Peatland geoengineering: an alternative approach to terrestrial carbon sequestration

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Terrestrial and oceanic ecosystems contribute almost equally to the sequestration of *ca* 50 per cent of anthropogenic CO_2 emissions, and already play a role in minimizing our impact on Earth's climate. On land, the majority of the sequestered carbon enters soil carbon stores. Almost one-third of that soil carbon can be found in peatlands, an area covering just 2–3% of the Earth's landmass. Peatlands are thus well established as powerful agents of carbon capture and storage; the preservation of archaeological artefacts, such as ancient bog bodies, further attest to their exceptional preservative properties. Peatlands have higher carbon storage densities per unit ecosystem area than either the oceans or dry terrestrial systems. However, despite attempts over a number of years at enhancing carbon capture in the oceans or in land-based afforestation schemes, no attempt has yet been made to optimize peatland carbon storage capacity or even to harness peatlands to store externally captured carbon. Recent studies suggest that peatland carbon sequestration is due to the inhibitory effects of phenolic compounds that create an 'enzymic latch' on decomposition. Here, we propose to harness that mechanism in a series of peatland geoengineering strategies whereby molecular, biogeochemical, agronomical and afforestation approaches increase carbon capture and long-term sequestration in peat-forming terrestrial ecosystems.

Keywords: peatland geoengineering; carbon sequestration; phenolic compounds; inhibition; decomposition; enzymic latch

1. Introduction

Anthropogenic carbon emissions exceed $8\,Pg\,yr^{-1}$ and significant cuts are considered necessary to prevent further climate change [1]. The Intergovernmental Panel on Climate Change (IPCC) emissions scenarios suggest that, without policies to reduce climate change, CO_2 concentrations could reach 535–983 ppm by 2100, with potentially 1.1–6.4°C of additional global warming [1]. It is generally accepted that this could be sufficient to cause significant problems, ranging from rising sea levels, drought or loss of habitat, to severe storms and increased ocean acidity [1,2]. Stabilizing CO_2 concentrations presents considerable economic and technological challenges, but geoengineering could help reduce the future extent of climate change or provide more time to address the challenges posed by

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mitigation, such as phasing out CO_2-emitting fossil fuel energy technologies and developing/deploying energy sources that are carbon neutral [2].

Although the concept of geoengineering is not new, interest in the topic is beginning to grow rapidly [3] in line with concerns about climate change. Many strategies have been considered, including (i) reducing incoming solar radiation, for example using aerosols such as sulfur dioxide or reflection technologies [2,4,5], and (ii) CO_2 sequestration underground [5] or in the oceans [6]. However, ecological or biogeoengineering options have also been proposed. These biological options include (i) ocean fertilization by supplementation with iron or macro- or micro-nutrients that are limiting [7,8], and (ii) carbon sequestration as biomass in agricultural and forest ecosystems [9,10]. There are also opportunities for (iii) reducing predicted increases in global surface temperatures by increasing the albedo of crop plants [11]. However, carbon-capture approaches are particularly attractive, as they address not just the symptoms of global warming, but also the rising CO_2 emissions that lie at the root of the problem.

When 'carbon capture and storage' is referred to in the media, the term is commonly assumed to involve 'geo-sequestration' in which captured CO_2 is stored in depleted oil and gas fields or in saline aquifers. However, this option involves substantial capital investment in large-scale projects and raises concerns about the financial implications of those projects. In contrast, much the same outcome can be obtained by harnessing the natural carbon-capture capacity of ecosystems on a much smaller scale and with considerably lower costs. Afforestation has long been recognized as one such potential approach [12], and certainly attracts the greatest media attention. However, primary producers in all ecosystems have an immense capacity for carbon capture, but with a major constraint arising from the small proportion of that carbon that enters long-term carbon stores such as soils. Carbon that enters those soil carbon stores can become sequestered on millennial time scales and with low risks of leakage back to the atmosphere [13,14]. The aim of any ecosystem-based terrestrial carbon-capture scheme must therefore be to increase the proportion of photosynthetically captured carbon that enters our long-term carbon stores. One approach proposed to increase the proportion of carbon sequestered is low-temperature pyrolysis (combustion under low-oxygen conditions) of plant materials. This results in a carbon-rich residue known as 'biochar', which can be stable for thousands of years [15]. However, several carbon costs are associated with the land-based production of biomass, transport to the bioenergy plant, pyrolysis itself and land application of biochar [16], and so even this approach could be improved by harnessing natural ecosystem properties to retain the captured carbon.

Useful guidance on the most promising strategies for enhanced carbon capture can be gained by comparing rates of carbon sequestration among different ecosystems. Peatlands have higher carbon storage densities per unit area of ecosystem than either the oceans or truly terrestrial systems [17,18]; peatlands cover 2–3% of the Earth's land (figure 1) but are vast global repositories of organic matter, storing approximately one-third of all soil organic carbon (390–455 Pg), and acting as sinks for atmospheric carbon [20]. This carbon storage capacity occurs because rates of primary production exceed particularly slow decomposition rates, resulting in the long-term accumulation of the partially decomposed organic matter known as 'peat' [20,21]. Traditionally, this impaired decay has been attributed to anoxia [20,22], low nutrients, low temperatures and
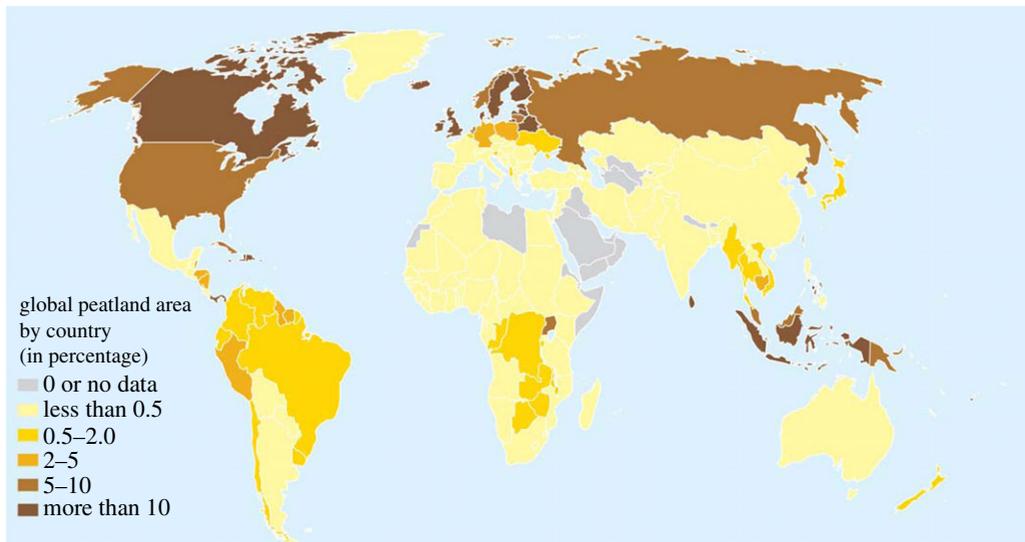
Figure 1. World peatland distribution [19]. (Online version in colour.)

low pH [20,23]. However, it was recently appreciated that oxygen constraints on a single class of enzymes exert a particularly potent control over the vast carbon stock held in peatlands [24,25]. Phenol oxidases are among the few enzymes able to fully degrade inhibitory phenolic compounds (derived from plant breakdown products) but require oxygen to operate efficiently [22]. The predominantly anoxic conditions in peat allow an accumulation of phenolic compounds, which, in turn, prevent the major agents of nutrient and carbon cycling, namely hydrolase enzymes, from carrying out their normal processes of decay [26,27], suppressing microbial enzymic decomposition of senescent vegetation and thus promoting sequestration of huge stores of carbon [19]. While this highlights the potential for carbon loss as a result of increased drought frequency, the recognition of this 'enzymic latch mechanism' [24] also allows us to propose valuable new carbon capture opportunities.

2. The 'enzymic latch' as a tool for carbon capture

Phenolic compounds are a highly diverse group of organic compounds, defined by the presence of at least one aromatic ring, bearing one (phenols) or more (polyphenols) hydroxyl substituents or their derivatives, e.g. esters, glycosides. Simple monomeric phenols include the flavonoids and the phenolic acids, occurring universally within the higher plants [28]. Woody plants are the main producers of polyphenols [29]. While lignins, being the most stable of the polyphenols, may have the largest long-term effect on litter recalcitrance, it is the tannins that have been recognized as the polyphenols with the greatest control over fine-scale decompositional dynamics [30]. While the importance of simple phenolics, particularly the phenolic acids, in decomposition and nutrient cycling has been realized [30–32], the dynamics of this complex group remain
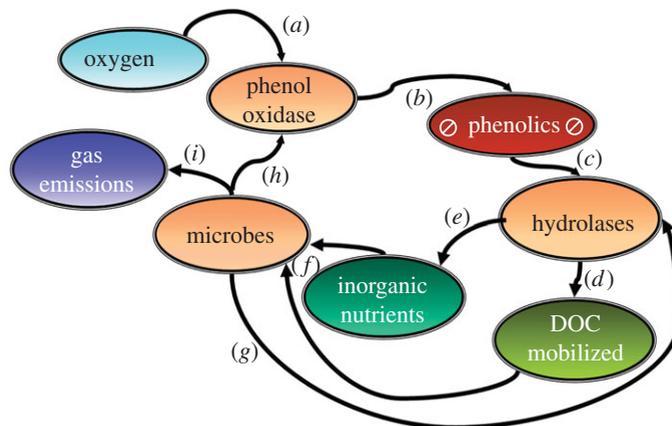
Figure 2. Illustration of the role of phenol oxidase in regulating peatland carbon storage through the 'enzymic latch' mechanism. (Online version in colour.)

underexplored [33] and so offer significant opportunities for further studies with the aim of manipulating the effectiveness of the enzymic latch. It is well documented that polyphenols inhibit organic decomposition [24,34,35].

Phenolic compounds form complexes with protein molecules, serving as polydentate ligands causing inactivation of hydrolase enzymes through competitive and non-competitive inhibition [26]. The polyphenols bind to the reactive sites of proteins and other organic and inorganic substrates, often rendering them inactive to further chemical activity and biological attack [36]. Soil environmental conditions may influence the potency of the inhibitory nature of polyphenols; the dissociation of polyphenol protein complexes, for example, being positively correlated with pH [37].

The extent to which phenolic inhibitors accumulate within the peatland soil is dependent on the activity of enzymes capable of their elimination. Phenol oxidases are oxidative copper-containing enzymes that catalyse the release of reactive oxygen radicals, which, in turn, promote a variety of non-enzymatic reactions to oxidize phenolic compounds [38,39]. Phenol oxidases instigate the oxidation of both complex polyphenols and simple phenolic compounds, with outcomes ranging from partial oxidation and the release of oxidative intermediates, to the complete degradation of phenolic compounds to non-phenolic end products.

Fungi, bacteria, actinobacteria and, to a lesser extent, plants, all contribute to extracellular phenol oxidase pools, with the general consensus that the basidiomycetous fungi are the major contributors in lignin-rich decompositional environments [40]. It is likely that the cycling of lignin and polyphenolic compounds in most soil decompositional environments is a result of the pooling of extracellular enzymes from a variety of both fungal and non-fungal producers, the specific community compositions of which being a key driver of an ecosystem's extracellular phenol-oxidizing capability [41].

In essence, the enzymic latch mechanism (figure 2) involves constraints, such as the absence of oxygen, preventing the following sequence of events: in the first step, oxygen stimulates phenol oxidase (*a*), and causes a decline in the abundance of inhibitory phenolics (*b*). The reduction in inhibitor abundance allows a
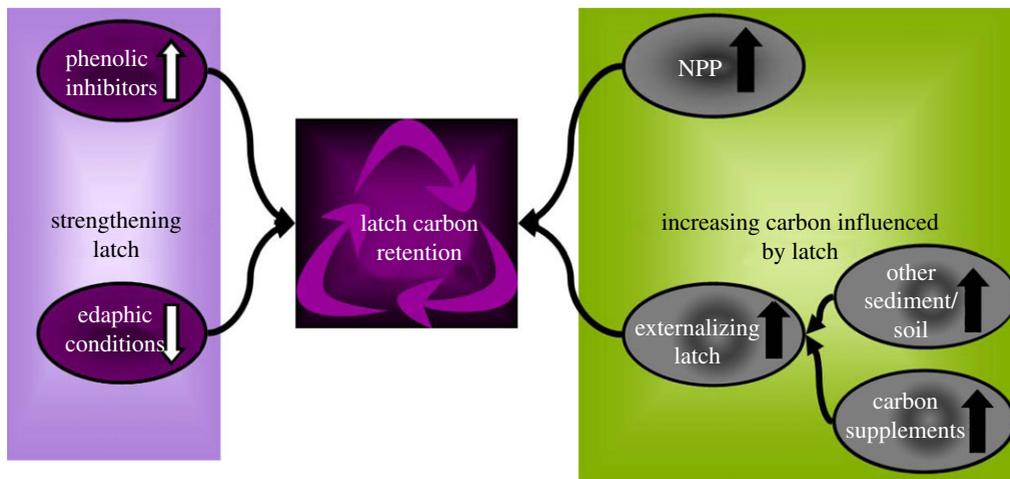
Figure 3. A summary of options available for enhancing peatland carbon sequestration. (Online version in colour.)

stimulation of the hydrolase enzymes within the soil matrix (c). The stimulated hydrolase activities create two responses: increased breakdown of low-molecular-weight labile dissolved organic carbon (DOC; d) and release of inorganic nutrients that were previously sequestered within the soil matrix (e). The latter two events provide substrates and nutrients to support enhanced microbial activity (f), and hence increased production of hydrolase enzymes (g) and phenol oxidase (h), together with enhanced emissions of biogenic trace gases such as CH_4, CO_2 and N_2O (i). The key regulators of this pathway are thus the inhibitory phenolics and the factors influencing the enzymes capable of depleting those phenolics.

Improvements in carbon capture could potentially be achieved through two approaches (figure 3): first, by *strengthening the enzymic latch* by increasing the abundance of phenolic inhibitors, or manipulating edaphic factors that slow decomposition in peatlands (e.g. redox potential, inorganic nutrient availability, labile carbon inputs and pH); and, second, by *increasing the amount of carbon influenced by the enzymic latch*, using methods either to increase peatland plant productivity and add externally captured carbon, or to transplant the 'latch mechanism' to non-peatland locations.

3. Options for strengthening the enzymic latch

The production of plant litter from net primary production (NPP) in Northern peatlands can reach $489 \, \mathrm{gC \, m^{-2} \, yr^{-1}}$ [42]. As Northern peatlands cover 346 million hectares ($346 \times 10^{10} \, \mathrm{m^2}$), peat litter production could potentially sequester $1.7 \times 10^{15} \, \mathrm{g \, yr^{-1}}$, or approaching 148 per cent of current transport carbon emissions. In fact, they only sequester an estimated 1×10^{14} or 9 per cent of that in the long term. This inefficiency arises because substantially less carbon enters long-term storage, 34–$52 \, \mathrm{gC \, m^{-2} \, yr^{-1}}$ [43], than is initially captured. In order to strengthen the enzymic latch, we must either increase the expression of phenolic

phenylalanine

phenylalanine ammonia lyase

trans-cinnamic acid

cinnamate 4-hydroxylase

p-coumaric acid

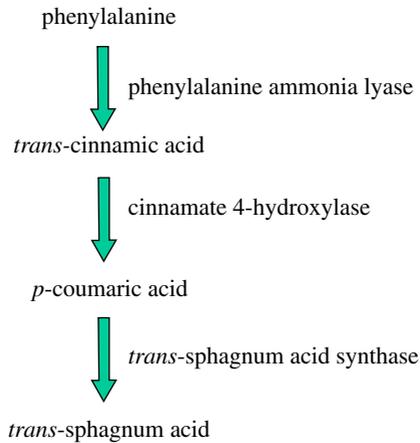*trans*-sphagnum acid synthase

trans-sphagnum acid

Figure 4. Synthesis pathway for the phenolic compound *trans*-sphagnum acid. (Online version in colour.)

inhibitors to increase their abundance in the soil medium, or create physico-chemical conditions within the soil environment that 'amplify' the inhibitory effects of phenolics on carbon cycling.

(*a*) *Increased expression of phenolic inhibitors*

Peatland plant communities clearly have an important role in ecosystem carbon dynamics and storage, with every species possessing a unique functional phenotype [44–46]. *Sphagnum* spp. are particularly important in this respect, as they are characteristic of both peat bogs and nutrient-poor fens [47], showing the greatest global ecological dominance of all bryophyte taxa [48]. The slow decomposition rates of *Sphagnum* tissues [49] make them the single most important carbon-accreting species in bogs [50]. Indeed, it has been estimated that more than half of the world's peat originated from *Sphagnum* spp., representing 10–15% of the entire terrestrial carbon stock [51].

The unusually low rates of decomposition of this genus are attributed to specific secondary compounds, most notably polyphenols, which have a potent inhibitory effect on microbial breakdown [24,52]. The most important polyphenol in *Sphagnum* mosses is a cinnamic acid derivative called *trans*-sphagnum acid that is unique to peat mosses. The available quantity of this derivative varies depending on species, season and the part of the plant investigated [53], but all species analysed are characterized by substantial quantities and also can secrete it into the external medium. There is considerable evidence that, while *Sphagnum* lacks lignin, the phenolic *trans*-sphagnum acid is synthesized via the phenylpropanoid pathway from phenylalanine [54]. The proposed synthetic route is shown in figure 4 (enzymic catalysers shown to the right of arrows).

Increased carbon storage could be achieved by increasing the absolute amount of phenolic inhibitors present, which in turn can be achieved by promoting phenolic production through the genetic modification of the *Sphagnum* plants responsible for phenolic synthesis. The enzyme (*trans*-sphagnum acid synthase, tSphA) responsible for the final catalytic stage resulting in the synthesis of *trans*-sphagnum acid remains to be isolated. However, the genes coding for

the other determining enzymes of the pathway have already been isolated from a variety of plants, including the moss species *Physcomitrella patens*. The determining enzyme of the phenylpropanoid pathway (phenylalanine ammonia lyase, PAL) has already been shown to be the key step regulating flux through the pathway—an increase in PAL levels leads to an increase in the accumulation of major phenylpropanoid pathway products [55]. We therefore suggest that the use of a transgenic approach, to increase the levels of *trans*-sphagnum acid in *Sphagnum* by increasing the expression of *Sphagnum* PAL, could offer great benefits to geoengineering.

While, at first consideration, successful introduction of a new form of *Sphagnum* into the environment may seem highly challenging, it should be noted that this would not be the first occasion on which a single *Sphagnum* plant had colonized an entire continent. A total of 100 per cent of the gene pool of *Sphagnum subnitens* in North America was contributed by one individual plant [56], and while this took place over 300 years as a natural process, it is likely to be achieved far more rapidly with human intervention.

(b) Physico-chemical enhancement of enzymic-latch-mediated carbon retention

By manipulating the strength of the enzymic latch, marked improvements in carbon capture can potentially be achieved even without affecting plant growth. Empirical testing of the enzymic latch concept across peatlands representing a nutrient gradient has identified in the latch regulatory pathway specific points that could markedly impair decomposition in both aerobic and anaerobic pathways (figure 2); adverse pH, oxygen, labile carbon and inorganic nutrient availability can all promote enzymic-latch-mediated suppression of decomposition, along with the generation of certain particularly inhibitory phenolic compound types. In earlier studies of the enzymic latch, we have found that phenol oxidase regulates key aspects of the biogeochemical decomposition process in peatlands through the sequence of events summarized in figure 2, key processes within which are amenable to manipulation using approaches such as those illustrated in figure 5.

(i) Process 1

Oxygen availability can be manipulated by raising water table levels and by reducing flow rates (hydrological manipulations such as the introduction of dams; figure 5) to reduce O_2 replenishment. There may also be value in adding chemical reducing agents to the soil. This will regulate activity in the form of de novo phenol oxidase synthesis in the microbial community and also in the form of pre-existing 'edaphic' exoenzyme activity in the peat itself.

(ii) Process 2

Acidification, by addition of sulfates, potentially from the solar radiation management (SRM) strategies mentioned earlier, will suppress phenol oxidase enzyme activities. Phenol oxidase activity is particularly sensitive to low pH [57,58] and will have indirect effects on hydrolase enzymes by allowing the accumulation of higher levels of inhibitory phenolic compounds. Indeed, the effects of ammonium sulfate, a physiological acid fertilizer, can increase wetland rice productivity while decreasing decomposition [59].
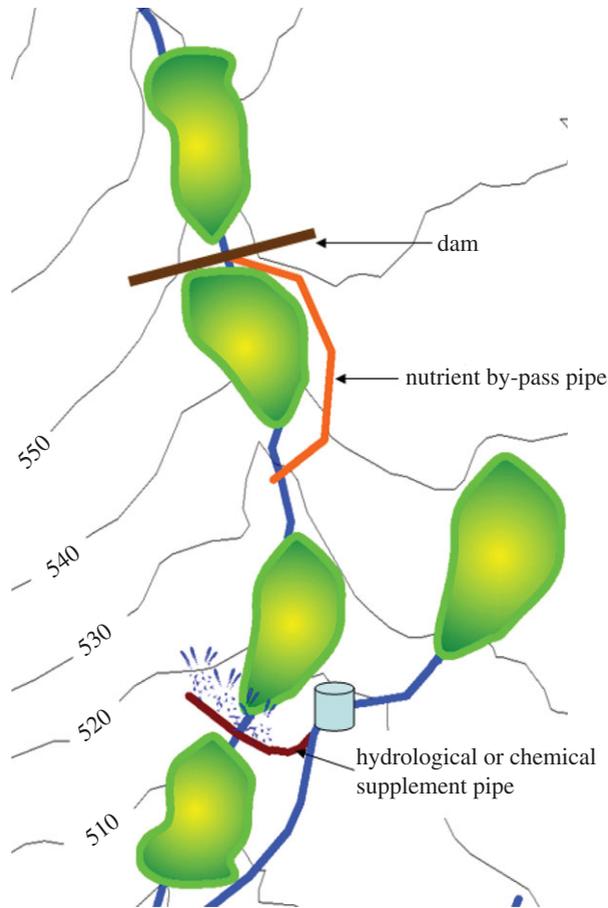
Figure 5. Peatland manipulation site with options for installing dams to increase waterlogging in peatlands above the dam. Pipes can take water from the dam to divert nutrients away from the wetland below to modify plant or microbial biodiversity. A supplement pipe can take waters from parallel watersheds to increase waterlogging/paludification in the test sites below. Nutrients can be added to increase *Sphagnum* productivity, or other chemicals (e.g. sulfates, exogenous phenolic inhibitors) can be added to the water to strengthen the enzymic latch and suppress enzymic decomposition. (Online version in colour.)

(iii) *Process 3*

Phenolic supplements can be applied to suppress (i) microbial metabolism and therefore de novo synthesis of enzymes (phenol oxidase and both carbon- and inorganic nutrient-cycling hydrolases) and (ii) edaphic enzyme activities (phenol oxidase and hydrolases). Sources of phenolic compounds might include naturally produced anaerobic compounds in peat leachates, *trans*-sphagnum acid collected *in vitro* or other analogue polyphenolic waste materials (e.g. coir, apple pulp from cider production and green compost) and liquids (e.g. olive waste, paper waste and green compost leachate) that release their nutrients slowly, while maintaining low soil-carbon turnover rates.

(iv) *Process 4*

Hydrolase enzyme activities can be reduced by lowering pH, labile carbon and inorganic nutrient supply (see process 5).

(v) *Process 5*

Lowering available inorganic nutrients and labile carbon will suppress further enzyme production by the microbial community (de novo synthesis) by the addition of complexing agents (e.g. high-molecular-weight organic carbon and phenolics) and hydrological manipulation to reduce the replenishment of nutrients. Furthermore, more subtle options such as manipulating microbe and plant biodiversity (see below) can also suppress enzyme production. While these options for peatland geoengineering of our climate represent a new concept, other forms of peatland manipulation have a long history. Drainage, for example, commenced before Roman times and was also recorded in *Domesday* [60]. The peak rate of drainage in the UK has been estimated to have reached $100\,000\,ha\,yr^{-1}$ in 1970 [61,62]. In Northern Ireland, there are only $169\,km^2$ of intact peat left compared with $1190\,km^2$ of total peatland [63]. Such figures give a clear indication of the potential for rapid regional-scale manipulation of peatlands.

4. Increasing the amount of carbon influenced by the enzymic latch

In addition to the approaches mentioned earlier, which all attempt to secure more effective retention of carbon entering peatlands at current rates, another option is to increase the amount of carbon entering the soil system. Strengthening the enzymic latch after increasing the amount of carbon retained would synergistically increase the amount of carbon sequestered.

(*a*) *Optimizing peat carbon capture*

Unlike conventional agriculture, where productivity has more than doubled in the past 40 years [64], no attempt has yet been made to increase the productivity (and hence carbon sequestration) rates of peatland plants. Established agronomical approaches (irrigation, warming, fertilizer addition, etc.) could therefore prove viable methods for increasing peatland NPP. Water is the most important factor conferring wetland properties [65], and global productivity patterns indicate that wetter microhabitats are the most productive in *Sphagnum* bogs [66]. Both water table and flow rates could then be manipulated in order to enhance NPP (figure 5). Mean annual temperature can also be manipulated as a key factor affecting global peatland productivity, with warm humid conditions being optimal for *Sphagnum* growth [66]. This can be achieved by manipulating the insolation of peat soils (through modification of plant cover characteristics). While current CO_2 levels may not be limiting to bryophyte NPP owing to their proximity to soil-respired CO_2, other peatland plant functional groups (e.g. grasses and sedges) can be stimulated by elevated CO_2 [46]. Waste CO_2 could be fixed in peatland mesocosms by plant and algal components and then used as soil amendments to 'pristine' or restored peatlands. Chapin *et al.* [67] found that

subtle changes in N : P ratios and pH can increase above-ground NPP in bogs and poor–intermediate fens during their investigations of the relative roles of nutrient limitation and pH stress in peatland plant community structure. Thus, even where the vegetation is adapted to acidic and oligotrophic conditions, the potential exists for increased carbon capture, which would then be available for long-term storage via the enzymic latch. Manipulation of N : P ratios using NH_4Cl and $NaH_2PO_4 + Na_2HPO_4$, for example, could therefore be investigated. Similarly, the effect of nitrogen applied as amino acids warrants research, because plants (including bryophytes) that are able to use amino acids directly from the soil may have a competitive advantage in these low-nitrogen ecosystems [68]. Application of ammonium sulfate, a physiological acid fertilizer, has been shown to increase wetland rice productivity while decreasing decomposition [59] and therefore could be investigated along with liming (addition of $CaCO_3$) to raise the pH. Finally, soil amendments could also be investigated to promote NPP. Application of organic matter in the form of *Sphagnum* litter would represent a good candidate, because this can be an important source of N for bryophytes [69], yet is also known to inhibit microbial decay. Similarly, anaerobically produced peat leachate (rich in phenolics) and analogue polyphenolic waste materials (e.g. coir, apple pulp from cider production and green compost) and liquids (e.g. olive waste, paper waste and green compost leachate) that release their nutrients slowly while maintaining low soil-carbon turnover rates would require testing.

Of course, long-term storage of carbon captured by NPP is inextricably linked with peatland plant functional groups [44–46] and, in addition to carbon capture and retention, the following are identified as mechanisms that could be optimized to promote latch-mediated carbon storage:

— Transport of O_2 below ground. Minimizing the abundance of plant species capable of translocating O_2 below ground (also implicated in CH_4 release) would strengthen the latch. Such plants also increase evapotranspiration compared with *Sphagnum*, the avoidance of which would reduce soil moisture loss and thus minimize aerobic carbon losses in the form of CO_2 and DOC.

— Certain phenolic compounds are more potent inhibitors [26] of microbial de novo enzyme synthesis and/or edaphic enzyme activity. Identifying the most potent would allow us to maximize carbon storage, for example, by promoting plant functional groups rich in such compounds.

— Root exudation. Minimizing plant labile carbon can strengthen the enzymic latch [25,70], as such exudates have been associated with priming (i.e. accelerated decomposition) in peatlands [35,44] and soils [71,72]. If priming was suppressed (e.g. via manipulating plant functional groups), it would represent a valuable net gain in carbon storage.

— Promoting plant groups that compete strongly for inorganic nutrients can also impair microbial decomposition rates in peatlands [45] and a similar mechanism can occur in upland soils [73].

— Lowering pH (by encouraging paludification, manipulating plant groups and hydrological regime) can inhibit phenol oxidase activity [57,58], in turn, creating conditions favouring inhibition of hydrolases and, thus, decomposition.

(*b*) *External capture: peatland storage*

While the concept of capturing carbon through afforestation is well established [12], it is recognized as only a temporary solution—decomposition or burning re-releases that carbon back to the atmosphere [74]. The novel approach of 'injecting' timber below the surface of peatlands could, though, offer a solution to this problem via long-term sequestration as a beneficial consequence of enzymic-latch-mediated suppression of decomposition. CO_2 sequestered in forested areas could be 'fixed' by injection of timber into deep peats where the enzymic latch would prevent re-release of that CO_2 back to the atmosphere. Oak's widespread nature, abundance and predominance as ancient archaeological remains [75,76] make it a candidate for research, although fast-growing, non-durable, commonly used species (such as poplar) could be more useful for carbon sequestration [77]. Pine has been found to possess particularly potent antimicrobial properties [78], and therefore could also be useful in this role if decay was found to be particularly slow, and similarly for tropical hardwoods, which possess higher levels of extractives than temperate hardwood [79]. Designing optimal methods of timber injection while ensuring minimal damage to the peatland ecosystem would be a prerequisite to field-scale application if such a technique were found to be viable at the microcosm and mesocosm scale. Timber could, for example, be inserted initially to create a path to facilitate vehicular access (figure 6), and then be hidden by inserting the timber below the surface as the heavy machinery withdraws from the site after inserting the timber. This approach would leave the vegetated surface in a relatively undisturbed state.

5. Risks and rewards

While the rewards of capturing carbon in terms of climate change mitigation and the 'commodification' or 'monetization' of the sequestered carbon are readily appreciated [80], it should be borne in mind that any such development must inevitably be associated with risks. Taking this to the extremes, perhaps the most disturbing of these is the prospect that we may be so successful at sequestering carbon that we might conceivably induce runaway carbon capture. The prospect of plunging the planet into another Ice Age [81] would certainly raise public concerns. However, it should be borne in mind that, unlike many other geoengineering options, carbon sequestered in peat can always be returned to the atmosphere, should such a risk ever develop. In recent times, we have become extremely effective at developing approaches to destroy peatland ecosystems (through drainage and fire), so re-releasing their sequestered carbon [21]. There is also a threat to the stability of geoengineered peatlands in the form of droughts [24]. The IPCC Fourth Assessment Report states that 'it is very likely that areas affected by droughts and warm spells will increase' [1]. While this must raise some concern about the fate of carbon sequestered in peatlands, there is evidence that phenolics can remain active inhibitors even under aerobic conditions [34]. Thus, provided that phenolic supplements are applied in excess, carbon loss during the more aerobic conditions associated with droughts should be minimized. A further source of potential risk lies in the fact that, by expanding peatland abundance, we are encouraging an ecosystem that contributes 20 per cent to total annual emissions of methane, the largest natural source of a greenhouse gas
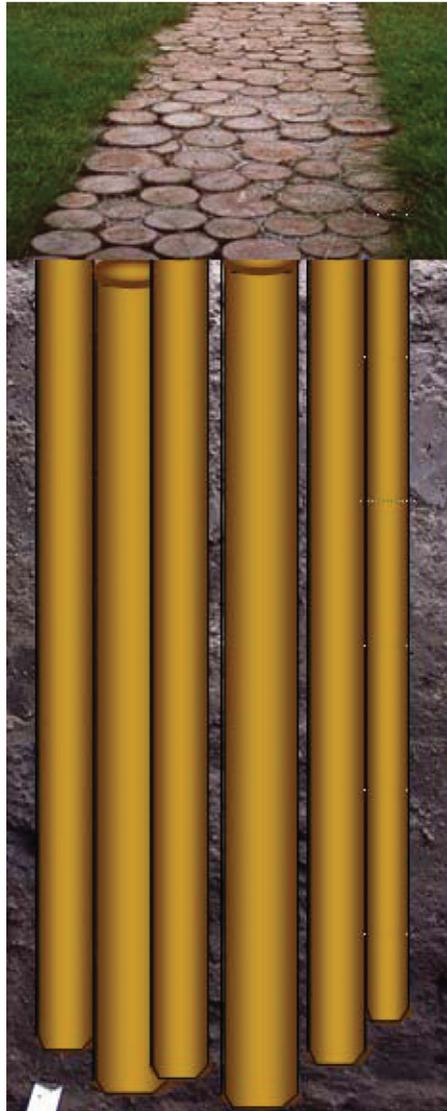
Figure 6. Photosynthetically captured carbon in the form of wood can be 'injected' into the peat, where the enzymic latch would fix that carbon at millennial time scales. (Online version in colour.)

with 25 times greater warming potential than CO_2 [1]. We acknowledge that it will be essential to ensure that any applied enzymic-latch-mediated enhancement of carbon sequestration does not add to the atmospheric burden of methane. Fortunately, by suppressing enzymic generation of labile low-molecular-weight substrates, the enzymic latch has the potential to constrain methane emissions in the same way that it suppresses CO_2 emissions. Concerns may be anticipated, however, about the application of transgenic *Sphagnum* in peatlands, although research in New Zealand suggests that the approach may be accepted by the public to a greater extent than has been the case for genetically modified foods. Genetic modification to promote a capacity for pollution control has

been shown to be looked upon relatively favourably, ranking alongside genetic modification for curing disease in terms of its acceptability [82]. There may also be risks to biodiversity, although whether introducing genetically modified plants such as *Sphagnum* could be considered damaging is yet to be determined [83]. Peatland geoengineering may be highly controversial in pristine ecosystems because, for example, it may alter natural pH gradients and a large part of peatland biodiversity is dependent on pH gradients. However, the addition of natural phenolic compounds or edaphic manipulation to acidify the system by natural mechanisms could preserve pH gradients and therefore biodiversity, while further slowing decay. Moreover, this could be highly valuable in protecting 'pristine' peatlands from haemorrhaging carbon during and after severe drought [84]. Furthermore, one could argue that pristine systems do not exist any more, given that (i) all are now bathed in high CO_2 [85] and (ii) many are either enriched with nutrients or recovering from SO_4 deposition. Application of the methods described in this study in the burgeoning field of peatland restoration could prove much more acceptable and highly valuable for both increased carbon storage and waste nutrient sequestration. It would also allow enhanced drinking water quality in peat-dominated catchments by lowering DOC exports into potable waters [86,87].

The two broad approaches to strengthening the enzymic latch and increasing its influence should create a capacity for increasing carbon capture via NPP and the efficiency with which that carbon is retained. For example, peat litter production alone could potentially sequester around 1.7×10^{15} g yr^{-1} were that primary production all sequestered effectively in the peat, even without external carbon capture. However, combining these two approaches to achieve maximum carbon accumulation may require a 'trade-off' between plant growth and decomposition rates; the balance will probably differ depending on the type of peatland (bog, fen or riparian) and dominant plant functional groups (bryophytes, sedges, grasses or dwarf shrubs) involved. Direct measurement of carbon sequestration is notoriously difficult though [88], and measuring potentially relatively small increases in carbon sequestration against high background carbon levels represented by peatlands requires careful consideration. One approach could be to combine stable isotopic labelling and soil carbon cycle modelling to partition net sequestration into changes in new, middle-aged and old carbon over the experimental period [44,88]. This partitioning is advantageous because new and middle-aged carbon accumulates (greater than 0), whereas old carbon is lost with time (less than 0) [88]. Using $^{13}C/^{12}C$ mass balance and inverse modelling, new and middle-aged inputs to the different carbon pools can be predicted versus decomposition of old carbon, allowing the estimation of carbon sequestration [87]. However, detailed life cycle analysis of treatments would be critical to determine the fate of carbon sequestered from the atmosphere and the wider effects on ecosystem function/services.

6. Conclusions

In conclusion, peatland geoengineering may be controversial in 'pristine' ecosystems, but, when compared with those physical geoengineering approaches that do nothing to reduce carbon emissions, *collateral damage* is potentially

far less because carbon capture and storage in peatlands simply harnesses the natural carbon-accreting and preservation properties of the ecosystem. Even injection of externally captured carbon as timber mimics the natural process of recruitment of wood into waterlogged environments [76,79] and, furthermore, many of these measures are essentially reversible. The challenges posed by these engineering activities cannot be underestimated. Injection of timber below the peat surface will require significant investment. Large-scale construction of dams is only feasible in areas that are relatively accessible by heavy machinery. With suitable incentives though, piecemeal small-scale interventions can result in landscape-scale changes by engaging land-owners in the carbon sequestration process. Adding supplements, whether in the form of acids, phenolics, nutrients or even modified *Sphagnum* plants, will also require research and investment in a suitable method of deployment. Considerable infrastructure for aerial deployment of solids and liquids is already available in agricultural areas, although more would clearly be required. It may also be possible to achieve such deployment as part of proposed SRM geoengineering methods using reflective aerosols in the stratosphere. Where sulfate aerosols are used, there is an added advantage that the acid character of the material is also known to suppress methane emissions from peatlands [89]. Clearly, while some of these strategies can only be attempted at a modest scale and are limited to accessible sites (figure 5), others are applicable at the largest scales (e.g. stratospheric deployment) and have the potential to impact upon peatlands in even the most inaccessible locations.

If peatland geoengineering is to become a significant carbon sequestration approach, then any carbon captured must be out of contact with the atmosphere for periods exceeding 100 years [1]. This is a length of time easily achievable in peatlands. Accelerated carbon capture and storage (as described by Stern's [90] review) would be of great value to society, if accomplished through peatland geoengineering. But, as with any geoengineering strategy or mitigation option, it does not represent a 'magic bullet' that can reverse the effects of anthropogenic emissions [10]. That said, our proposed approach does possess some beneficial supplementary features: it is reversible (through combustion and drainage) should a need arise to return the sequestered carbon to the atmosphere; and it has great potential value as a method for producing peat carbon as a renewable energy source/biofuel, and one that does not compete with food production, owing to its location within non-agricultural lands.

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