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Soil organic carbon in rehabilitated coal mine soils as an indicator for soil health

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Abstract

Rehabilitation intends to provide a safe, stable and sustainable environment. Soil health is often used as a parameter, which describes the success of reclamation, the performance of the soil and its associated soil system functions. Reclaimed and therefore young soils are in general deprived of soil organic carbon. They are not in equilibrium with their environment and undergo changes over time, faster than natural and developed soils. Carbon content as a summarising criterion for soil health status can be used as an indicator as it reflects the performance of important soil processes, like water holding capacity, drainage and aeration potential and nutrient supply and storage. It is well established that carbon content affects soil functions like hydraulic conductivity by creating structural elements through aggregation processes. Increasing carbon content leads to increased water infiltration, reduced surface runoff and erosional risks, and increases the exchange rate of gases and improves aeration and has in general positive consequences for microbiological activity. Results from a study of soil covers of different ages emphasise this consequence.

The evaluation of the rehabilitation success in coal mining using carbon content is complicated due to the difficulty distinguishing between carbon forms: organic carbon naturally formed by decomposition vs. carbon originating from coal as coal dust or charred material. Furthermore, the assessment of the performance of rehabilitated soils is strongly affected by climatic conditions, which affect the production, decomposition and translocation of organic matter.

Litter and dead organic matter from plants are decomposed on the soil surface and incorporated through organisms into the soil profile. Dissolvable organic constituents may be transported with infiltrating water down the profile. Consequently, carbon is primarily concentrated close to the surface. In semi-arid environments the accumulation depth may only be centimetres as was found from a study on the performance of the carbon pool of rehabilitated soils across sites up to 35 years of age. This has implications for the sampling strategy and the assessment of the performance of soils over time.

As the carbon content in soils at coal mines can be affected by precipitation and incorporation of coal dust into the soil, the content of new organic carbon representing soil health status can be misleadingly interpreted. Therefore, separation of carbon fractions is necessary to identify the "green" carbon pool (carbon originating from plant litter and residue) as best as possible and extract the correct fraction to assess the performance of soil development. A method has been developed and is presented which allows the separation between the various carbon pools.

From the presented study, the following conclusions were drawn: 1) Soil carbon is an easy to measure indicator for the assessment of the performance of soil health of rehabilitated soils; 2) soil functional properties are affected by carbon content and age and hence change with soil development; 3) only green carbon represents soil health and appropriate methodology has to be in place to exclude other carbon pools; 4) carbon storage in rehabilitated soils of semi-arid environments of Australia is below that of natural soils.

Keywords: *soil organic carbon, soil health, soil functions*

1 Introduction

Successful rehabilitation is commonly associated with the successful establishment of vegetation. Vegetation is the primary cause for the accumulation of plant-derived carbon in soils, referred to as green carbon (Mackey, 2008). Decomposition of organic matter originating from green carbon will add to organic carbon stored in soils and is a key parameter for soil formation (Chan et al, 2014b). Decomposed organic carbon is incorporated and accumulated in the soil over space and time as soil organic matter (SOM). This process is controlled by factors such as soil texture, climate, type of vegetation and time. The accumulation of SOM on rehabilitated sites is highly desired as it improves the functional properties of soils such as water flow, infiltration and gas exchange, stabilises soil from a mechanical viewpoint and increases storage of nutrients and water (Ontl and Schulte, 2012). It stimulates microbial activity which in turn supports mineralisation of organic compounds and leads to provision of nutrients for plant growth. SOM also plays a vital role in carbon (C) storage as the largest natural C sink globally.

The term soil health has been introduced to summarise the status of the complex composition of soil functions as listed above. As a surrogate and to overcome the difficulty of comparing the individual contribution and value of soil functions, soil health status has been linked to soil organic carbon as it directly affects these functions. Quantifying SOM originating from various carbon sources and fluxes is a means to assess soil health in reclaimed mining environments. Particularly for poor quality soil substrates with low clay contents, like many spoils from open-cut mining, elevating the SOM is an ideal amendment to improve soil quality. Therefore, an increase of SOM in agriculture, as well as rehabilitation, is in general highly desired.

Landuse affects SOM levels. A study on SOM levels in South-East Queensland, Australia, showed that a transition from woodland to cropping land reduces the SOM levels (Maraseni et al., 2008). Soils used for rehabilitation are commonly low in SOM content, with contents ranging well below 0.5% green carbon derived SOM. In contrast to natural sites, recently rehabilitated sites usually contain reduced quantities of SOM, if previously stripped topsoil is used for rehabilitation, or lack SOM, if subsoil is used. Hence these soils maybe considered as degraded soils as shown in Figure 1. The spatial distribution of SOM within the profile at this point is usually uniform throughout the depth of the horizon due to mixing of the disturbed soil. Over time, the distribution of SOM will re-build following the natural equilibrium of accumulation and decomposition. Organic compounds will be concentrated towards the surface, being the primary point of deposition of dead organic matter. It will be translocated through mass flow by water through the pores and biological activity (organisms; root growth), and gradually decreases with depth. The plant-root soil interaction plays an essential role in the increase of green carbon at depth. Quantifying the magnitude and intensity of this soil-forming process can be utilised as a means to assess the success of rehabilitation.

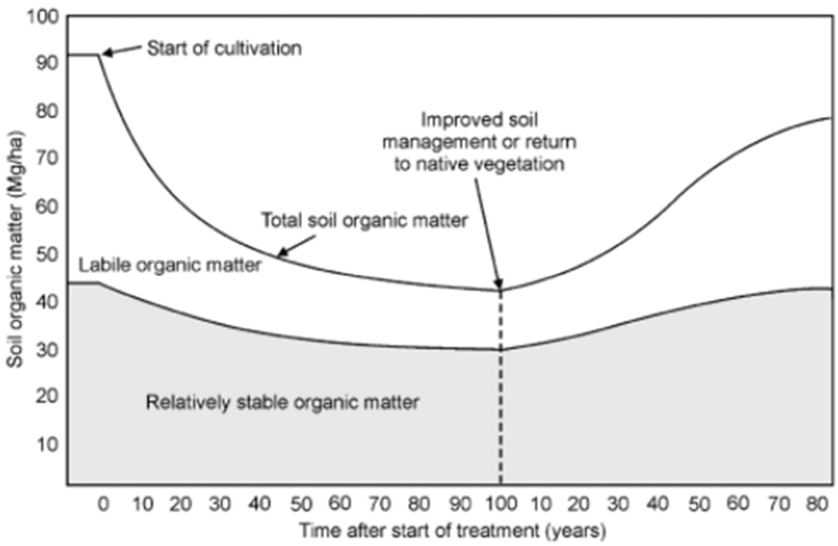

Figure 1 Changes in fractions of soil carbon content after deforestation/cultivation and reforestation (after: Hillel and Rosenzweig, 2009)

Carbon in soils is not all the same. Carbon can be separated into different fractions, including inorganic and organic carbon of different properties, and the latter further distinguished into green carbon, black carbon or charcoal and coal (Lal, 2008). Green carbon fraction is the most critical in rehabilitation as it has the highest decomposition rate and has its origin from plant litter or died biomass, i.e., it can be linked directly to the success of revegetation and soil health status.

Differentiating the various properties of the organic carbon pool is hampered in the coal mining industry, where other carbon sources like coal dust or coal residue, but also charcoal as the reminder of historic fires can add substantially to the total carbon concentration. The various forms of carbon cannot be easily differentiated as they transition from an initial form of green carbon on one end of the spectrum to pure coal at the other end of the spectrum. Methodologies have been developed attempting to quantify some of the carbon fractions. A combination of these methods can be used to account for the total carbon pool.

The objective of this paper is to emphasise soil carbon as an indicator to describe the status of soil health and rehabilitation success and presenting soil carbon as a parameter which reveals this dynamic of soil development. The role of carbon for structure formation as a representative example for soil functional properties is presented in more detail. Furthermore, the importance of the use of appropriate sampling procedures and methodologies for analysis is highlighted.

2 Carbon accumulation in soils post-rehabilitation

2.1 Methods

The investigated site is located in the Bowen Basin, Central Queensland, Australia characterized by many coal mine sites. Opencast mining in the Bowen Basin leaves behind spoil piles of overburden sediments, often consisting of high clay content and dispersive nature. Spoil is very susceptible to dense packing and landform construction with heavy machinery creates dense subsoils with low permeability. Typically, topsoil is secured prior to excavation and stored until used for rehabilitation. Rehabilitation is carried out by spreading this topsoil across the spoil landform at a depth of commonly < 0.3m, due to the lack of sufficient amounts of suitable topsoil. Rehabilitation sites were vegetated with trees, bushland communities (*Senna* grass) or grass (dominated by *Buffel* grass).

The presented study investigated in total 15 soil profiles which have been sampled with a focus on the topsoil horizon (0-20cm) overlying the mentioned hard and dense spoil layer, also including samples from two unmined (natural) sites. At each sampling site, vegetation and litter were cleared and a pit was dug. The time since rehabilitation ranged from one year to 35 years. Soil samples were collected using a trowel and placed in a plastic bag before cold storage (4℃). For all sites, the depth increments gathered were 0-2, 2-5, 5-10 and 10-20cm. The high spatial differentiation was chosen to take into account expected low turnover rate of litter typical for semi-arid environments (here: 600-700mm rainfall/year) and limited transport of organic matter to depth. Bulk density samples (soil cores of 4cm height and $100cm^3$ volume) were taken at each site from the surface and at the lowest sampling depth. Total organic carbon (TOC) of samples was determined following the 'Heanes' wet oxidation method (Heanes, 1984).

2.2 Results and discussion

Total organic carbon was determined for the four depth increments. Figure 2 shows the depth profile for each of the sampled soil profiles. The organic carbon content is highest for all sites in the top 0-2cm depth increment and reduces to a more or less constant value from a depth of 5cm onwards. The average value across all sampled sites shows the TOC content being by a factor of >2 higher in the top layer than in the lower profile depths. The uniformity of the depth distribution of TOC amongst the soil profiles below a depth of 5cm was considered characteristic and defined as the baseline for the spoil/soil used and applied for the quantification of change since rehabilitation. Interestingly, the same depth distribution characteristic can be seen for the unmined ('control') soils, but at higher concentrations from the surface but comparable concentrations as the rehabilitated soils at greater depth. The consistency in the higher TOC values above a a soil depth of 5cm is a strong indicator that the accumulation of green carbon as a result of litter decomposition and transport into the soil (at the local semi-arid climatic conditions) occurs primarily close to the soil surface. The difference between the baseline TOC content in the lower profile and the increased TOC has been used to calculate the amount of carbon which has been introduced through biological activity since rehabilitation. Figure 3 shows the rate of TOC with time since rehabilitation. The rate of increase in TOC accumulation ranges across a relatively wide range and has no statistical trend. There is no difference in the performance between rehabilitated soils and unmined soils. The quantities are relatively small, with amounts less than 20 Mg/ha, yet there is a strong trend of increase of TOC with time (Figure 4). However, carbon stocks of rehabilitated sites are in majority well below those of the unmined sites. The carbon stock calculated for the unmined sites with values of 19 and 29 tons/ha is within the range determined for Australian soils for the depth 0-30 cm with a mean value of 29.7 tons/ha (Viscarra Rossel et al, 2014)). At least for natural soils and the dominating climatic conditions of Australia being semi-arid to arid, the depth 20-30 cm is not expected to contribute significant amounts of SOM to the total stock and allow the comparison with our study. A study at a coal mine in Kalimantan, Indonesia, determined carbon stocks after 9 years of re-vegetation to 23.2 tons/ ha (Agus et al, 2016). This value was close to carbon stock contents of a former secondary forest (28.5 tons/ha) and showed a much faster carbon rebuilding potential in this tropical climate from an initial value after land clearing of 4.3 tons/ha.

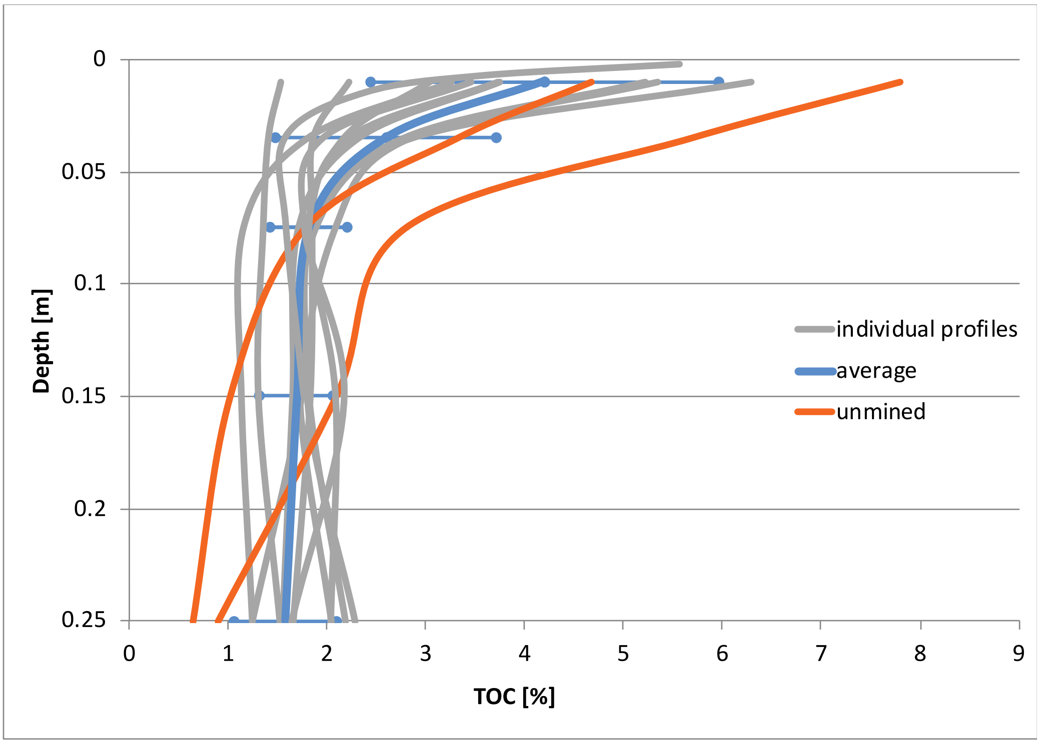

Figure 2 **Depth profiles (0-2, 2-5, 5-10. 10-20cm) of measured TOC for 13 sampling sites (mine site in Bowen Basin, Australia) of individually rehabilitated profiles and their average and unmined soils**

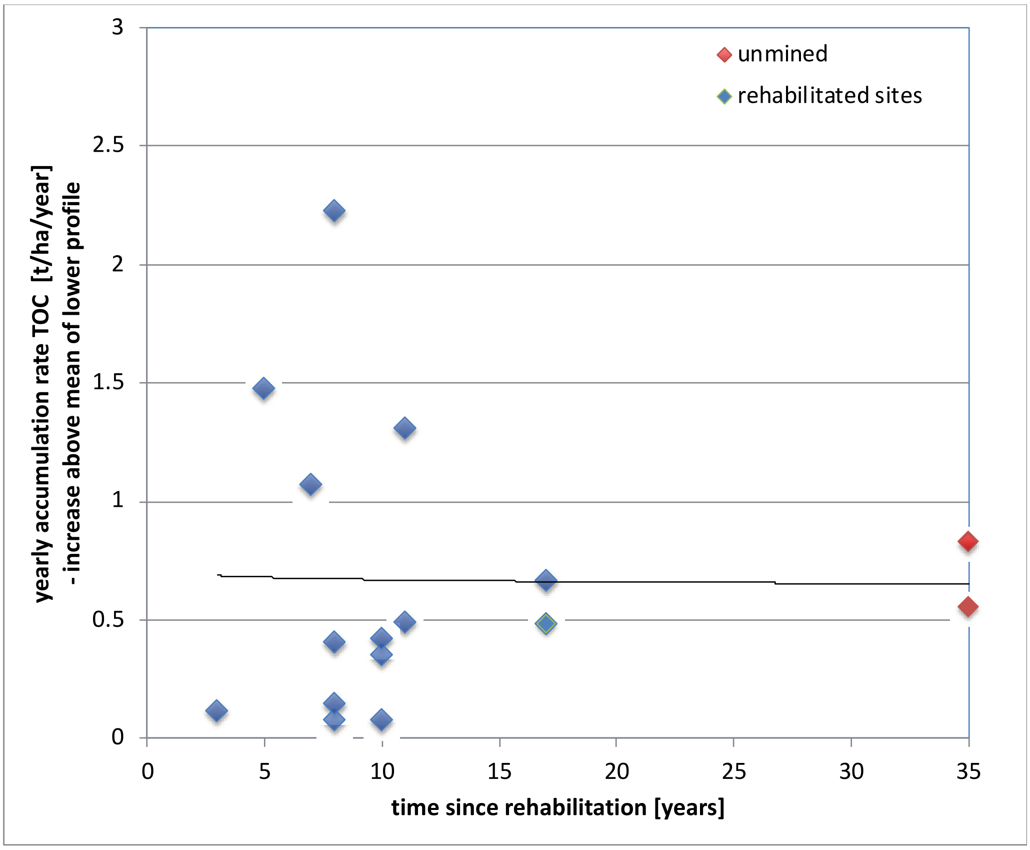

Figure 3 Rate of annual TOC accumulation for different times since rehabilitation based on TOC increase above the subsoil mean value for rehabilitated sites and unmined soils

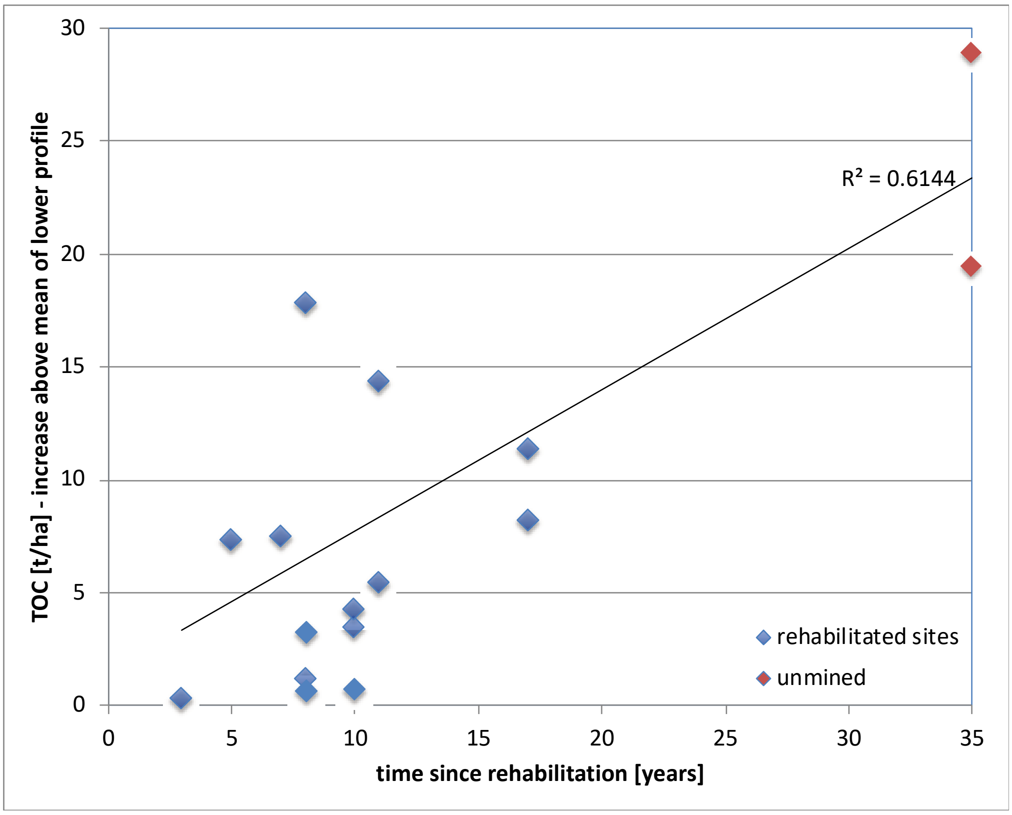

Figure 4 TOC content for different times since rehabilitation calculated based on TOC increase above the subsoil mean value for rehabilitated sites and unmined soils

3 The impact of soil organic carbon on soil structure

Organic carbon, particularly green organic carbon, positively affects the nutrient status and storage in soils, enhances biological life, and improves soil functions in general. An essential component for highly functional soils is the mechanical stability of rebuilt soils in combination with the ability of the soil to allow water and gas permeation, which can be expressed as the ability of soils to develop structural units. Soil structure, as a functional property describing soil health, can be quantified by the degree of aggregation and the formation of aggregate units.

3.1 Method

Topsoils on rehabilitated landforms and rebuilt at different times at a coal mine in Victoria, Australia, have been investigated for their carbon content and soil structural units. The wet sieving method has been employed to measure the degree of aggregation and aggregate stability. Five different locations have been sampled with an emphasis on the topsoil layer from 0-4cm.

3.2 Results and discussion

The quantification of the soil organic carbon content shows an increase in carbon content over time. For the different sites, the amount of organic carbon ranged from 2.5% for the youngest rehabilitated soil to 6% for the 40-year-old topsoil layer, and there is a clear relationship between age and carbon content (Figure 5). Figure 6 shows a clear correlation of an increase in the fraction of large aggregate size with age. While other factors than organic carbon may affect the degree of aggregation, it is well established that organic matter is conducive to the formation of aggregates and soil structure. From a functional point of view, the noticeable increase of large aggregates is considered positive. The large aggregates are commonly partnered with an increase in hydraulic permeability and hence fosters infiltration of rainfall. Microbial activity and biological activity, in general, are likewise improved by forming large aggregates, which is usually linked to an increase in the macropore system.

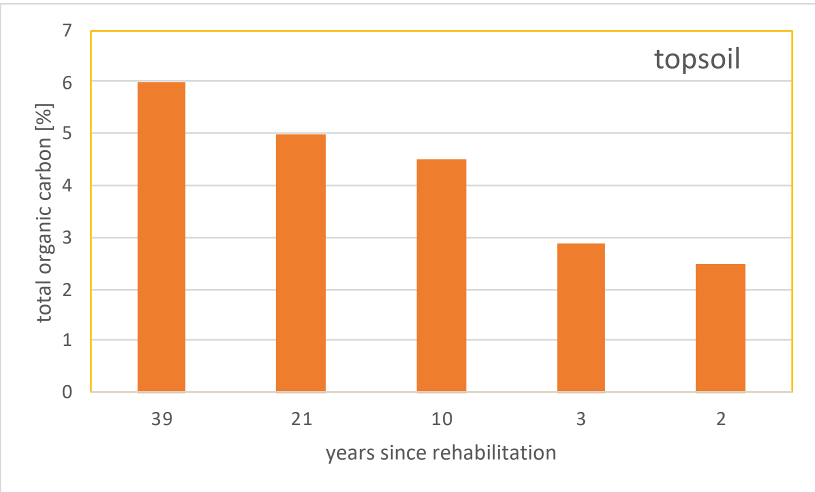

Figure 5 Total organic carbon in topsoil (0-4cm) of rehabilitated soils of different age (Victoria; Australia)

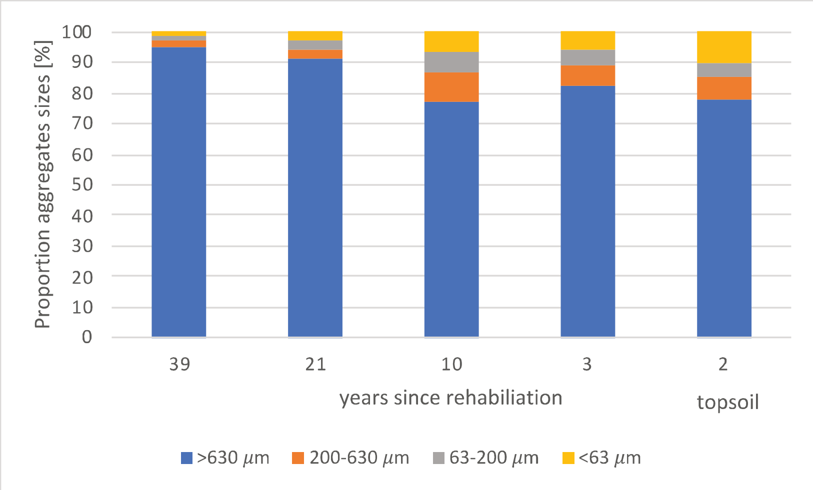

Figure 6 **Aggregate size distribution as an indicator for soil structure formation in topsoils (0-4cm) of rehabilitated soils of different age (Victoria; Australia)**

4 Separation of carbon fractions in rehabilitated soils of coal mining

Soils may contain a range of different types of carbon fractions, which are differentiated by their chain length, extent of their reactive nature through their radicals and other factors. These decide how well organic matter can be mineralised and through biological activity and weathering like green carbon or whether on the other extreme carbon is inert and non-reactive. A methodology is presented, which was used to identify the different carbon fractions of organic matter.

4.1 Methodology

The method of thermogravimetric analysis (TA) was used to identify the various fractions of carbon. The method is based on the principle that different carbon fractions require specific energy (heat) to transition from solid to gaseous phase. In practice, the mass of a sample is measured over time as the temperature increases. In addition, the tests were coupled with evolved gas analysis (EGA) to improve accuracy. The resulting spectrograms were statistically analysed using multivariate curve resolution (MCR). This analysis identifies carbon fractions using statistical software to process the numerous calculations involved in chemometric analysis. Multivariate curve resolution – alternating least squares (MCR-ALS) is a chemometric method used to separate mixtures into their respective representative components. Details of the methodology can be found in Chan et al. (2014a) and Chan et al. (2017).

While the method requires further refinement to improve accuracy, it provides a sufficient insight into the characteristic of the composition of the stored organic carbon within and between profiles.

4.2 Results and discussion

Two sites of the same mine site with the same age of rehabilitation (20 years) have been compared for their carbon fractions. The quantitative proportions of fractions determined using the TA-EGA and MCR analysis have been calculated proportionally to the TOC of each of the depths (see Figure 7a, 7b). Disregarding the contribution by inorganic carbon, it is obvious, that the soil profile of Figure 7a has only minor contribution of coal and charcoal (black carbon). In contrast, these fractions dominate the soil of Figure 7b. From the point of view of the success of rehabilitation, the soil of Figure 7b not only has much less green carbon, but the TOC content is also much reduced. Interestingly, this soil was built from topsoil, and it has to be assumed that in the process of moving and storing topsoil charred carbon and coal must have been mixed into the soil.

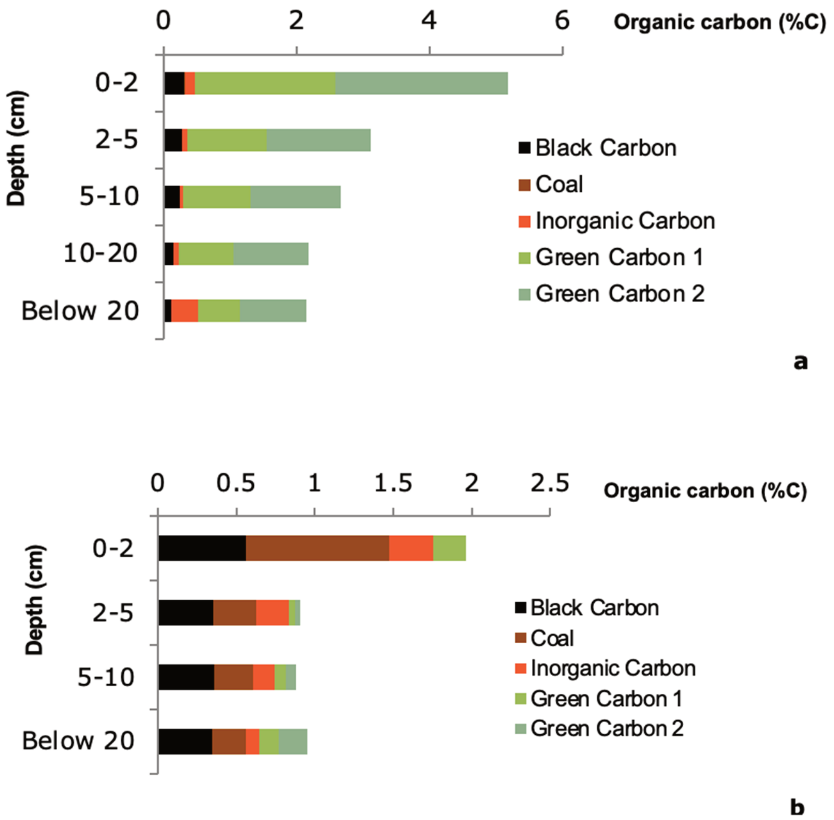

Figure 7 Carbon fraction in soil profiles of a mine site (Bowen Basin; Australia) at different locations; the rehabilitation age of both sites is 20 years. Green Carbon 1 and 2 are components identified from the thermograms of the TA-EGA analysis and both attributed to the fraction of organic carbon originating from fresh plant litter

5 Summarising conclusion

Soil carbon is an important indicator to assess soil health and the success of rehabilitation

Increase of carbon concentration by incorporation of green carbon as a result of decomposition of litter only close to the surface and hence requires adapted spatial sampling in soil profile, at least for semi-arid environments

Constant TOC concentration below a depth of 5cm, independent of type of vegetation, reflecting carbon accumulation is occurring primarily at the surface with only limited translocation to depth for the investigated periods of at maximum just over three decades since the start of rehabilitation

Total carbon stocks increase with time but remain below those of natural sites with similar climatic conditions.

Carbon stocks of rehabilitated sites are below values reported in literature for natural sites in Australia or coal mine rehabilitated sites in tropical climates.

The occurrence of char and/or coal can create a bias and the different carbon fractions need to be separated for a valid assessment of soil health with (green) carbon as an indicator.

Soil carbon increase and accumulation over time in rehabilitated soils improves functional criteria of soils through improving soil structure

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