

REFEREED PAPER

## SOIL ORGANIC CARBON (SOC) CHANGES INDICATED BY HOT WATER EXTRACTABLE CARBON (HWEC)

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### ABSTRACT

Labile carbon responds readily to changes in soil management practices and has been identified as a site-independent indicator for monitoring soil organic carbon (SOC). The problem is, however, that there are no easy, reliable methods available to measure this fraction. For this paper the hot water extractable carbon (HWEC) method has been evaluated to determine whether it is able to quantify carbon from the labile pool of soil and to detect short term changes in carbon content. Samples from long-term experiments in Germany and South Africa with a well established differentiation in SOC were exchanged. The SOC and HWEC were determined to establish the relationship between them. The effect of management practices on the HWEC fraction was tested using soils from selected sites of the sugarcane growing areas in South Africa under different management (trashed, burnt, uncultivated). The relationships derived between SOC and HWEC were comparable to the German results for soils with clay contents ranging between 10 and 40%. For these soils the analysed HWEC values multiplied by a factor of 15 to 19 gave a good estimate of the labile carbon portion in the soils. The virgin (uncultivated) soils generated the highest HWEC values (87% higher than burnt), followed by the trashed soils (66% higher than burnt). The HWEC method showed reproducible results.

*Keywords:* soil sustainability, soil health indicator, soil organic carbon fractions, labile carbon

### Introduction

Soil organic carbon (SOC) decline has been recognised as one of the major threats to soil productivity. There are a number of human activities which accelerate the decline, such as converting virgin land or pastures into arable land, intensive soil cultivation, cropping systems that do not replace organic matter, and soil erosion (Miles *et al.*, 2008). The changes, however, are very slow and difficult to detect.

The SOC can be subdivided into fractions with different rates of decomposability, i.e. the labile carbon fraction and the non-labile carbon (stable carbon fraction). The stable SOC is largely bound to clay particles. Therefore SOC values are highly site dependent and show a strong correlation with clay content. On the other hand, changes in SOC content due to a change in management practice and/or ongoing degradation or recovering

processes will first be visible in the labile fraction (Franko 1997; van Antwerpen, 2005). The labile fraction is responsive to soil management practices and has thus been identified as a more sensitive indicator, and is relatively independent of site conditions. It does, however, consist of various organic compounds which mean that no analytical procedure exists for a direct determination. Methods to quantify labile carbon in soils can be grouped based on the principals for analysis:

- a) Incubation experiments - Determination of carbon and/or nitrogen mineralisation under controlled conditions over time (Stanford and Smith, 1972; Meyer *et al.*, 1983; Weigel *et al.*, 1997; Curtin *et al.*, 2006).
- b) Physico-chemical methods based on the interaction between SOC and mineral soil particles: density fractionation, light fraction-OC (Hassink, 1995; Christensen, 2001).
- c) Chemical extraction methods such as (i)  $\text{KMnO}_4$ -oxidizable carbon (Blair *et al.*, 1995; Tirol-Padre and Ladha, 2004; Graham, 2004), (ii) hot water extractable carbon (Schulz, 1990; Sparling *et al.*, 1998) and (iii) cold water extractable carbon (Ghani *et al.*, 2003).
- d) Nuclear magnetic resonance (NMR) spectroscopy, mid-infrared diffuse reflectance spectroscopy (DRIFTS) and near-infrared reflectance spectroscopy (NIRS) (Golchin *et al.*, 1994; Kögel-Knabner, 1997; Zimmermann *et al.*, 2007).

Incubation experiments are the most reliable methods, but are rather time consuming. Using spectroscopy to identify the labile carbon promises rapid and cheap information, although the results are still not convincing because of the large diversity of substances in the non-humified organic matter (Kolář *et al.*, 2009).

The hot water extractable carbon (HWEC) method has been described by Schulz (1990) as an easily applicable and reliable method. It consists of a chemical extraction using distilled water to represent 'near to nature' conditions of ongoing mineralisation processes. The extracted fraction contains soil microbial biomass, simple organic compounds, and compounds which are hydrolysable under the given extraction conditions (Leineweber *et al.*, 1995; Schulz, 1997). According to Schulz (1997) the method is applicable to all soils and clearly shows the effect of changes in management. Other advantages listed are that samples can be taken during any season and air-dried, and stored samples can be used for analysis. For the northern European climate (400-800 mm annual precipitation, mean annual temperature 6-10 °C) the following HWEC-classes were derived by Körschens and Schulz (1999) for sandy and loamy soils (values in mg C/kg soil):

|          |               |
|----------|---------------|
| ⇒ low    | <200 mg/kg    |
| ⇒ medium | 200-400 mg/kg |
| ⇒ high   | >400 mg/kg.   |

According to these values a soil with less than 200 mg/kg HWEC can be regarded as SOC-depleted.

## Materials and Methods

### Standard samples

Eight samples (single, air-dried, 0-200 mm) from the four main treatments of two long-term experiments with a well established management-caused differentiation in SOC in Germany (Static Fertilisation Experiment from 1902, Bad Lauchstädt) and South Africa (BT1 from 1939, Mount Edgecombe) were exchanged between the two countries (termed 'standard samples'). Details about the sites and the experiments are given in Table 1. The exchange of samples was undertaken to conduct a comparison to prove that the HWEC method, which is routinely used in the German laboratory, could be successfully established in South Africa. The SOC and HWEC were determined to establish the relationship between them.

**Table 1. Selected details of two long-term experiments (Körschens et al., 1994; van Antwerpen et al., 2001).**

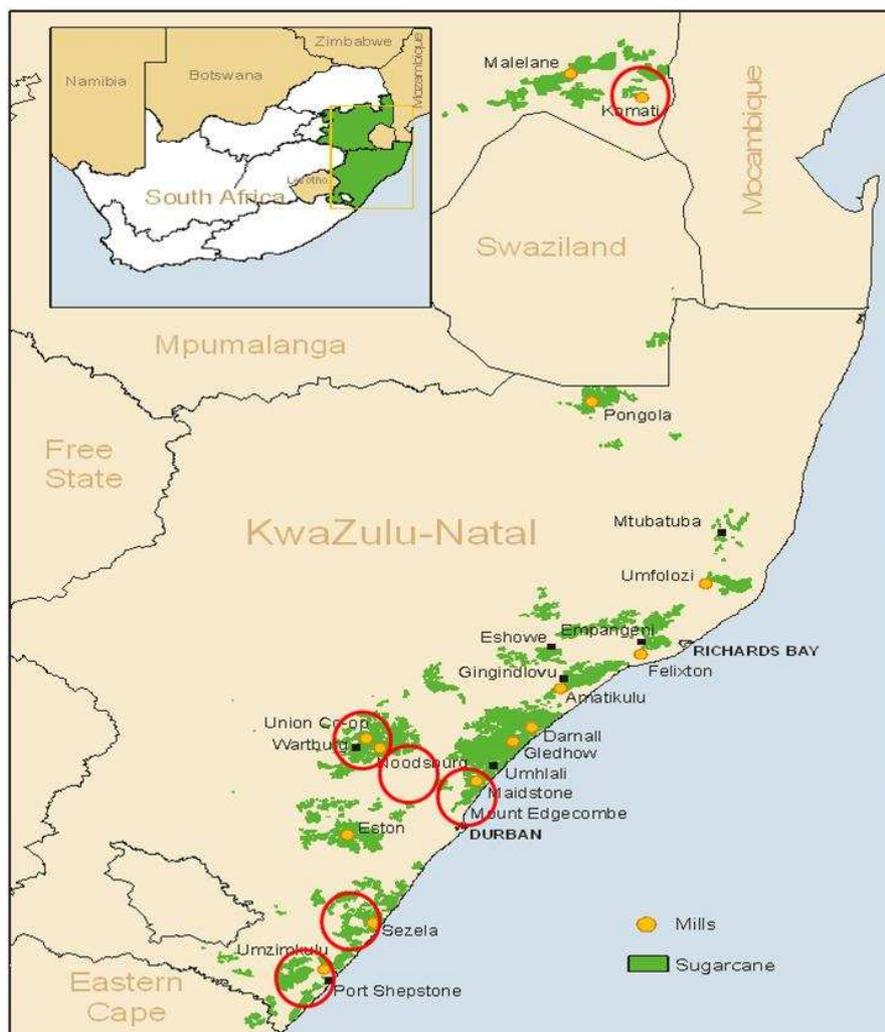
| Experiment  | Static Fertilisation Experiment, Bad Lauchstädt, Germany         | BT1 Experiment, Mount Edgecombe, South Africa             |
|-------------|--|---|
| Established | 1902   | 1939  |
| Soil form   | Phaeozem <sup>1</sup>  | Vertisol <sup>1</sup>                                     |
| SOC         | 1.6 - 2.3%   | 2.5 - 3.8%  |
| Clay        | 21%  | >50%  |
| Climate     | Rainfall: 480 mm per year<br>Average annual temp. 8.8 °C         | Rainfall: 950 mm per year<br>Average annual temp. 20.9 °C |
| Crop        | Crop rotation of sugar beet, spring barley, potato, winter wheat | Monoculture of sugarcane                                  |
| Treatments  |  |   |
| 1           | Without fertilisation  | Burnt   |
| 2           | NPK (mineral fertilisation)                                      | Burnt+NPK (mineral fertilisation)                         |
| 3           | FYM <sup>2</sup> (organic fertilisation)                         | Trashed   |
| 4           | FYM+NPK (organic+mineral fertilisation)                          | Trashed+NPK (mineral fertilisation)                       |

<sup>1</sup>WRB classification (IUSS Working Group WRB 2006) <sup>2</sup>FYM=farmyard manure

### Field samples

The effect of three land management practices on the HWEC fraction was tested using soils from selected sites of the South African sugar belt. Altogether, 50 samples were taken from six sites representing different climatic regions and soil textures (Figure 1).

The sample selections concentrated on sites where burnt and trashed fields were in close proximity to non-cultivated (virgin) sites. Samples were taken with an auger at three depths (0-100, 100-200 and 0-200 mm) and transported in cooler boxes. The next day they were mixed, sieved (2 mm sieve) and divided into two subsamples: one group of subsamples was used immediately for microbial biomass and basal respiration analysis, the other group of subsamples was air-dried and analysed for HWEC, SOC, total nitrogen (N) and texture. The objectives were to evaluate the sensitivity of this method to quantify labile carbon for a range of soils under three land management options and to search for SOC related parameters that correlate with HWEC. A site specific evaluation of the HWEC parameter was done by categorising the samples according to their clay content in order to select the most appropriate conversion factor. For ANOVA, regression and correlation analyses Genstat v. 11 was used.



**Figure 1. Sites for the hot water extractable carbon (HWEC) project field samples.**

### Methods

Standard samples: for HWEC 20 g of air-dried soil was boiled in 100 ml of distilled water under reflux for one hour (Schulz *et al.*, 2003). In South Africa, the carbon (C) content of the extracts was analysed in a Shimadzu C/N analyser at 680 °C after centrifugation and filtration. The SOC was determined by a dichromate wet oxidation procedure (Sahrawat, 1982). In the German laboratory the C content of the hot water extracts was analysed by using a Multi N/C analyser (Fa. Analytik Jena) at 450 °C. The SOC content was determined by dry combustion in a C-Mat 550 (Fa. Strohlein).

Field samples: HWEC and total C was determined as described above. Total N was analysed using semi-micro Kjeldahl digestion with colorimetric determination of the liberated ammonium (Forster, 1995). Soil texture was determined with the hydrometer method (Day, 1965). Microbial biomass and basal respiration were both estimated with the fumigation-extraction method based on the difference between C extracted with 0.5 M  $K_2SO_4$  from chloroform-fumigated and unfumigated soil samples using a Kc factor of 0.38 (Vance *et al.*, 1987). All analyses were done in duplicates.

## Results and Discussion

### Standard samples

The HWEC results for the standard samples from the two long term experiments are presented in Table 2.

**Table 2: German (GER) and South African (SA) hot water extractable carbon (HWEC) results\* for the standard samples.**

| Treatments                                   | HWEC_GER<br>mg/kg | HWEC_SA<br>mg/kg | SA_HWEC ÷<br>GER_HWEC** | HWEC_GER<br>relative | HWEC_SA<br>relative |
|--|-------------------|------------------|-------------------------|----------------------|---------------------|
| <b>BT1 (SA)</b>                              |                   |                  |                         |                      |                     |
| Burnt  | 400               | 412              | 103                     | 100                  | 100                 |
| Burnt+NPK                                    | 658               | 752              | 114                     | 164                  | 182                 |
| Trashed                                      | 735               | 841              | 114                     | 184                  | 204                 |
| Trashed+NPK                                  | 1433              | 1548             | 108                     | 358                  | 376                 |
| <b>Static fertilisation experiment (GER)</b> |                   |                  |                         |                      |                     |
| Without fert.                                | 181               | 298              | 164                     | 100                  | 100                 |
| NPK  | 228               | 398              | 174                     | 126                  | 134                 |
| FYM <sup>1)</sup>                            | 352               | 722              | 205                     | 194                  | 243                 |
| FYM+NPK                                      | 410               | 763              | 186                     | 226                  | 256                 |

\*average of two replicates, \*\*GER\_HWEC=100, <sup>1)</sup> farmyard manure

The results show a good agreement between the SA and GER analyses for the BT1 samples, where the SA values are only 3 to 14% higher than those from the German laboratory. All samples analysed using the HWEC, even the treatment which has been burnt and without additions of fertiliser since 1939, gave values that were above the high range (400 mg C/kg soil) for European conditions for sandy to loamy soils. It is clear that those classes cannot be applied to South African soil and climatic conditions.

The values obtained for the German soils in South Africa are about 46 to 105% higher than those obtained for the same soils when analysed in Germany. One explanation could be differences in the equipment used: the C/N analysers used in Germany operated at 450°C whilst the Shimadzu C/N analyser in the SA laboratory operated at 680°C. However, it remains unclear why the BT1 samples were less affected.

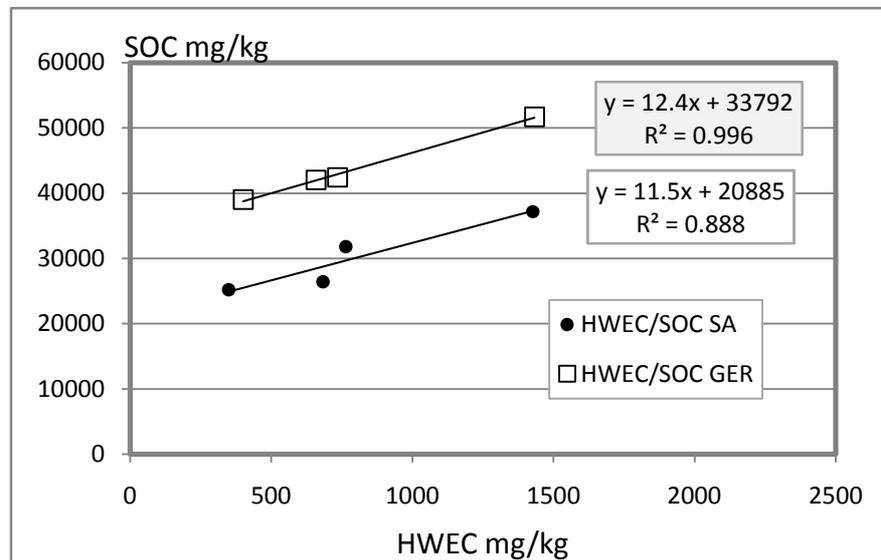
Although the absolute values are different, the relative differences between the treatments for both experiments from both laboratories are comparable (Table 2, columns 4 and 5). In the BT1 experiment, application of NPK in the burnt treatment increased the HWEC values by 64-82%. Values in the trashed treatment were 84-104% higher when compared to the burnt treatment. The highest values (258-276% higher than burnt) were found for trashed+NPK. The ranking for the treatments from the German long-term experiment is the same (Table 2): without fertilisation < NPK (+26-34%) < organic manure (+94-143%) < organic manure +NPK (+126-156%). The distinct differentiation of the HWEC values due to different management (burnt/trashed) and fertilisation (organic/mineral) can be seen as the key factor and demonstrates the success of the method.

Figure 2 shows the linear regressions for HWEC and SOC of the BT1 experiment for the German and South African values. The coefficient of determination is very high for both

set of values (0.99 German values, 0.88 SA values). The trend lines are not congruent because of SOC having been analysed in Germany with the dry combustion method and in SA with the wet oxidation method. The slope of both regression lines is, however, almost the same (12.4 German values, 11.5 SA values). The factor for converting HWEC into labile carbon can be derived from the slope of the regression line. Factors between 13 and 16 (average 15) have been found by Freytag (1987) from a large number of samples from various long-term experiments in Europe:

$$\text{Labile carbon} = 15 \cdot \text{HWEC}$$

The slopes of both regression lines for the BT1 samples are slightly lower than the factors derived from Freytag (1987), indicating a larger pool size of the labile fraction. The opposite might be expected bearing in mind that the much higher average temperature under South African site conditions will enhance mineralisation of SOC, leading to a decline in the labile fraction.



**Figure 2. Relation SOC and HWEC for the main treatments of the BT1 experiment.**

On the other hand, the soil of the BT1 experiment is a Vertisol with more than 50% clay. In clayey soils the mineralisation rate is generally low and the clay stabilises the carbon (Oades 1988).

#### *Field samples*

The average results for the HWEC values and related soil values are presented for trashed, burnt and virgin sites in Table 3.

The clay content for the burnt and trashed fields was similar and ranged from 6-61% and from 4-64.8% respectively. The clay content for the virgin sites however ranged from 2.0 to 48.2 what resulted in significantly lower average clay of 22.6% compared to 36.5% and 37.7%. for the burnt and trashed fields.

The SOC values from the burnt fields average 1.51% and are the lowest values measured followed by those from the virgin sites (1.8% SOC), with the highest values on the trashed soils (2.3% SOC). SOC content from only the latter was significantly higher compared to the burnt sites (Table 3). The same ranking applies to total N with both trashed and virgin sites containing significantly higher values compared to the burnt sites. Similar to van Antwerpen *et al.* (2009) it was noticed that, despite the distinctly lower clay contents for virgin soils, their SOC and total N, values exceed those of the burnt management. Similar to Dominy *et al.* (2002) this clearly demonstrates the influence that cultivation and reduced carbon returns to soils have on the carbon decline. It shows, assuming a linear relationship between clay and SOC, that the burnt soils have lost almost 50% and trashed soils about 25% of their original carbon values.

**Table 3. Average, minimum (Min) and maximum (Max) of selected soil parameters for trashed, burnt and virgin sites.**

|   | Average            | Min   | Max    | Relative to burnt |
|---|--------------------|-------|--------|-------------------|
| <b>BURNT, without organic amendments or green manure crops (n=48)</b> |                    |       |        |                   |
| Clay content (%) [7.414]  | 36.0 <sup>b</sup>  | 6.0   | 61.0   | 100               |
| SOC content wet oxidation (%) [0.472]                                 | 1.51 <sup>a</sup>  | 0.30  | 3.0    | 100               |
| Total N content (mg/kg) [225.6]                                       | 802 <sup>a</sup>   | 300   | 2000   | 100               |
| HWEC (mg/kg) [211.0]  | 493.4 <sup>a</sup> | 169.8 | 1153.5 | 100               |
| Microbial biomass (µg C/g) [29.79]                                    | 114.4 <sup>a</sup> | 33.9  | 294.7  | 100               |
| Basal respiration (µg CO <sub>2</sub> -C/g per day) [2.431]           | 7.62 <sup>a</sup>  | 0.72  | 20.09  | 100               |
| <b>TRASHED, with organic amendments or green manure (n=38)</b>        |                    |       |        |                   |
| Clay content (%)  | 37.7 <sup>b</sup>  | 4.0   | 64.8   | 104.7             |
| SOC content wet oxidation (%)   | 2.3 <sup>b</sup>   | 0.4   | 4.0    | 152.3             |
| Total N content (mg/kg)   | 1181 <sup>b</sup>  | 500   | 2600   | 147.2             |
| HWEC (mg/kg)  | 820.3 <sup>b</sup> | 282.6 | 2203.9 | 166.0             |
| Microbial biomass (µg C/g)  | 143.5 <sup>b</sup> | 46.7  | 288.8  | 125.4             |
| Basal respiration (µg CO <sub>2</sub> -C/g per day)                   | 9.0 <sup>a</sup>   | 0.5   | 26.9   | 118.1             |
| <b>VIRGIN, not cultivated (n=50)</b>                                  |                    |       |        |                   |
| Clay content (%)  | 22.6 <sup>a</sup>  | 2.0   | 48.2   | 62.7              |
| SOC content wet oxidation (%)   | 1.8 <sup>a</sup>   | 0.4   | 4.8    | 119.2             |
| Total N content (mg/kg)   | 1098 <sup>b</sup>  | 100   | 2700   | 136.9             |
| HWEC (mg/kg)  | 923 <sup>c</sup>   | 195.4 | 3041.9 | 187.1             |
| Microbial biomass (µg C/g)  | 168.4 <sup>b</sup> | 44.8  | 385.6  | 147.2             |
| Basal respiration (µg CO <sub>2</sub> -C/g per day)                   | 9.4 <sup>a</sup>   | 0.77  | 21.51  | 123.4             |

In brackets [ ] = LSD (p=0.05)

Microbial biomass and basal respiration were highest for the virgin sites (+47% for microbial biomass and +23.4% for basal respiration respectively compared to the burnt fields) followed by the trashed sites (+25.4% for microbial biomass and +18.1% for basal respiration respectively, compared to the burnt fields). The differences were significant

only for microbial biomass. This may be because all measured values for microbial biomass and basal respiration were low, probably due to the samples being taken during the dry season.

The HWEC values cover a very wide range with a minimum of 169.8 mg/kg and a maximum of 3041.9 mg/kg. The virgin sites with an average of 923 mg/kg had the highest average HWEC values, 87% higher than the burnt fields. It should be emphasised that the total SOC for the virgin sites content was only 19% higher than for the burnt fields. A much larger proportion of the total SOC is thus labile carbon on the virgin sites. The SOC/HWEC ratio, calculated on basis of the average values in Table 3, was 19.5 for virgin sites and 30.6 for burnt sites, demonstrating that the labile carbon fraction has been smaller for the latter.

The effect of trash as an organic amendment on labile C was clearly reflected in the HWEC values, which were on average 66% higher than those of the burnt fields, while the SOC of the trashed sites was 52% higher. The calculated SOC/HWEC ratio of 28 was still distinctly higher compared to the ratio of 19.5 for the virgin sites. Although the pool of labile carbon for the trashed sites was larger compared to the burnt fields, a considerable part of the 'trash effect' is only visible in the total SOC values. This could be an indication that trash contributes more to soil structure. In addition, regular tillage in the cultivated fields will reduce the labile carbon pool regularly and limit its size.

When comparing trashed and burnt sites, the minimum values are of particular interest. For HWEC, 200 mg/kg has been identified in Germany as a threshold value for marking poor soil conditions (Körschens and Schulz 1999). The results in Table 3 show that only some soils under burnt managed have HWEC below 200 mg/kg, while the lowest value for trashed sites was 282.6 mg/kg, i.e. distinctly above the threshold. However, the very wide range of HWEC values measured for the South African soils indicates that the European derived threshold values are not applicable to South African site and climatic conditions.

#### *Relationships between HWEC and other soil properties*

The performance of the HWEC method was evaluated by calculating the correlations between the hot water extractable fractions and the other carbon related parameters analysed in the project. Table 4 summarises the respective correlation coefficients.

**Table 4. Correlation coefficients (r) for hot water extractable carbon (HWEC) versus various soil characterising parameters.**

| Parameter         | HWEC (n=136) |
|-------------------|--------------|
| Clay              | 0.153        |
| SOC               | <b>0.741</b> |
| Total N           | <b>0.842</b> |
| Microbial biomass | 0.602        |

Bold = significant (P<0.05)

No correlation was found between clay and HWEC. This is in accordance to the hypothesis that the HWEC fraction is less site-dependent than SOC and will better reflect changes due to management. The best correlation with HWEC was found to be total N content, which is supported by literature (Körschens *et al.*, 1990; Manzke, 1995). It has

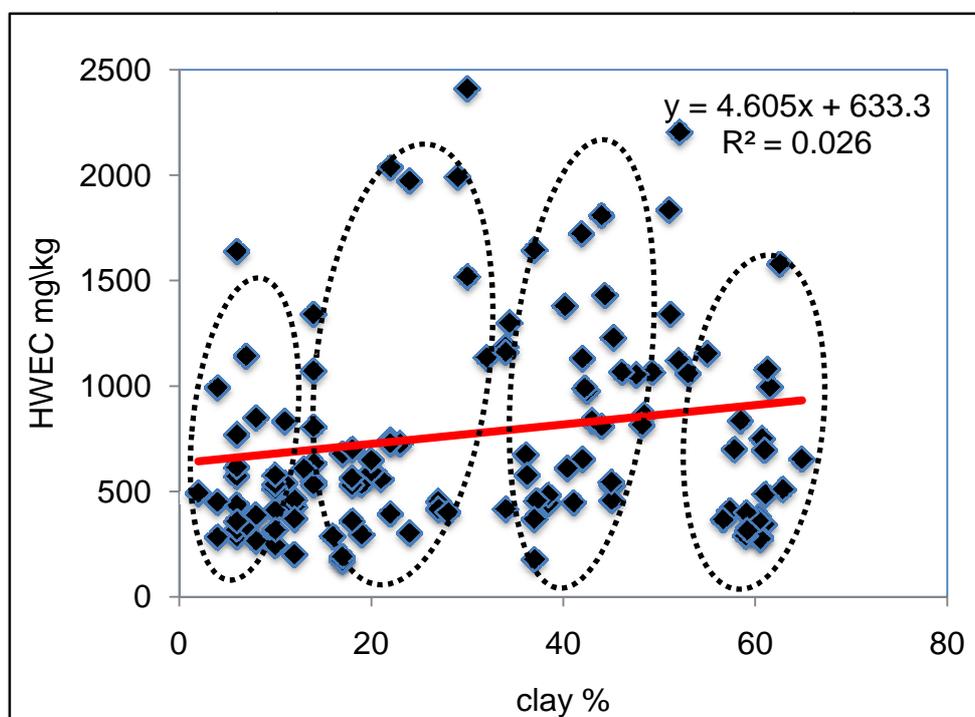
been reported that the labile carbon fraction has a closer C/N ratio than the stable carbon pool (Leineweber *et al.*, 1995). Several approaches therefore were made to derive conversion factors for an estimate of potential mineralisable nitrogen in soils from the labile carbon pool (Curtin *et al.*, 2006; Weigel *et al.*, 1998).

The relationship between SOC and microbial biomass has often been reported in literature (Insam and Domsch, 1988; Sparling, 1992). The correlation of HWEC with microbial biomass is surprisingly low. However, the relationship of the labile carbon fraction represented here by the HWEC method should be even stronger as microbial biomass is part of the labile carbon fraction (Sparling *et al.*, 1998; Franzluebbers, 1999). This weaker than expected relationship is probably due to the seasonal variability of microbial biomass which has often been described in literature (Kaiser and Heinemeyer, 1993; Haynes and Francis, 1993; Diaz-Raviña *et al.*, 1995). Most of the samples were taken during the dry season at a time of very low microbial activity.

#### *Hot water extractable carbon and soil texture*

The HWEC method was originally developed on data from sandy to loamy soils (Körschens and Schulz, 1999). The clay content of the project samples used in this study, however, ranged from 2% clay (almost pure sand) to 64.8% clay (very heavy clay). To test the suitability of the HWEC for various soil textures the dataset was divided into clay classes.

Based on the assumption of similar site conditions in one class a close correlation between HWEC and SOC per class was to be expected, because SOC differences are then less site-related than management-related. Also, a close relationship between SOC and HWEC in all the clay classes/categories would confirm suitability of the HWEC fraction to detect short-term changes of SOC across a range of soil textures.



**Figure 3. Relationship between hot water extractable carbon (HWEC) and clay content (n=136).**

In plotting HWEC against clay content (Figure 3), four groups of data were identified where the clay content was similar (within a group) but the HWEC values differed substantially. On the basis of this observation, it was decided to group the dataset into four categories (Table 5).

**Table 5. Identified clay categories for the field sample data set.**

| Clay category | Clay (%)    |
|---------------|-------------|
| Category 1    | <15% clay   |
| Category 2    | 15-30% clay |
| Category 3    | 30-45% clay |
| Category 4    | >45% clay   |

A summary of linear regressions between SOC and HWEC is presented for each clay category in Table 6. The coefficient of determination ( $R^2$ ) is highest for the clay Category 2 (soil with 15-30% clay,  $R^2=0.91$ ), which is the clay range of the soils on which the method was originally tested and validated in Europe. The method also correlated fairly well for soils in Category 3 (soils with 30-44% clay,  $R^2=0.82$ ). Both clay Categories have a distinctly higher  $R^2$  than that of the overall linear regression ( $R^2=0.55$ ), which supports the assumption that the HWEC method is useful for reflecting changes in land management. The slope of the regression curve (15 to 19) is comparable to that reported in the literature (Freytag, 1987; Manzke, 1995; Körschens *et al.*, 1997). The latter confirms the applicability of the method also for South African conditions for soils with clay content between 15 and 44%.

The coefficients of determination for Categories 1 and 4 are much weaker (Table 6). Possible reasons for the much lower coefficient of determination for Category 4 (>45% clay) soils are: soil with higher clay content have a higher C-stabilisation level (Dominy *et al.*, 2002), and hot water might not be a sufficiently effective extractant for soils with a high clay content due to the protective nature of structured soils to SOC (Oades, 1988).

**Table 6: Linear regression HWEC vs. SOC (regression function and coefficients of determination for the clay categories).**

| Clay-category     | HWEC vs. SOC regression function | $R^2$ |
|-------------------|----------------------------------|-------|
| 1 to 4 (n=136)    | 16.08 x + 9050                   | 0.550 |
| 1 =<15 % (n=40)   | 6.403 x + 5881                   | 0.204 |
| 2 = 15-30% (n=33) | 15.02 x + 3459                   | 0.908 |
| 3 = 30-44% (n=31) | 19.46 x + 5234                   | 0.815 |
| 4 >45% (n=33)     | 8.907 x + 22175                  | 0.567 |

The relatively poor performance of the HWEC method for the clay Category 1 soils means that <15% clay needs still to be investigated in detail. It is possible that the heterogeneity of the site conditions in this group is larger than in all the other groups. It is, for example, an enormous difference to work with a soil of just 2% clay compared to one of 10% clay. This difference of 8% clay is not as important for the other groups. Another possible reason is the lack of C protection (Oades, 1988) and high aeration,

which combined results in quick decomposition of organic matter. More samples are therefore needed to analyse and describe the conditions in this group.

### Conclusions

The HWEC method showed reproducible results and the analysed values were acceptable for soils between 15 and 44% clay. For these soils the analysed HWEC values multiplied by a factor of 15 to 19 gave a good estimate of the labile carbon portion in soils.

HWEC was not related to clay, but showed a strong correlation to SOC at similar site conditions. This confirms that the HWEC fraction is more related to labile carbon and thus reflects carbon changes as affected by land management. The close correlation between HWEC and total nitrogen should be further explored as it might be useful in predicting potential N-mineralisation.

The measured absolute HWEC values reported in this paper were distinctly higher than those reported in literature for work conducted in Europe, and hence the assumption that the threshold values identified for European conditions are not suitable for South African site and climatic conditions. A new set of threshold values should therefore be developed for the southern African regions.

### REFERENCES

- Blair GJ, Lefroy RDB and Lisle L (1995). Soil Carbon fractions based on their degree of oxidation and the development of a Carbon Management index for agricultural systems. *Aust J Agric Res* 46: 1459-1466.
- Day PR (1965). Particle fractionation and particle-size analysis. pp 545-567 In: Black CA (Ed.) *Methods of Soil Analysis, Part 1. American Society of Agronomy. Inc., Madison, Wisconsin.*
- Christensen BT (2001). Physical fractionation of soil and structural and functional complexity in organic matter turnover. *European Journal of Soil Science* 52: 345-353.
- Curtin D, Wright CE, Beare MH and Callum FM (2006). Hot water extractable Nitrogen as an Indicator of Soil Nitrogen Availability. *Soil Sci Soc Am J* 70: 1512-1521.
- Díaz-Raviña M, Acea MJ and Carballas T (1995). Seasonal changes in microbial biomass and nutrient flush in forest soils. *Biol Fertil Soils* 19: 220-226.
- Dominy CS, Haynes RJ and van Antwerpen R (2002). Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. *Biol Fertil Soils* 36: 350-356.
- Forster JC (1995). Soil nitrogen. pp 79-87 In: Alef K and Nannipieri P (Eds.) *Methods in Applied Soil Microbiology and Biochemistry*. Academic Press, San Diego, USA.
- Franko U (1997). Modelling of soil organic matter turnover. *Arch Acker Pfl Boden* 41: 527-547.
- Franzluebbers AJ, Haney RL and Hons FM (1999). Relationship of chloroform fumigation-incubation to soil organic matter pools. *Soil Biol Biochem* 31: 395-405.
- Freitag HE (1987). Gleichzeitige Ermittlung der Parameter  $C_{pot}$  und  $k$  für die C-Mineralisierungsfunktionen aus  $CO_2$ -Messungen unter konstanten Bedingungen. *Arch Acker Pfl Boden* 31: 23-31.

- Ghani A, Dexter M and Perrott KW (2003). Hot-water extractable carbon in soils: A sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil Biol Biochem* 35: 1231-1243.
- Golchin A, Oades JM, Skjemstad JO and Clarke P (1994). Structural and dynamic properties of soil organic-matter as reflected by <sup>13</sup>C natural-abundance, pyrolysis mass-spectrometry and solid-state <sup>13</sup>C NMR-spectroscopy in density fractions of an oxisol under forest and pasture. *Aust J Soils Res* 33: 59-76.
- Graham MH (2004). The effect of various crop residue management practices under sugarcane production on soil quality. PhD Thesis, University of KwaZulu-Natal, South Africa.
- Hassink J (1995). Density fractionation of soil macro organic matter and microbial biomass as predictor of C and N mineralisation. *Soil Biol Biochem* 27: 1099-1108.
- Haynes RJ and Francis GS (1993). Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. *Journal of Soil Science* 44: 665-675.
- Insam H and Domsch A (1988). Relationship between soil organic carbon and microbial biomass on chronosequences of reclamation sites. *Microb Ecology* 15: 177-188.
- IUSS Working Group WRB (2006). World reference base for soil resources 2006. 2nd edition. World Soil Resources Reports No. 103. FAO, Rome.
- Kaiser E and Heinemeyer O (1993). Seasonal variations of soil microbial biomass carbon within the plough layer. *Soil Biol Biochem* 25: 1649-1655.
- Kögel-Knabner I (1997). <sup>13</sup>C and <sup>15</sup>N NMR spectroscopy as a tool in SOM studies. *Geoderma* 80: 243-270.
- Kolář L, Kuzel S, Horacek J, Cechova J, Borova-Batt J and Peterka J (2009). Labile fractions of soil organic matter, their quantity and quality. *Plant Soil Environment* 55: 245-251.
- Körschens M and Schulz E (1999). *Die organische Bodensubstanz. Dynamik – Reproduktion – ökologisch begründete Richtwerte* (Soil organic matter. Dynamic – reformation – ecological founded approximations. UFZ-Bericht 13/1999, ISSN 0948-9452.
- Körschens M, Schulz E and Behm R (1990). Heißwasserlöslicher C und N im Boden als Kriterium für das N-Nachlieferungsvermögen (Hot water extractable C and N of soils as indicator of soil N supply). *Zentralbl Mikrobiol Jena* 145: 305-311.
- Körschens M, Stegemann K, Pfefferkorn A, Weise V and Müller A (1994). *Der Statische Düngungsversuch nach 90 Jahren*. BG Teubner Verlagsgesellschaft Stuttgart, Leipzig, 179 pp.
- Körschens M, Weigel A and Schulz E (1997). Turnover of soil organic matter (SOM) and long-term balances - Tools for evaluating sustainable productivity of soils. *Z Pflanzenernähr Bodenkd* 161: 409-424.
- Leineweber P, Schulten HR and Körschens M (1995). Hot water extracted organic matter: chemical composition and temporal variations in a long-term field experiment. *Biol Fertl Soils* 20: 17-23.
- Manzke F (1995). Bodenmikrobiologische und bodenchemische Kenngrößen zur Beurteilung des Umsatzes organischer Bodensubstanz in unterschiedlichen Bodennutzungssystemen. Dissertation Univ. Göttingen. 162 pp.
- Meyer JH, Wood RA, McIntyre RK and Leibbrandt NB (1983). Classifying soils of the South African Sugar Industry on the basis of their Nitrogen Mineralizing Capacities and organic matter contents. *Proc S Afr Sug Technol Ass* 57: 151-158.
- Miles N, Meyer JH and van Antwerpen R (2008). Soil organic matter data: What do they mean? *Proc S Afr Sug Technol Ass* 81: 324-332.
- Oades JM (1988). The retention of organic matter in soils. *Biogeochemistry* 5: 35-70.

- Sahrawat KL (1982). Simple modification of the Walkley-Black method for simultaneous determination of organic carbon and potentially mineralizable nitrogen in tropical rice soils. *Plant and Soil* 69: 73-77.
- Schulz E (1990). Die heißwasserextrahierbare C-Fraktion als Kenngröße zur Einschätzung des Versorgungszustandes der Böden mit organischer Substanz (OS) (The hot water extractable C-fraction as indicator for the status of soil organic matter). *Tag Ber Akad Landwirtsch Wiss Berlin* 295: 269-275.
- Schulz E (1997). Charakterisierung der organischen Bodensubstanz (OBS) nach dem Grad ihrer Umsetzbarkeit und ihre Bedeutung für Transformationsprozesse für Nähr- und Schadstoffe (Characterization of soil organic matter according to its degradability and its significance to transformation processes of nutrients and pollutants). *Arch Acker Pfl Boden* 41: 465-484.
- Schulz E, Deller B and Hoffmann G (2003) Hot water extractable Carbon and Nitrogen. Standard method. *VDLUFA Methodenbuch*, 4. Teilfg. 2003, VDLUFA-Verlag, Bonn.
- Sparling G (1992). Ratio of microbial biomass carbon to soil organic carbon as sensitive indicator of changes in SOM. *Aust J Soil Res* 30: 195-207.
- Sparling G, Vojvodić-Vuković M, Schipper LA (1998). Hot-water-soluble C as a simple measure of labile soil organic matter: the relationship with microbial biomass C. *Soil Biol Biochem* 30: 1469-1472.
- Stanford G and Smith JJ (1972). Nitrogen mineralisation potential of soils. *Soil Sci Soc Am Proc* 36: 465-472.
- Tirol-Padre A and Ladha JK (2004) Assessing the reliability of permanganate oxidizable carbon as an index of soil labile carbon. *Soil Sci Soc Am Proc* 68: 969-978.
- van Antwerpen R, Meyer JH and Turner P (2001). The effects of cane trash on yield and nutrition from the long-term field experiment at Mount Edgecombe. *Proc S Afr Sug Technol Ass* 75: 235-241.
- van Antwerpen R (2005). A review of soil health indicators for laboratory use in the South African sugar industry. *Proc S Afr Sug Technol Ass* 79: 179-191.
- van Antwerpen R, Berry SD, van Antwerpen T, Sewerpsad C and Cadet P (2009). Indicators for soil health for use in the South African sugar industry. A work in progress. *Proc S Afr Sug Technol Ass* 82: 551-563.
- Vance ED, Brookes PC and Jenkinson DS (1987). An extraction method for measuring microbial biomass C. *Soil Biol Biochem* 19: 703-707.
- Weigel A, Klimanek EM, Körschens M and Mercik S (1997). Investigations of carbon and nitrogen dynamics in different long-term experiments by means of biological soil properties. pp 335-344 In: Lal R (Hrsg.): *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton.
- Weigel A, Kubat J, Körschens M, Powlson DS and Mercik S (1998). Determination of the decomposable part of soil organic matter in arable soils. *Arch Acker Pfl Boden* 43: 123-143.
- Zimmermann M, Leitfeld J and Fuhrer J (2007). Quantifying SOC fractions by infrared spectroscopy. *Soil Biol Biochem* 39: 224-231.