 °C, and curb heat-related deaths by 39.5%. It was estimated that some 2644 of the 6700 premature deaths recorded in 2015, that were ascribed to higher urban temperatures, could have been prevented had the tree cover been greater [135].

Climate change is expected not only to increase temperatures, but also humidity. This is apparent from the Clausius-Clapeyron equation, which indicates that for a rise in temperature of 1 °C from the global mean of 15 °C, the water content of the air would increase by 6% [136]. It is the combination of increasing temperature and humidity that is particularly dangerous, as the threshold at which the human body is unable to keep itself cool by sweating is approached: if sustained, this is likely to be fatal, even to fit and healthy people. One means for assessing this is by the wet-bulb temperature, and previously, 35 °C (at 100% humidity) was believed to be the upper limit that the human body can withstand. However, a recent study [137] assessed this value at 31 °C, and further determined that, should global temperatures increase by 2 °C above pre-industrial levels, some 4 billion people would experience, annually, "many hours of heat that surpass human tolerance": these include 2.2 billion living in the Indus River valley of Pakistan and India, 1 billion in eastern China, and 800 million in sub-Saharan Africa. Although the results indicate that people will be worst affected in poorer nations, and where rapid population growth is predicted during the coming decades, given the highly interconnected nature of globalised civilization, even in wealthier countries no one will remain unscathed by climate change [137]. However, it has been shown that the presence of trees and tree canopies can provide effective protection against extreme heat stress in urban environments, especially during the daytime [138].

Green corridors can be introduced as a means for keeping cities cool, and to mitigate urban heatwaves. One successful example of this is in Medellin, Columbia's second-largest city, with a population of 2.5 million. Its "green corridors" project has become recognised worldwide as a means for creating cooler public spaces. At a cost of $16.3 million, 8800 trees and palms were planted in 30 corridors that cover an area of 65 hectares, thus reducing average city temperatures by 2 °C, along with increased uptake of carbon via plant growth, capturing particulate matter ($PM_{2.5}$) to improve air quality, and increasing urban biodiversity from the establishment of more wildlife-friendly habitats [139].

11. Nature Based Solutions

Some of the approaches so far considered may be included among the arsenal of "Nature Based Solutions" (NBS), "Climate Based Solutions" (CBS), or "Natural Climate Solutions" (NCS)—the choice of term depending on the intended emphasis—and it is important to identify how these might be integrated to overall best effect. A hierarchy of actions [140]. has been offered for NBS: "Protect; Manage; Restore"—a similar mantra to "Reduce; Reuse; Recycle" in the overall context of sustainability, to which a fourth *R* should be added, "Regenerate" [141], as is inherent to *natural systems.* The methodologies of NBS fall broadly into the regions: forests, wetlands, grasslands, and (restorative; regenerative) agriculture. Forestry practices may include planting new forests, natural regeneration, and more effective forest management. Grasslands can be preserved by avoiding their conversion for other purposes. Wetland-related practices involve the conservation and restoration of peatlands and also coastal wetlands, for example mangroves. Restorative (regenerative) agriculture covers many different methods for building soil carbon, for example no-till agriculture and rotation of cover crops, agroforestry and more effective control of livestock [140–142].

Trees are essential within some of the key strategies proposed for NBS/NCS [140]: as a first line of defence, the protection of existing forests (along with wetlands and grasslands); better forestry management (and also that of farmland and grazing land); and finally, restoration of forests (and wetlands). A comprehensive analysis has been reported of twenty (NCS) conservation, restoration, and/or improved land management actions that might be adopted in order to increase carbon sequestration and/or to curb emissions of greenhouse gases globally, across forests, wetlands, grasslands, and agricultural lands. It was deduced that one-third of the climate mitigation needed up to 2030 as required to keep global heating below 2 °C could be provided by such NCS methods [142]. Concerns have been expressed that the clear promise of NBS is steering attention away from the necessity of phasing out fossil fuels and preserving existing intact ecosystems [143]. Thus, the need to correctly frame and broadcast NBS is emphasised, so to deliver sustainable benefits to society: (1) NBS are not a substitute for the rapid phase out of fossil fuels; (2) NBS involve a wide range of ecosystems on land and in the sea, not just forests; (3) NBS are implemented with the full engagement and consent of Indigenous Peoples and local communities in a way that respects their cultural and ecological rights; and (4) NBS should be explicitly designed to provide measurable benefits for biodiversity [143].

A paper [144] reporting (the) *World Scientists' Warning of a Climate Emergency*, also includes the oceans in its coverage of conserving what is already intact, noting that: "We must protect and restore Earth's ecosystems. Phytoplankton, coral reefs, forests, savannas, grasslands, wetlands, peatlands, soils, mangroves, and sea grasses contribute greatly to sequestration of atmospheric CO_2. Marine and terrestrial plants, animals, and microorganisms play significant roles in carbon and nutrient cycling and storage. We need to quickly curtail habitat and biodiversity loss, protecting the remaining primary and intact forests, especially those with high carbon stores and other forests with the capacity to rapidly sequester carbon (proforestation), while increasing reforestation and afforestation, where appropriate, at enormous scales." [144]. Practical actions, along with specific timescales, including governance and leadership aspects, are addressed in a subsequent *World Scientists' Warnings into Action, Local to Global*, paper, which focuses on six key areas, Energy, Atmospheric Pollutants, Nature, Food systems, Economic Reform, and Population, for dealing with the underlying problem of human ecological overshoot, of which climate change is but one symptom [54]. The concept is taken to a deeper level in a follow-up paper, which proposes that a Human Behavioural Crisis lies at the root of overshoot, but that acknowledging this may also provide a critical point of intervention for curbing our hyperconsumption of natural resources [145].

12. Trees and One-Planet Living—A Summary Set of Guidelines

Protect existing mature (primary) forest ecosystems—stop deforestation—and allow them to grow to their full potential (*this has an immediate effect*).

Natural regeneration, *assisted* if necessary. Expand areas around mature forests, allow secondary forests to grow (*cheaper*, *easier*, *and richer in biodiversity than planting*).

If planting is to be done, plant mixtures of "native" tree seedlings ("whips") or seeds in areas *where forest previously existed*; avoid projects that convert grasslands or peatlands to forest, or clearing established forest to grow tree plantations, e.g., or palm oil.

Avoid introducing undesirable "alien" species, of trees or parasites.

Mangroves, and ocean "forests" of kelp and seaweed to be established and protected.

Still need to reduce carbon dioxide (and other GHG) emissions at source, and not rely on natural climate solutions alone to continue with Business as Usual. *The overall problem is "overshoot"*.

13. Conclusions

There are estimated to be about 3 trillion trees on Earth, or about half the number that existed before the dawn of human civilization. Trees are vital to at least four major biogeochemical cycles, namely, the carbon, water, nitrogen and oxygen cycles. In addition to absorbing carbon, and releasing oxygen through photosynthesis, trees are critical for maintaining biodiversity, providing habitat for 80% of land based wildlife, feeding the soil, generating clouds and increasing albedo (thus causing global cooling), influencing rainfall and weather patterns. The loss of trees, therefore, weakens our chances of reaching climate and biodiversity targets, and so proforestation and other practices to stringently preserve the functionality of and holistically restore forest ecosystems, must be adopted as a matter of urgency, paying due attention to soil, and species diversity including mycorrhizae; not being limited to insouciant "tree planting" solutions. Indeed, due to the tardiness of our actions to repair the Earth and its climate, severe restrictions to the cutting of mature trees must actually be enabled globally.

Nonetheless tree growing [with a focus on (assisted) natural regeneration, rather than just tree planting] alone is not enough to offset climate change. It must be integrated with all other forms of land, wetland, grassland and agricultural protection and restoration. Taken together, such NBS could provide more than one-third of the cost-effective climate mitigation needed by 2030 to keep within the 2 °C global heating limit.

It is also critical to reduce emissions, not only of CO_2 but all other greenhouse gases, at source, by implementing both low-carbon, renewable energy, and energy demand reduction strategies, such as insulating buildings, relocalisation, and local food growing.

Finally, even climate change is not *the* problem, but a symptom of ecological overshoot, which is underpinned by a human behavioural crisis that needs to be addressed.

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