

AS I SEE IT

Regulation of atmospheric carbon dioxide by vegetation fires

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ABSTRACT: Vegetation fires release some fraction of the carbon in the biomass back to the atmosphere as CO₂ and deposit some of the carbon onto the ground as charcoal or pyrogenic carbon. It is an open, but not unanswerable, question as to whether the formation of pyrogenic carbon can effectively sequester carbon from atmospheric CO₂. The purpose of this article is to conceptualise the question in terms of the global Charcoal Challenges, which deal with the scientific and socio-economic questions associated with increasing the refractory (or long-term) black carbon pool at the expense of the atmospheric carbon pool, and to investigate the formation and decay of charcoal within this paradigm. Three particular Charcoal Challenges are examined: (1) the feasibility of lowering atmospheric CO₂ by biochar production, (2) the tension between nature's use of fire to distribute carbon between long-term black carbon and short-term atmospheric pools and humans' need to suppress fire and (3) the premise that black carbon is a sink for CO₂ only if its rate of formation exceeds its rate of decay; otherwise, it is a source. I show how the thermal decomposition of cellulose, the major constituent of vegetation, during fires acts as a thermokinetic oscillator that regulates the global distribution of carbon between atmospheric and black carbon reservoirs. I conclude that we cannot yet assume with certainty that the global black carbon reservoir is a carbon sink.

KEY WORDS: Pyrogenic carbon · Charcoal · Vegetation fires · Carbon sink · Thermokinetic oscillator

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1. INTRODUCTION

Pyrogenic carbon (PyC) is charcoal produced by thermal decomposition of biomass, and it is one of nature's long-term carbon warehouses. PyC has been made by nature for some 400 million years in open vegetation fires (Taylor 2010), which therefore sequesters some of the carbon in vegetation into the global black carbon (BC) pool, as well as deposits carbon into the atmospheric greenhouse gas (GHG) pool. Conversion of waste biomass into biochar in kilns and pyrolysis reactors and distribution of the biochar in soils has been advocated as a method of removing and sequestering CO₂ from the atmosphere (Lehmann et al. 2006). (A brief glossary of BC terminology is given in Table 1.)

But is PyC really a sink for atmospheric CO₂? What is the dynamical mechanism by which PyC is formed? What is the role of vegetation fires in regulating global carbon cycles and the oxidised carbon loading of the atmosphere? This article is intended to draw attention to an important issue regarding the potential use of PyC production as a geoengineering strategy: namely, that PyC can accumulate only if its rate of formation exceeds its rate of oxidation. These questions are conceptualised in terms of what I designate as the global Charcoal Challenges, which in general deal with the global scientific and socio-economic questions associated with increasing the PyC pool at the expense of the atmospheric CO₂ (and methane) pool, given that the major route into the PyC pool is through thermoconversion of biomass.

Table 1. Some useful black carbon terminology

Charcoal, char	Anhydrous, carbon-rich, porous solid of indeterminate molecular weight, which varies structurally in a single sample from partially unsaturated regions to stacks of aromatised clusters and crystalline carbon. Charcoal produced as a result of open vegetation fires has an average hydrogen:carbon molar ratio of about 0.4
Pyrogenic carbon	Charcoal that is produced by thermal decomposition of biomass
Biochar	Charcoal that is manufactured, usually from waste biomass, for the purpose of providing beneficial soil amendment and carbon storage
Black carbon	Char that originates from all sources, including fossil fuel burning, biomass burning and microbiological production
Soot	Aerosol black carbon
Refractory black carbon	Black carbon in the environment that is resistant to oxidation for more than ~100 yr, or longer than the average lifetime of CO ₂ in the atmosphere

Three particular Charcoal Challenges are posed within this framework: (1) the feasibility of lowering atmospheric CO₂ by biochar production, (2) the tension between nature's use of fire to distribute carbon between long-term black carbon and short-term atmospheric pools and humans' need to suppress fire and (3) the premise that black carbon is a sink for CO₂ only if its rate of formation exceeds its rate of decay; otherwise, it is a source. Progress has been made towards providing answers to these difficult questions and a guide for further research.

It has been recognised since the work of Seiler & Crutzen (1980) that the use of charcoal as a soil amendment sequesters carbon from the atmosphere. A tentative estimate was made by Seiler & Crutzen (1980) that the effect of fires on the global carbon budget could range between a net uptake or net release of 2 Gt C yr⁻¹. But concern has been expressed that the role of PyC was neglected. Carvalho et al. (2006) point out that production of charcoal from forest fires is an important, but poorly understood, mechanism of carbon sequestration. It was concluded by DeLuca & Aplet (2008) that over-restriction of fires in forests may reduce long-term carbon storage and that wildland fire should not be viewed only as a cause of carbon loss to the atmosphere, demanding suppression, but rather, as a driver of long-term carbon sequestration.

Recently any neglect of the role of open vegetation burning in carbon sequestration has been overturned, with a great flowering of interesting new studies motivated by the contribution of charcoal to ecosystem carbon sinks and affirming its important role, although achieving rigorous quantitation has been difficult. Some ecosystems that have been studied with respect to charcoal formation are boreal forests (or taiga) (Ohlson et al. 2009, Makoto et al. 2012), Australian savannas (Richards et al. 2011),

Florida pine forest (Carvalho et al. 2011) and peaty moorland in the UK (Clay & Worrall 2011).

It is useful to distinguish a number of different BC reservoirs that collectively comprise the world's BC inventory. The major BC reservoirs are surface, buried, and sedimentary PyC, aerosol soot from fossil fuel and biomass burning, and fossilized charcoals. BC from the use of biofuels in cooking stoves and fires is a minor reservoir, which nevertheless is locally significant, e.g. in India. Also, different reservoirs may be defined on purpose, e.g. BC from tropical rainforest burning.

In Section 2 the first and second Charcoal Challenges are described, as motivators for the results described in Section 3. In Subsection 3.1 I elucidate the BioPy thermokinetic oscillator, which provides the mechanism by which products of biomass thermal decomposition are distributed between charcoal and combustible volatiles, and highlight its crucial role in maintaining biomass combustion. In Subsection 3.2 I juxtapose putative rates of char formation and decay, a simple analysis which illustrates and aids understanding of critical issues and from which the third Charcoal Challenge arises. The 3 Charcoal Challenges raised in this article are summarised in Section 4.

2. FIRST AND SECOND CHARCOAL CHALLENGES

The first Charcoal Challenge arises from the discussion in Section 1:

- Is it possible to produce and distribute enough biochar, in kilns or by management of open vegetation fires, safely and without otherwise adding to environmental problems, to lower atmospheric CO₂ levels significantly in a timeframe compatible with human responses to climate change? In other words, is this an ecologically responsible strategy?

The Intergovernmental Panel on Climate Change (IPCC) (Metz et al. 2007) estimated that in order to stabilise atmospheric CO₂ at 440–485 ppm it will be necessary for emissions to peak between 2010 and 2030 and to achieve a change in global emissions of –30 to +5 % of year-2000 emissions. Some authors see a realistic potential for biochar creation to remove about 1 Gt C yr⁻¹ (Lehmann 2007, Sohi et al. 2010). Therefore, the removal target set by the Virgin Earth Challenge (see www.virginearth.com) of 1 Gt of CO₂ (or 0.3 Gt C) per year for 10 yr may be, in principle, an effective contributor to achieving the IPCC scenario. Table 2 gives calculations of estimates of the rates of biomass thermoconversion that would be necessary if this removal target were to be met by PyC production alone, either in kilns or in open vegetation fires. Terrestrial biomass is produced at a rate of about 120 Gt yr⁻¹ (Houghton et al. 2001). Can we subject about 2–6 % of the terrestrial biomass per year to char-producing thermal treatment for 10 yr? Should we?

There may be significant unforeseen and unintended consequences of large-scale escalation of PyC production. For example, consider the possible effects on the dynamics of vegetation carbon. The sunlight-exposed, charcoal-enhanced ash beds of open vegetation fires usually promote rapid new growth locally, but links between large-scale creation of biochar in kilns and vegetation renewal and regrowth must be engineered. Another example relates to transport of part of the soot fraction of PyC as aerosol: it is known that soot deposited on snow and ice decreases the reflectance, leading to increased retention of heat near the earth's surface (Hadley & Kirchstetter 2012).

From this discussion it follows that global carbon management strategies and geoengineering schemes involving biochar should be based on a thorough understanding of the role of fire in regulating carbon cycles. Vegetation fires, including wildfires, land management fires and peat fires, are great movers and shapers of the terrestrial environment and significantly influence global carbon balances (Belcher et al. 2010). This brings us to a second Charcoal Challenge, which may be expressed as follows:

- The large-scale burning of fossil fuels at a furious pace by humans over the past 150 yr has increased atmospheric CO₂ to the point where dangerous global warming is likely to occur.
- Vegetation fires can sequester carbon from the atmospheric CO₂ pool into the global BC pool, but the widespread and frequent conflagrations that create PyC in nature are at the very least disagreeable, and often deadly, to humans. Human society, its aspirations, economic and cultural activity, and wildfires cannot coexist in harmonious equilibrium, so human activities, over the long term, tend to suppress fires.
- Given the above 2 points, are, then, the human imperatives to remove CO₂ from the atmosphere and curb wildfires fundamentally incompatible? Have we cornered ourselves?

This second Charcoal Challenge articulates a social dimension to the global charcoal inventory and its dynamics. The physicochemical processes that give rise to it are discussed in Subsection 3.1, where the counter-intuitive effects of suppressing or enhancing vegetation fires are linked to the fundamental nonlinearity of the thermochemical oscillator that governs biomass thermal decomposition, and in Subsection 3.2 in relation to a third Charcoal Challenge.

Table 2. Background carbon data and calculations of the estimates of the rates of biomass thermoconversion that would be necessary to remove 1 Gt of CO₂ from the atmosphere per year for 10 yr

Quantity	Value
Typical carbon content of dry vegetation	50 % by mass (DeLuca & Aplet 2008)
Carbon content of a typical biochar	80 % by mass (DeLuca & Aplet 2008)
Charcoal conversion efficiency in a kiln	30 % (Antal & Gronli 2003)
Charcoal conversion efficiency in an open forest fire	1–10 % (Preston & Schmidt 2006)
Mass of dry vegetation burned to capture 1 t of carbon	
(a) By making charcoal in kilns	8.3 t
(b) In open vegetation fires	25–250 t
Rate of thermoconversion of dry vegetation needed to remove 1Gt yr ⁻¹ CO ₂ from the atmosphere	
(a) By making charcoal in kilns	2.3 Gt yr ⁻¹
(b) In open vegetation fires	6.8–68 Gt yr ⁻¹

3. PROCESS KINETICS AND THERMOCHEMISTRY, GLOBAL RATES

3.1. The biomass pyrolysis (BioPy) thermokinetic oscillator

Biomass combustion is governed by the thermal decomposition chemistry of cellulose, the major constituent of the terrestrial biomass and by far the most abundant biopolymer on earth. The flames of a vegetation fire that we observe are the incandescent emissions of visible light from excited electronic states of gaseous species. Before flaming combustion occurs, therefore, non-combustive thermal decomposition of the vegetation must produce these vapour-phase species. At the heart of this process is a thermokinetic oscillator. Its existence and mechanism are well-established (see Sullivan & Ball [2012] and references therein). Briefly, it is a competitive, autocatalytic oscillator, the effect of which is to periodically switch the thermal decomposition between the emission of flammable vapours and the path that results in charcoal formation.

To understand the oscillatory dynamics in more detail, the thermochemistry and kinetics of the 2 fundamental processes are considered: volatilisation to combustible vapour-phase species such as levoglucosan and charring to solid black charcoal residue. Relevant thermochemical and kinetic data are given in Table 3.

Fig. 1 schematises these 2 processes and the key thermal and chemical feedbacks. Crucial to fire ecology, and to the global carbon cycle on the whole, is the *competitive* nature of volatilisation and charring; as indicated in Fig. 1, volatiles are produced at the *expense* of char and vice versa. This reciprocal linkage was originally suggested by Kilzer & Broido (1965) and has been verified by numerous experiments since, as reviewed by Sullivan & Ball (2012).

The instantaneous balance between charring and volatilisation is governed by the temperature in the reaction zone. The charring reactions have low to moderate activation energies (Table 3) and, therefore, set in at relatively low temperatures. The water

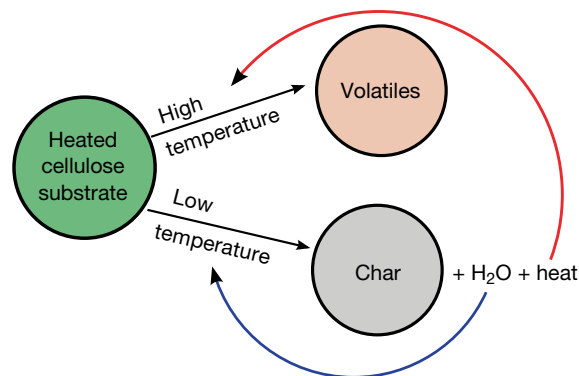


Fig. 1. Chemical feedback autocatalyses the charring path, but the heat produced promotes the competing volatilisation process

produced biases the competition towards, or autocatalyses, the charring path. But charring is highly exothermic (Table 3), because cross-linking ensures that more chemical bonds are formed than broken and significant aromatisation occurs. The self-heated reaction zone enables the high activation energy volatilisation reactions to kick in and take over—for a short time. Volatilisation is endothermic so locally it self-damps, thus switching the reaction field again to the charring path.

This competitive process provides the mechanism for a thermochemical oscillator (Ball et al. 1999, 2004); an example time series of such an oscillator is given in Fig. 2. The temperature (Fig. 2a) rises slowly as the charring reactions proceed, as measured by the production of water vapour from the chemical dehydration of cellulose fragments (Fig. 2b). Heat accumulates in the reaction zone, and the temperature spikes because the exponential rate of reactive heat release overtakes the linear rate of heat removal. Just before the temperature jump, water vapour is at a maximum and volatiles are at a minimum (Fig. 2c). After the jump, volatilisation begins to cool the system down; the volatiles increase to a maximum, causing a temperature collapse, then fall off and the lower temperature charring path takes over again.

This is the BioPy thermokinetic oscillator. Understanding its properties and mechanisms is crucial to understanding the spread of bushfires (Sullivan & Ball 2012) and to engineering biomass pyrolysis. It is related to other well-studied thermokinetic instabilities (Gray & Scott 1990), but distinct in that it features reciprocally coupled endothermic and exothermic reactions.

Table 3. Thermochemical and kinetic data for volatilisation and charring of cellulose (Ball et al. 1999)

Reaction	Activation energy (kJ mol ⁻¹)	Pre-exponential factor (s ⁻¹)	Reaction enthalpy (J g ⁻¹)
Cellulose → volatiles	200–250	3.2 × 10 ¹⁴	540 (volatiles)
Cellulose → char	110–180	1.3 × 10 ¹⁰	–2000 (char)

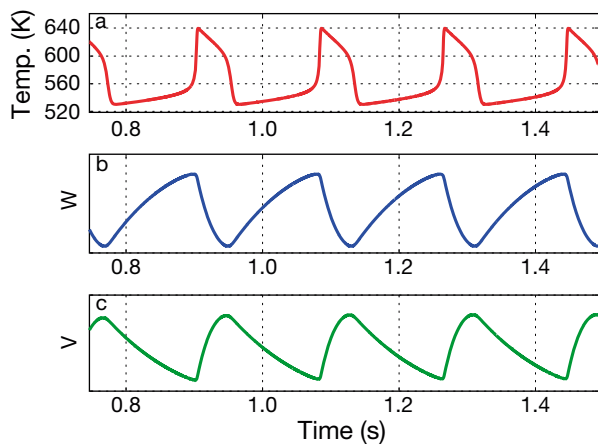


Fig. 2. A time series from the dynamical model for cellulose thermal decomposition in Ball et al. (2004) shows classic relaxation oscillations: (a) temperature; (b) water vapour concentration (W) in the reaction zone, a measure of the extent of charring; (c) the concentration of volatiles (V) in the reaction zone. The absolute values of W and V are not relevant for the purpose of illustrating the phase relationships between them and the temperature

In fact it is not difficult to see the BioPy oscillator in action, although few people these days have the apparatus for doing so—a domestic slow-combustion stove. The flames of a wood fire under air control typically flicker, falter and fluctuate as the charring and volatilisation pathways alternately dominate, effectively visualising the pulses of volatiles released with the temperature spikes. (If you do not have your own wood stove and a spare long winter's evening, try watching in slow motion some of the videos found on YouTube by a search on 'wood fired stove'.) In an open fire the BioPy oscillator tends to be masked by turbulence, but it has been observed experimentally by Moussa et al. (1977) and described as transient smoldering.

To appreciate the important role of the BioPy oscillator in maintaining biomass combustion, consider the situation illustrated in Fig. 3 where lightning ignites a mass of very damp biomass (perhaps in a wet tropical rainforest). Here the heat of charring and heat of combustion preferentially drive the evaporation of water, an endothermic process requiring some 41 kJ mol^{-1} , because with this activation energy it is kinetically favoured over both volatilisation and charring. Flaming combustion is extinguished due to lack of volatile fuel to sustain it, the BioPy oscillator is short-circuited, and the entire thermoconversion rapidly fizzles out. Thus, for combustion to

be maintained, the BioPy oscillator must be operational.

With reference to the second Charcoal Challenge, we can also understand why large-scale, long-term suppression of vegetation fires would have the effect of depositing *more* carbon into the atmospheric CO₂ pool than an unperturbed burning regime. It is fundamentally because the rate of burning depends on the reaction rate of volatilisation (rate of fuel supply), which is inextricably linked to the reaction rate of charring. Curbing vegetation fires reduces the rate at which carbon can accumulate in the PyC pool and enhances the rate of return to the atmospheric CO₂ pool by decay, or respiration.

3.2. Rates of PyC formation and decay, and a third Charcoal Challenge

PyC accumulates in soils and sediments if its rate of formation exceeds its rate of oxidation. How much charcoal is produced globally from fire activity per year? What is the rate of PyC oxidation? These are 'wicked problems', in that there is no agreement yet on how to define and solve them, there are no formulas that spit out accurate numerical answers, the uncertainties are many and large, and much research effort will be expended before there is a confident consensus on the answers. Therefore, oversimplified solutions are presented that make no claims to be 'right', but provide valuable insight into the role of charcoal and fire in the global carbon budget and point out ways forward.

Literature estimates of the rate of PyC formation and deposition are given in Table 4. The rates vary

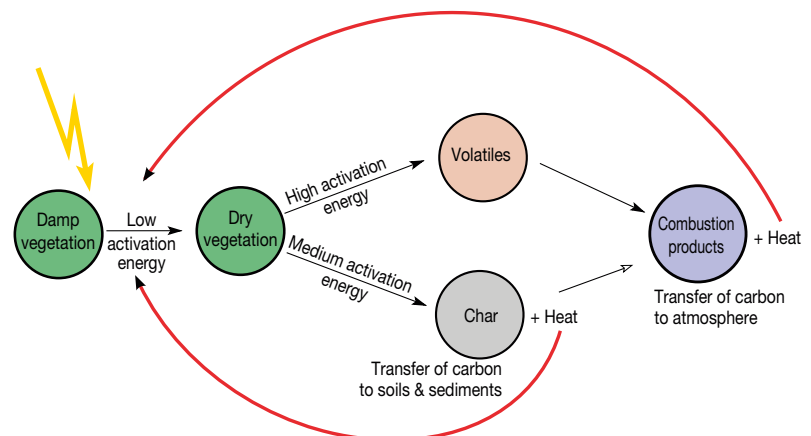


Fig. 3. Combustion of wet vegetation quickly fizzles out because the enthalpy of vaporisation of water short-circuits the biomass pyrolysis oscillator. The smaller arrow with unfilled head signifies that usually only a small fraction of the char is consumed by glowing combustion

by a factor of 40, but let us use the average value of 0.36 Gt yr^{-1} . We can assume that this rate is independent of the mass of PyC. For the rate of PyC oxidation in soils and sediments, let us observe, first, that measured kinetic parameters for high-temperature charcoal combustion cannot be extrapolated to normal soil temperatures.

Even the relatively low activation energy of 125 kJ mol^{-1} and pre-exponential factor of $5.3 \times 10^5 \text{ s}^{-1}$ (Wicke 1955, Janse et al. 1998) for charcoal combustion at 573 K yields a mean residence time at 298 K of 1.1 billion years. This absurd but useful result tells us that weathering of PyC at soil temperatures must proceed with a much lower activation energy by micro-organism enzyme activity and/or by formation of peroxide complexes on the char surface (Jones & Townend 1998). Literature estimates of refractory charcoal weathering times (Knicker 2011), the derived decay time constants and an averaged value are given in Table 5.

The rate of oxidation of refractory charcoal (\dot{m}) in soils and sediments can be defined, assuming first-order kinetics and a steady state, in Gt yr^{-1} as:

$$-\dot{m} = km \quad (1)$$

where m is the global mass of refractory PyC and the decay time constant $k = 8.0 \times 10^{-4} \text{ yr}^{-1}$, from Table 5. Eq. (1) and the averaged formation rate from Table 4 are plotted in Fig. 4 against total global PyC inventory.

In Fig. 4a, the rates intersect at $m = 430 \text{ Gt}$; above this critical mass of PyC the rate of oxidation is

Table 4. Estimates of global rates of formation of pyrogenic carbon (PyC)

Rate of PyC formation (Gt yr^{-1})	Source
0.5–1.7	Seiler & Crutzen (1980)
0.15–0.25 ^a	Prather & Logan (1994)
0.05–0.3	Kuhlbusch & Crutzen (1995)
0.044–0.194	Kuhlbusch & Crutzen (1996)
0.044	Preston & Schmidt (2006)
0.044	Forbes et al. (2006)
0.36 (mean)	

^aAssuming an average conversion to PyC of 5% C

Table 5. Weathering times of refractory charcoal from soils and sediments and first-order decay constants. In general the mean residence time (MRT) is the ratio of a system's volume to the volumetric flow rate of a substance through the system, and turnover time is the ratio of the standing amount of a substance to its production rate

Charcoal loss time (yr)	Measure	Decay time constant k (yr^{-1})	Source
1160–5040	MRT	8.62×10^{-4} – 1.98×10^{-4}	Schmid et al. (2002)
2400	MRT	4.2×10^{-4}	Masiello (2004)
6623	Half-life	1.047×10^{-4}	Preston & Schmidt (2006)
1300–2600	MRT	7.7×10^{-4} – 3.8×10^{-4}	Lehmann et al. (2008)
2000	MRT	5×10^{-4}	Kuzyakov et al. (2009)
652	Median ¹⁴ C age		Ohlson et al. (2009)
266–1600	MRT	0.0038 – 6.3×10^{-4}	Zimmerman (2010)
2000	Turnover time	5.00×10^{-4}	Foereid et al. (2011)
2000	MRT	5×10^{-4}	Knoblauch et al. (2011)
		8.0×10^{-4} (mean)	

greater than the rate of formation and total BC reserves must decrease. In this case, BC becomes a source of atmospheric CO_2 rather than a sink. In Fig. 4b, the rate of PyC formation is decreased by 20%. This could be achieved by suppressing open biomass fires and/or promoting drier hotter fires and/or by combustion of the charcoal. Here the critical mass of PyC is significantly lower, around 380 Gt. In Fig. 4c, the rate of PyC formation is increased by 20% over that in Fig. 4a. This could be achieved by cooler, more frequent open vegetation fire regimes and/or industrial biochar production in globally significant quantities. The critical mass is considerably greater, around 470 Gt.

The global inventory of BC in soil was estimated by Eswaran et al. (1993) as 80 Gt, so according to Fig. 4 it is still a carbon sink. But, as I have already said, Fig. 4 does not necessarily portray the 'right' answers, but is intended to provide qualitative insight and guidance; thus, these numbers should not be taken too literally. Furthermore, evidence presented by Masiello & Druffel (1998) points to a much larger terrestrial and/or marine BC pool, and the estimates tabulated by Masiello & Druffel (1998) of the percent of BC according to sedimentary organic carbon (SOC) vary by a factor of 350. Hence, it is by no means certain that the world's BC reserves are not actually a source of atmospheric CO_2 rather than a sink.

This brings us to a third Charcoal Challenge:

- How much carbon is stored in the various global BC reservoirs? What are the rates of formation and decay of PyC in different environments? What are the dynamics? A steady state was assumed in Eq. (1), but the dynamics, i.e. dm/dt , are not zero. What is the temperature dependence of the decay constant k , i.e. the activation energy?

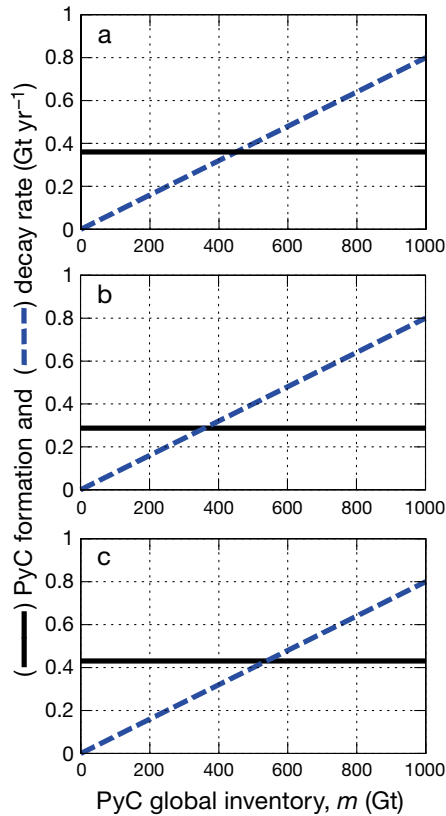


Fig. 4. Rates of pyrogenic carbon (PyC) formation (solid lines) and oxidation (dashed lines) versus the total global mass of PyC. The intersection of these rates determines the critical mass of PyC in the black carbon (BC) reservoir above which BC becomes a source of atmospheric CO₂. The rate of PyC is decreased by 20% in (b) and increased by 20% in (c) over that in (a)

These are crucial questions because the answers will determine whether human intervention to escalate biochar production on a grand scale is of any use at all as a CO₂ sequestration strategy. Forbes et al. (2006) have tabulated estimates of BC stocks and carbon deposition rates into several BC reservoirs that vary by factors of 3 to 7, but there are many gaps in their tabulation.

Human activity both promotes and suppresses fire. Results by Schultz et al. (2008) suggest there has been a significant increase globally in emissions from wildfires during the period 1960–2000, due to forest and peat burning. In the Amazon basin, human activity has promoted fire since the 1970s (Cochrane & Barber 2009). The occurrence of forest fires in Southeast Asia is believed to have increased greatly since the 1960s, and currently prevailing socioeconomic conditions are likely to promote tropical biomass burning short term (Taylor 2010). Yet charcoal records clearly show that global biomass burning declined globally from AD 1–1750, and abruptly declined fur-

ther after 1870, the latter reduction being due to agricultural and pastoral expansion and fire suppression in intensively farmed areas (Marlon et al. 2008). O'Connor et al. (2011) nominate the conversion of high-latitude coniferous forests to deciduous forests and croplands, conversion of temperate forests to agricultural lands and the recent increase in urban and semiurban proximity to wildlands as human activities that have suppressed fire over the past 100–150 years.

Human-mediated suppression of open vegetation burning is likely to continue globally. The widespread fires that have been used to clear tropical rainforests for the planting of crops and to create settled communities with higher standards of living are a transient phenomenon, after which it will be in those communities' interests to suppress fire.

4. DISCUSSION AND CONCLUSIONS

In this article some urgent issues concerning the production of PyC and its role in global carbon cycles have been canvassed. The global Charcoal Challenge is a conceptual framework within which 3 key particular Charcoal Challenges are addressed concerning the use of charcoal (from managed open vegetation fires and from manufacture of biochar) as a carbon sink.

In the global Charcoal Challenge paradigm wildfires, land management fires and burning of crop residues open the 'hatch' that pours carbon into the long-term global BC reservoir. This is a sink for atmospheric CO₂ if the rate of BC production (or dimension of the hatch) is greater than the rate of BC decay. The hatch mechanism is the BioPy thermokinetic oscillator, which is effectively short-circuited when open vegetation fires are suppressed. If we want to control the global production of charcoal from open vegetation fires we will need to make greater—and more skilful—use of controlled land management fires, which will tend to inhibit the development of wildfires.

The first Charcoal Challenge asks the questions: Can we make enough biochar to stabilise the climate short term, without adding to environmental problems? Should we?

The second Charcoal Challenge asks whether we have painted ourselves into a corner; it asks whether nature's use of fire to distribute carbon between long-term BC and short-term atmospheric pools is fundamentally incompatible with humans' need to suppress fire.

The third Charcoal Challenge is the most important. Schemes to geoengineer the earth, such as making and distributing biochar on a global scale, could backfire (as it were) disastrously unless we first obtain accurate quantitative data on the amounts of carbon, and on the PyC production and oxidation rates in all the various BC reservoirs. Then we may be able to make progress on designing and implementing scientifically sound, socioeconomically benign global carbon management strategies.

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