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RESEARCH ARTICLE

Sugarcane phytoliths: Encapsulation and sequestration of a long-lived carbon fraction

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Abstract The potential to reduce emissions from agriculture and increase the amount of carbon captured in soils is currently being examined by researchers in a number of countries. This paper describes a process of carbon capture and long-term storage using silica phytoliths and, provides the results of a study of this process on newly planted and ratooned sugarcane varieties. Our results indicate that a) there was significant variation in the phytolith occluded carbon (PhytOC) content of different varieties, b) this did not appear to be directly related to the quantity of silica in the plant but rather the efficiency of carbon encapsulation by individual varieties and c) it was possible to accurately quantify this carbon fraction prior to its incorporation into soil. The carbon content of the varieties tested under the particular suite of environmental conditions for which they were grown ranged from 0.12 t e-CO_2 ha-y^{-1} to 0.36 t e-CO_2 ha-y^{-1}. This PhytOC process provides an approach, which reduces emissions from agriculture for the long-term (millennia), as opposed to many other soil organic carbon fractions that may decompose over a much shorter time. Moreover, the ability to quantify PhytOC prior to its incorporation into the soil will provide a distinct practical advantage for the quantification of this carbon form over other soil carbon fractions in emerging emissions trading and offset markets.

Keywords Soil organic carbon; phytoliths, phytOC, terrestrial carbon sequestration, occluded carbon; organic matter decomposition

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Introduction

The United States Department of Energy has estimated that the world carbon dioxide (CO_2) emissions for 2005 were around 26.33 billion metric tons and are projected to increase to 30.20 billion metric tons by the year 2010. Therefore, as well as reducing atmospheric CO_2 by the introduction of new methods of low emission energy production, carbon also needs to be sequestered by as many new and innovative methods as possible. Sequestration of carbon is currently largely dependant on existing forestry or hardwood plantations broadly described as 'woody plants'. However, the land area available for woody plant production has become limited due to the increasing demand for agricultural production. With this in mind a more recent approach has been to look at increasing the world's soil carbon stocks: these have been estimated to be around 2.4 g C m^{-2} yr^{-1} (Schlezinger, 1990). Thus with a growing population and increased demand for food production, improving methods to store additional terrestrial carbon, in agricultural soils and degraded landscapes is a logical approach. Nevertheless, uniform results when quantifying soil carbon is not always easily achieved. This is largely due to differences in methodologies, the range of soil carbon fractions and rates of decomposition resulting in both spatial and temporal variability (García-Oliva and Masera, 2004; McKenzie *et al*., 2000; Skjemstad *et al*., 2000). Moreover, the rigor necessarily required in soil carbon quantification can involve the collection of many samples and costly analyses (García-Oliva and Masera, 2004). An alternative approach is to this is to quantify a carbon fraction before it is incorporated into the soil. One natural carbon process that can be calculated before it is integrated into the soil matrix is the phytolith

occluded carbon (PhytOC) fraction produced by some plants (Parr and Sullivan, 2004, 2005). Previous studies have indicated that sugarcane is particularly efficient at this process (Sullivan and Parr, 2005, 2007). In this paper we discussed the process of PhytOC production in plants, and how this carbon fraction can be increased and accurately quantified.

Phytoliths are found in many plants particularly grasses and are prolific in sugarcane which is grown on around 20 million hectares worldwide (FAO, 2001). Also referred to as 'plantstones' or 'plant opal', phytoliths are silicified cell structures that occlude carbon (Wilding *et al.*, 1967). The silicified epidermal cells of the leaf and stem within all grasses are particularly good at occluding carbon (Parr and Sullivan, 2005). This carbon fraction is likely made up of the internal cytoplasmic organic cellular material (Wilding *et al.*, 1967). Upon harvest in the case of crops, or at maturity with e.g. pasture or native grasses, leaf material is deposited onto the soil surface: phytoliths later become incorporated into the soil matrix during decomposition of the plant organic material.

The occlusion of carbon within phytoliths has been demonstrated to be an important long-term terrestrial carbon fraction (Parr and Sullivan, 2005) representing up to 82% of soil carbon in some buried soils after 2000 years depending on the overlying vegetation type and drainage regime (Fig. 1). Moreover, it has been demonstrated that relative to the other soil organic carbon fractions that decompose over a much shorter time scale, the carbon occluded in phytoliths is highly resistant against decomposition (Wilding *et al.*, 1967; Wilding and Drees, 1974; Mulholland and Prior, 1993; Parr and Sullivan, 2005). With dates acquired by radiocarbon dating of the phytoliths themselves, our research demonstrated that those extracted from palaeosols and peat sediments reach ages of at least 8000 years BP (Parr and Sullivan, 2005) and in another

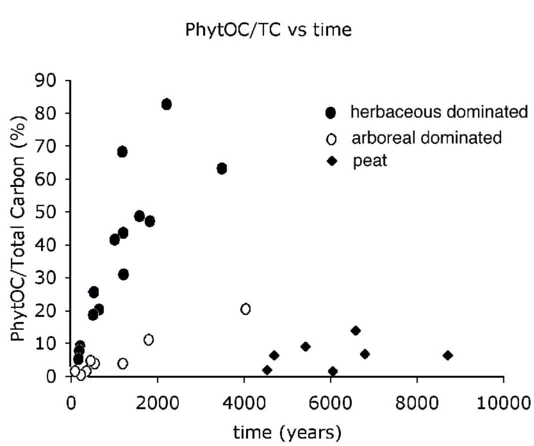

Fig 1. PhytOC as a proportion of Total Carbon over time for the Numundo (West New Britain) upland buried soils, and a peat wetland soil (Byron Bay, Australia) after Parr and Sullivan (2005).

study a date of 13,300 ± 450 BP was acquired (Wilding, 1967). While under some circumstances bioturbation may move them up or down a soil profile, or erosion and dust storms may transport phytolith assemblages over some distance, or they may be burnt in a grass fire, or pass through the digestive system of an animal, their durability and persistence against such processes has been well documented (Baker, 1959; Baker, 1961; Baker *et al.*, 1961; Jones and Milne, 1963; Jones and Handreck, 1967; Wilding, 1967; Wilding *et al.*, 1967; Sangster and Parry, 1981;Rovner, 1986; Piperno, 1988; Pearsall, 1989; Humphreys, 1994; Hart and Humphreys, 1997; Parr, 2006; Bowdery, 2007). Moreover, the ability to radiocarbon date phytoliths themselves demonstrates that they can remain stable encapsulators of carbon under all the above circumstances for millennia. However, while PhytOC has been shown to be an important long-term soil carbon fraction (Parr and Sullivan, 2005) the full potential of this carbon fraction for increasing soil carbon sequestration during sugarcane production has not previously been described in detail. Below we discuss (a) how this carbon sequestering process can be managed to increase carbon sequestration during sugarcane production, (b) the optimal times to measure PhytOC, and (c) describe the basics of a technique for the accurate quantification of the PhytOC carbon fraction.

Materials and Methods

Plant material

In this study the variability of PhytOC yields within various varieties of sugarcane was examined. The importance of variability of PhytOC content within different cultivars of the same species is that such variability would allow, by the selection of a high PhytOC yielding cultivar over a lower yielding cultivar, an increase in the amount of terrestrial carbon sequestered by enhanced PhytOC yields. Cultivars of sugarcane were grown in divisions within the same large paddock, on the same soil type under the same environmental conditions at Mcleods Creek near Tweed Heads, New South Wales (NSW), Australia.

Sampling of plant material

The accumulation of silica has been found to be greater in plants at maturity than in juvenile plants (Motomura *et al.*, 2002; Norris and Hackney, 1999). Our own greenhouse and laboratory trials have also confirmed this (Parr and Kerr, unpublished data). Thus it was decided that the best time to sample the sugarcane cultivars would be at maturation. Cultivars sampled included high sugar yielding Q varieties (e.g. Q170) and NSW varieties commonly grown in eastern Australia, of which, five were newly planted (N) and five ratooned (R) one-year-old growth plants. Samples of each sugarcane cultivar (Table 1) were collected in triplicate for

PhytOC quantification just prior to harvest. The complete plant of each cultivar were cut at ground level and collected in pre-labelled bags.

Phytolith extraction and occluded carbon analysis

Plant material was dried at 70ºC for 24 hours in a fan forced dryer. While we are aware that phytoliths occur in the entire plant epidermis, culm and leaf and may possibly be returned to the paddock at a later date in the form of bagasse or mill mud or waste from cogeneration of electricity (Parr, 2006) for the purpose of this study the analysis was refined to leaf material.

We have tried a number of phytolith extraction and cleaning methods (Rovner, 1972; Clifford and Watson, 1977; Bowdery, 1989; Lowther, 1980; Parr *et al*., 2001a,b; Dolgin *et al*., 2005). While the actual method used is not fully outlined (Parr and Sullivan, 2004) the basic method adopted here is a modified version of a stepped microwave digestion process (Parr *et al*., 2001a) followed by a Walkley-Black type digest (Walkley and Black, 1934). This is a similar method to that used in the preparation of phytoliths for radiocarbon dating (Wilding, 1967; Parr and Sullivan, 2005). The phytolith isolates were then combusted in an Elementar CNS analyser to determine carbon contents. Using these data PhytOC percentages per hectare were then quantified (Parr and Sullivan, 2004).

Results and Discussion

The phytolith extraction method used in this study was relatively quick and completely removed all extraneous cellulose material. Phytolith content of the sugarcane cultivars varied between 1.3% and 2.6% of the mass of the original plant material (Table 1). There was considerable variation in the mean PhytOC content of the sugarcane cultivars, however, there was no correlation between PhytOC and Si-Phytolith content (Table 1). This is consistent with results from other studies on sorghum and wheat where there was high variation of PhytOC between varieties yet no evidence of a relationship between PhytOC and silica content nor a trade off in crop biomass or yield (Sullivan and Parr, 2007; Nowak, 2008). In addition, there was no evidence of advantages between newly planted varieties and ratoon plants with ratoon plants having both the highest and lowest recorded PhytOC contents in this study (Table 1). The lowest PhytOC yielding variety of sugarcane was 0.12 t e-CO_2 ha-y^{-1} and the highest was 0.36 t e-CO_2 ha-y^{-1} (Table 1). These results represent those for the particular suite of environmental conditions under which these cultivars were grown and may consequently vary with soil type and other environmental variables. While the PhytOC content of sugarcane varieties examined in this study (Table 1) were lower than the 0.66 t e-CO_2 ha-y^{-1} reported for one variety in a previous study (Parr and Sullivan, 2005) there were significant quantities of carbon encapsulated in the cultivars examined. Thus if a farmer previously growing the lowest PhytOC yielding variety then chose to grow the highest PhytOC yielding variety in this study there would be a net increase of 0.24 T e-CO_2 ha-y^{-1} of carbon securely sequestered in phytoliths. Based on predicted opening prices ($56.09 USD per tonne) for the Australian Emissions Trading Scheme to come online in 2010, this additional carbon would be worth around $13.53USD per hectare to the farmer or cooperative.

Were this process to be used on all land growing sugarcane (i.e. ~0.2 million km^2 (FAOSTAT 2007)), and assuming that low PhytOC yielding cultivars are presently being grown, this could effectively result in the additional sequestration of carbon in soil by ~5 Mt e-CO_2 yr^{-1}. This is a substantial amount of carbon sequestered based on a simple choice by sugarcane farmers selecting from currently growing varieties high PhytOC yielding cultivars over low PhytOC yielding cultivars. Moreover, as was shown in the results of a previous study where the highest PhytOC yielding cultivar provided 0.66 t e-

Table 1. Variety new (N) ratoon (R), Si-Phytolith content as a percentage of plant weight, carbon contents of phytoliths, PhytOC contents of the sugarcane varieties, PhytOC in carbon dioxide equivalents (e-CO_2) per hectare each year, and their value based on predicted opening prices for the Australian Emissions Trading Scheme 2010 in USD.

Sugarcane cultivar	Mass of dry plant material (g)	Mass remaining after digestion (g)	Si-Phytolith in plant material (%)	Carbon content of isolated phytoliths (%)	PhytOC yield (proportion of dry material) (%)	PhytOC yield* t/ e-CO_2	Price per ha at at $56.09 USD per tonne
N-1	8.0483	0.1288	1.6%	12.35	0.9940	0.2893	$16.23
N-2	8.0599	0.2134	2.6%	6.06	0.4884	0.2349	$13.17
R-3	7.7758	0.1495	1.9%	8.51	0.6615	0.2395	$13.43
R-4	8.0499	0.1740	2.2%	3.88	0.3126	0.1229	$ 6.89
N-5	8.0157	0.1965	2.5%	9.56	0.7663	0.3431	$19.24
R-6	8.0580	0.1497	1.9%	11.81	0.9516	0.3212	$18.02
R-7	8.0431	0.1177	1.5%	11.21	0.9016	0.2402	$13.47
N-8	7.7824	0.1581	2.0%	11.66	0.9074	0.3468	$19.45
R-9	8.0388	0.1038	1.3%	19.26	1.5483	0.3641	$20.42
N-10	7.7792	0.1721	2.2%	8.40	0.6535	0.2721	$15.26

* assumes typical dry biomass production of 40 tonnes ha^{-1} yr^{-1} for sugarcane on this property.

CO_2 ha-y[-1] there is a potential to substantially further increase the component of long-term sequestered carbon. It is not suggested here that sugarcane varieties be solely selected on the basis of their PhytOC content but rather considered in combination with other desirable traits such as biomass and sugar yield. Further research is currently underway to examine changes in PhytOC levels at various sampling times over the growing season, accumulation rates of PhytOC in soils and PhytOC production for the same varieties grown on different soil types.

Conclusions

In this paper we have outlined a process that allows accurate determination of carbon occluded in phytoliths. The carbon content for the varieties tested in this study are relevant to the particular suite of environmental conditions under which they were grown and may vary under different growing conditions. Nevertheless, we have shown that the quantity of carbon occluded in phytoliths varies considerably between different sugarcane varieties. This indicates that farmers simply choosing to grow cultivars of high PhytOC yields over those that have lower PhytOC yields could sequester substantial amounts of additional carbon. The results presented in this paper do not represent the full potential of this process, which could be significantly improved by selective breeding. Our field trials on various crops indicate that the selection of cultivars for this trait may be undertaken with no apparent loss in yield or plant biomass or other desirable traits under current farming practice. Significantly, carbon encapsulated within phytoliths provides an approach, which reduces emissions from agriculture for the long-term (millennia), as opposed to many other soil organic carbon fractions that may decompose over a much shorter time-scale. Finally, we have discussed methods of quantification and demonstrated that the ability to accurately quantify this carbon fraction for each plant type prior to incorporation into soils is possible. This will provide a distinct advantage for individual sugarcane farmers and/or cooperatives wishing to calculate and trade in carbon.

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