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Changes in Microbial Community as Affected by Soil Compaction and Organic Matter Amendment

Lily Ishak[#], Philip H. Brown[*]

[#] *Department of Soil Science, University of Khairun, Ternate,North Maluku, 97719, Indonesia*
E-mail: lily.ishak@unkhair.ac.id

**School of Medical and Applied Sciences,Central Queensland University, Bundaberg Campus, QLD, 4670, Australia*
E-mail: p.h.brown@cqu.edu.au

***Abstract*— Soil compaction may threaten agricultural sustainability through its impact on altering soil microbial structure and function. This occurs as a result of the limitation of air permeability and oxygen availability, which has implications for soil nutrition and soil-borne disease. The present study aimed to assess compaction effect on changes of soil microbial communities over time and whether these changes were influenced by organic matter (OM) amendment. An experiment consisted of two levels of compaction (1.1 and 1.4 g cm^{-3}) and two levels of OM (0 and 10 g kg^{-1}). Soil microbial community attributes investigated were soil respiration, microbial biomass, activity and diversity. Data on microbial attributes were obtained from three-sampling times (10; 20; 80 days). The results showed that microbial respiration, biomass, activity and diversity changes over time and were higher in compacted soil than uncompacted soil in day-10, but then higher in uncompacted soil at day-20. An increase in microbial biomass, activity and diversity in uncompacted soil within 20 days were presumably associated with the availability of soil organic carbon (SOC), void space and aeration. However, microbial biomass, activity and diversity across the treatments declined in day-80, where bacteria and fungi performed a different pattern. Bacterial community was lower in compacted soil at day-80 and this might be an indicator of the effect of compaction and of the reduction in SOC availability. Meanwhile, fungal community was found to be higher in compacted soil over 80 days confirming the ability of fungal communities to survive under such an environment.**

***Keywords*— organic matter amendment; soil compaction; soil microbial community; temporal changes.**

I. INTRODUCTION

Soil compaction is a serious problem confronting horticultural production systems globally and occurs more readily in tropical systems as a consequence of wet dry climatic oscillations in these regions. A large volume of literature exists on soil compaction with the majority of the research confined to studies on the effects of compaction on soil physical and chemical properties, and limited attention paid to soil microbiological impacts. However, some researchers estimated that compaction can adversely influence soil microbial communities through a combination of soil factor changes caused by compaction [1, 2, 3, 4, 5]. The size of the bacterial and fungal community in soil is mostly impacted by changes in total soil pore volume and pore size distribution [6]. Also, it has been estimated that reduction of pore space to less than 0.2 µm in diameter will result in pores being inaccessible to these microbial groups [7]. Other researchers conclude that compaction alters soil aeration status and therefore influences soil microbial community structure and activity [1,2]. Yet, the knowledge about the relationships between soil compaction and microbial communities is limited, particularly in association with soil microbial community dynamics in tropical environment. Soil organic matter has been well known to have an important role in regulating soil microbial communities [8, 9]. Soil organic matter is beneficial to improved soil structure and therefore provides a favourable habitat for soil microbial communities [10]. Soil organic matter also contributes to the availability of carbon substrate compounds that support soil microbial diversity and activity [11]. However, what is less clear is whether the availability of OM and its fluctuation in compacted soil can influence changes in soil microbial communities. Factors that are dominantly involved in the changes of soil microbial communities in compacted soil have not been clearly defined. In order to gain better understanding about the relationships between soil compaction and changes in soil microbial community, the present study was completed with the aims at: (1) assessing whether soil microbial communities changed over time in compacted soil and (2) whether

enhanced soil organic matter availability were involved in temporal changes in soil microbial communities in compacted soil. It was hypothesized that: (1) the temporal dynamic of soil microbial activity and diversity would differ in uncompacted and compacted soils, and (2) increased availability of soil organic matter in compacted soils would enhance soil microbial activity and diversity.

II. Materials and Methods

A pot trial was set up in a randomised block design with factorial arrangement in the Bundaberg region, Queensland, Australia, from January to April 2015. Soil used in the trials was a Red Ferrosol [12]. The first treatment was two levels of compaction: 1.1 g cm^{-3} (uncompacted) versus 1.4 g cm^{-3} (compacted) bulk density; and the second treatment was two levels of OM addition (0 and 10 g OM/kg soil). The use of these two levels of OM was based on the total carbon (1.36%) contained in the soil, so that the addition of 1% of OM was expected to have an effect on soil microbial community. Each treatment combination consisted of three replicates.

Soil compaction was made up in PVC cylinder pots with a uniform size (90 mm in diameter and 20 cm in length). Air-dried soil samples to be compacted had a moisture level of 15% of volumetric water content (or equivalent to 0.06 g g^{-1} oven-dried soil based on gravimetric method). Soils were sifted through a 5 mm sieve to remove litter, soil biota and gravel before the trial commenced. Then compaction was established according to a known soil volume (with an 18 cm soil height in pot) and bulk density (1.1 g cm^{-3} and 1.4 g cm^{-3}).

The organic material used in this experiment was made up of mill mud and decomposed sawdust with a pH of 7.0. Mill mud is a by-product of sugar production and is composed of farm top-soil and sugar cane fibre. The organic material was sifted through a 2 mm sieve before added into the soil. Then, the fine organic material was mixed with soil prior to the establishment of compaction.

Response variables observed were: soil microbial community estimated by microbial respiration; microbial biomass; and microbial functional diversity analysed by community level physiological profiles (CLPP)) method. Microbial respiration and substrate-induced respiration rates were investigated for five times interval: 10, 20, 40, 60, and 80 days; whilst total soil carbon was also measured at day-10, -20, and -80.

Microbial respiration was measured by recording of CO_2 efflux using a PP system soil respiration chamber (SRC-1) (PP systems Amesbury, MA) attached to an environmental gas monitor EGM-3, whilst microbial biomass was measured using substrate-induced respiration (SIR) method, which was also monitored by the soil respiration chamber. The chamber had a diameter of 10 cm and a height of 15 cm, which can effectively measure 78.5 cm^2 of substrate surface. The recording of CO_2 efflux presented in gCO_2 $m^{-2}h^{-1}$ was taken 30 s initially and
continued every 2 h for 6 h. The 2 hours recorded data was therefore used to compare the differences among the treatments.

For CLPP analyses, three soil samples from no OM and OM amended soil treatments were used. Determination of bacterial and fungal activity and diversity used the Biolog Eco-plates™ system and Biolog FF-plates™ system. The 96 h absorbance data were chosen as single-point absorbance readings to be used for determining average well colour development (AWCD) and Shannon-Weaver index (H).

Soil organic carbon (SOC) was determined in no OM and OM amended pots at three times period in terms to track changes in soil organic carbon over time, which can help explain the differences among microbial biomass carbon. One bulked-soil sample from each treatment was used to analyse soil organic carbon. Finely-ground soil was oven-dried at 70 °C for 24-48 h to constant weight and carbon content was determined using a computerized-LECO system (TruMacCN, Carbon/Nitrogen Determinator, version 1.3x).

Responses of soil microbial attributes and SOC on compaction were determined using Generalised Linear Model (GLM). Analyses were performed using Minitab version 16.

III. Results and Discussion

The effects of soil compaction on temporal changes in soil microbial community were observed. The measurement of soil microbial attributes such as microbial respiration, biomass, activity and diversity provides sensitive parameters to assess microbial changes to compaction.

A. Microbial respiration and biomass responding to soil compaction and organic matter amendment

The finding revealed that there were no significant differences in mean microbial respiration among different soil compaction levels. The interactions between the main factors (that is compaction, OM and time) also had no significant effects on microbial respiration. Microbial respiration was significantly affected by OM ($F_{(1,59)} = 5.05$; $p = 0.029$) and time period respectively ($F_{(1,59)} = 25.84$; $p = 0.0001$) respectively. Highest microbial respiration occurred in organic amended soil treatments at the 10 and 20 days period. Interestingly, at the tenth-day period, highest microbial respiration was found in compacted soil treatment, but the peak rates switched to uncompacted soil treatment at the twentieth-day period. The addition of OM to compacted soil had little influence on microbial respiration from 20 days onwards, while in contrast microbial respiration was higher in uncompacted soil with OM added compared to uncompacted soil with no OM added. However, microbial respiration declined in uncompacted soil treatments after 20 days, with a similar rate of decline in both OM added and no OM treatments (Fig. 1).

In contrast to soil microbial respiration, there was a significant effect of the interaction between soil compaction and time on microbial biomass ($F_{(1,59)} = 8.99$; $p = 0.004$), whereas the interaction between soil compaction, OM and time had no significant effect on microbial biomass. Soil microbial biomass carbon was found to be higher in compacted soil treatment with OM addition at 10 days, but the level of soil microbial biomass changed temporally when reached 20 days period, where the higher level of soil microbial biomass was found in uncompacted soil treatment with OM addition. Microbial biomass carbon across all treatments started to decline after 20 days with the level of

soil microbial biomass being higher in uncompacted soil treatment than the other three treatments (Fig. 2).

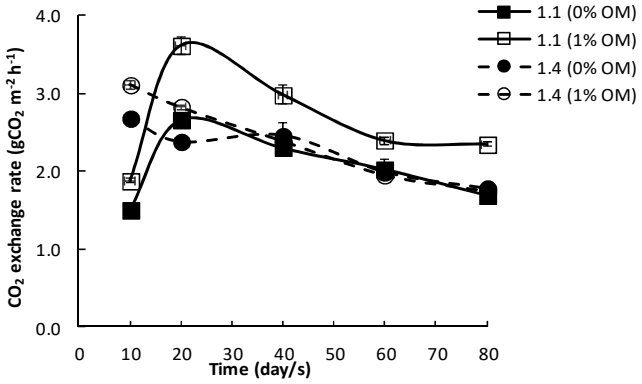

Fig. 1 Temporal changes in basal respiration rates among different levels of soil compaction and OM over an 80-day period and values are means ± S.E. (n = 3).

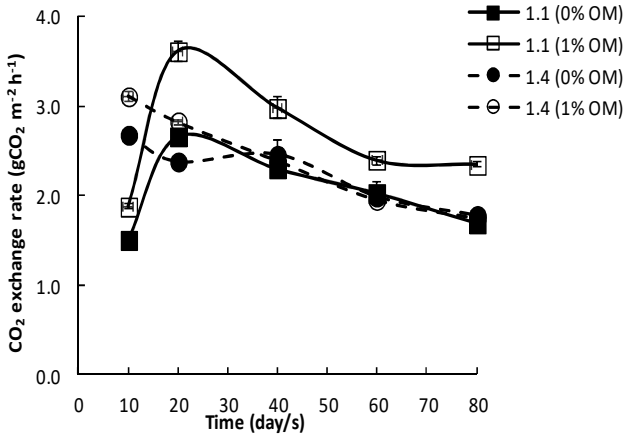

Fig. 2 Temporal changes in substrate-induced respiration (SIR) rates among different levels of soil compaction and OM over an 80-day period and values are means ± S.E. (n = 3).

B. CLPP responding to soil compaction and organic matter amendment

The result of CLPP analyses showed that the interaction between soil compaction, OM and sampling time significantly affected bacterial activity (determined by the values of AWCD ($F_{(2,359)}$ = 17.51; p = 0.0001). Using the AWCD values at 96 h of incubation time as the active growth period for bacterial communities, it is noted that bacterial activity was higher in compacted soils with OM addition at 10 days, whereas the lower activity was found in uncompacted soils with no OM amended. But at 20 days sampling time the activity was higher in uncompacted soils with OM added, whilst the lower activity was in uncompacted soils with no OM addition. Conversely, bacterial activity in uncompacted soils with OM addition reduced at 80 days sampling time. Meanwhile, there was a slight increase in bacterial activity in compacted soils with no OM addition, whilst the lower bacterial activity was found in the compaction treatment with OM amendment at 80 days sampling time (Fig. 3).

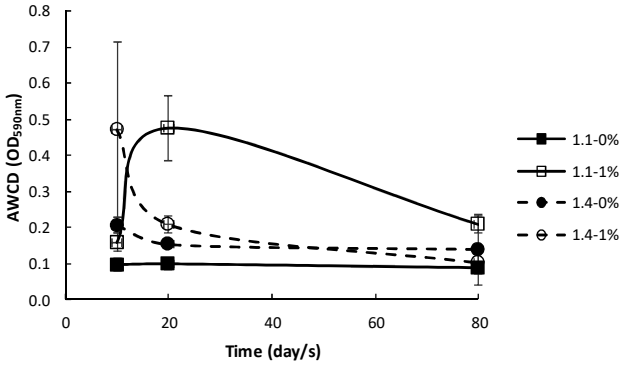

Fig. 3 Comparison of average well colour development (AWCD) at 96 h of incubation time among soil bacterial communities over an 80-day period in uncompacted (1.1 g cm^{-3}) and compacted (1.4 g cm^{-3}) soil treatments.

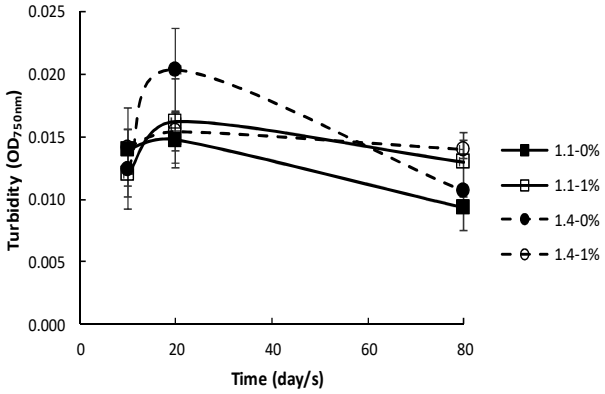

Fig. 4 Comparison of turbidity with optical density of 750 nm ($OD_{750\ nm}$) at 96 h of incubation time among soil fungal community over an 80-day period in uncompacted (1.1 g cm^{-3}) and compacted (1.4 g cm^{-3}) soil treatments.

Similarly, there was a significant effect of the interaction between soil compaction, OM and sampling time on fungal activity (determined by turbidity values at 96 h of incubation time) ($F_{(2,35)}$ = 8.08; p = 0.002). At 10 days sampling time, higher fungal activity was found in compacted soils with added OM, whilst lower fungal activity was found in both compacted soils with no added OM. Interestingly, fungal activity in compacted soil treatment with no OM addition increased at 20 days sampling time and swapped the higher position across the treatments, whereas fungal activity in uncompacted soils with no OM that was high within 10 days period reduced at 20 days to the lower position. The activity of fungal communities across the treatments slightly reduced at 80 days sampling time (Fig. 4).

The finding also revealed that the interaction between soil compaction and OM had significant effect on soil bacterial diversity (determined by Shannon index) ($F_{(2,35)}$ = 4.40; p = 0.047). In addition, the significant effect identified in the experiment was resulted from the interaction between soil compaction and sampling times ($F_{(2,35)}$ = 5.22; p = 0.013). At 10 days sampling time, higher bacterial diversity was found in compacted soils with OM addition, whereas lower bacterial diversity occurred in uncompacted soils with OM addition. There was a trend for bacterial diversity to be

higher in uncompacted soil with amended OM than in other treatments at twenty days sampling time, but the trend gradually declined after that period of time. Similarly, a slight increase of bacterial diversity was shown in both uncompacted soils with no OM addition and compacted soils with OM amendment at 20 days sampling time, but then dropped off afterwards. An exception to this was a small decrease of bacterial diversity in compacted soils with no OM addition from 10 to 20 days sampling time, but then increased slightly at 80 days sampling time (Fig. 5).

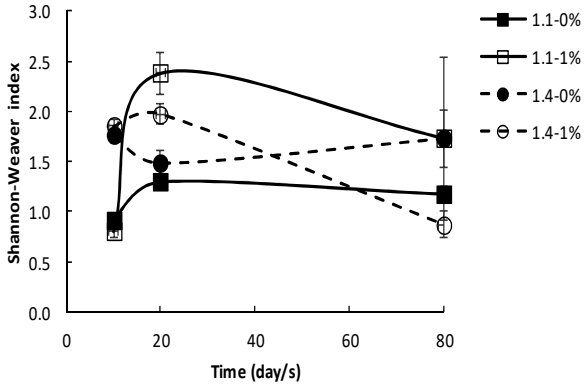

Fig. 5 Temporal changes in Shannon index of soil bacterial community over an 80-day period in uncompacted (1.1 g cm^{-3}) and compacted (1.1 g cm^{-3}) soil treatment and values are means ± S.E. (n = 3).

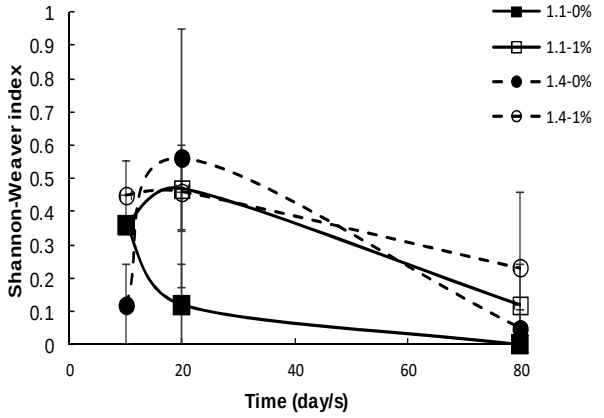

Fig. 6 Temporal changes in Shannon index of soil fungal community over an 80-day period in uncompacted (1.1 g cm^{-3}) and compacted (1.4 g cm^{-3}) soil treatment and values are means ± S.E. (n = 3).

Diversity of fungal community was also affected significantly by the interaction between soil compaction, OM and time respectively ($F_{(2,35)} = 17.00$; $p = 0.000$). Higher diversity of the fungal community was found in compacted soils with OM addition at 10 days sampling time, whereas lower fungal diversity was found in compacted soils with no OM amendment. At 20 days sampling time, there was an increase in fungal diversity in compacted soils with no OM addition that placed the higher position across the treatments. Fungal diversity in low compacted soils with OM addition also increased at 20 days period, whilst the diversity in both low compacted soils with no OM addition and high compacted soils with OM amendment decreased at the 20 days period. Fungal diversity in all treatments showed a gradual decline at 80 days sampling time (Fig. 6).

It is noted that temporal changes in the attributes of microbial communties as shown by respiration and SIR rate as well as CLPP analyses are presumably related to the changes in soil physical characteristics due to the formation of compaction in the soil. The following description may provide us a better understanding of these changes. For example, higher biomass, activity and diversity of microbial communities in the compacted soil treatments than in uncompacted soils at ten days after compaction was established was likely associated with the swelling/shrinking characteristics of clay particles contained in the Red Ferrosol. In many soils, compaction can result in reduction in aggregate stability with modifications in soil structure [13] as a consequence of a significant decrease in total soil macropores and pore size distribution [14]. But for soils such as the Red Ferrosols containing high clay mineral content [12] an increase in compaction may increase meso-porosity and increase the ability of the soil to retain moisture [4]. It was noticed particularly when the soil was compacted under drier conditions (containing only 15% (v/v) soil water content), that swelling process took place at the first time the compacted soil was irrigated, where water percolated down the soil profile. This swelling process was closely related to the plastic behaviour of clay minerals [15]. The observed increase in microbial communities may be an indication that the swelling process had increased biopore distribution in the compacted soil, increasing pore accessibility for microbial communities and availability of soil water to support microbial activity [4].

After a 10-day period, soil microbial communities in compacted soil dramatically decreased, whilst soil microbial communities in uncompacted soil treatment increased over the initial 20-day period and then reduced. The increase in microbial communities noted in the current study in uncompacted soil may be related to the availability of aeration and soil moisture, the main factors regulating soil microbial activity and diversity [8, 16]. In compacted soil, however, decreased soil microbial activity may be related to effects of consecutive drying-wetting cycle on the biopore habitat of the microbial communities [17, 18]. Consecutive drying-wetting cycles can induce a rearrangement of soil particles leading to a decrease in void space or air-filled pores over repeated wetting and drying cycles. The decrease in void space may then reduce aeration and therefore change the composition of microbial communities leading to the reduction in soil microbial activity [19]. Our previous study indicated that compacted soils might also change soil microbial communities as a result of the limitation of air permeability and oxygen availability [20]. Further, retaining high moisture content in compacted soils with low void space may create an anaerobic condition that could reduce microbial biomass and activity [21]. This can have implication to the onset of soil-borne disease.

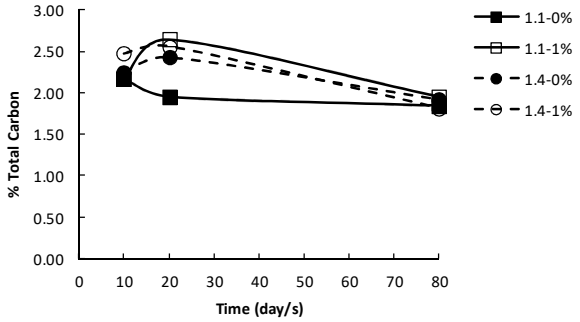

Fig. 7 Temporal changes in total soil carbon (%) among different levels of soil compaction (g cm^{-3}) and organic matter addition over an 80-day period.

Interestingly, the present study revealed that the effect of compaction on soil microbial communities altered when organic materials were added into soil. Soil microbial respiration and biomass, for instance, were higher in both uncompacted and compacted soil treatment with added organic matter compared to those treatments without organic matter input in the 20-day period after commencement of the experiment. In this present study, soil microbial respiration and microbial biomass had a close link to organic materials available in soil. The present study found that the concentration of SOC at 10 days was higher in compacted soils with OM addition, whilst the lower SOC was found in uncompacted soils with no OM addition. At day-20, higher SOC was found in uncompacted soils with OM amendment, whereas SOC content in uncompacted soils with no OM addition was at the lower level across the treatments. Soil organic carbon across the treatments showed a decline at day-80 (Fig. 7). A finding reported by a journal article [22] suggest that microbial respiration is produced from metabolic activity of microbial communities using organic materials available in soil. Further, higher SOC content in soils within a 20-day period presumably resulted from higher microbial respiration and microbial biomass. According to [23], the availability of organic materials might boost soil microbial respiration and thereby increase soil carbon stock, whereas the decrease in organic materials might reduce soil microbial respiration and therefore reduce soil carbon storage.

The pattern of dynamic in bacterial community activity was consistent with the dynamic of soil microbial biomass over an 80-day period, as bacterial community increased in uncompacted soil treatment with added organic matter within 20 days and declined thereafter. This is consistent with microbial biomass and abundance being regulated by carbon substrate availability in soil [24]. Meanwhile, higher fungal community in compacted soil was likely associated with their function in soil stabilisation at the micro-aggregate level [25]. Increased microbial communities in compacted soil might help in overcoming the destruction of soil disease suppression that can be induced by compaction.

Further, bacterial and fungal activity and diversity in both uncompacted and compacted soils were also higher with the addition of OM than those in the treatments without organic matter amendment. A study conducted by [11] using lupin as organic matter amendment have found that the organic material has a significant effect on the increase in soil microbial community and activity. They, however, have found that doubling the amount of organic matter do not result in a proportional increase of microbial community size, indicating a non-linear relationship between microbial response and organic amendment. This statement is also supported by our previous study in relation to the availability of SOM, where bacterial diversity was at the level of moderate ($2.50<H<3.0$) at lower SOM content of between 2 and 4%. When SOM level was between 6 and 8%, the diversity of bacteria gradually increased and reached a peak ($H>3.0$). Thereafter, bacterial diversity declined when the concentration of SOM incresed to between 10 and 12%. Meanwhile, fungal diversity was lower when SOM was between 2 and 4%. The diversity of the fungal community increased 4-fold when the level of SOM increased up to between 6 and 8%, and then declined when SOM > 10% [20].

In addition, the present study found that soil microbial activity and diversity gradually reduced after a 20-day period. Microbial activity and diversity reduced as a result of the gradual decrease in total soil carbon. A previous study reported that soil microbial activity correlates with total C inputs, where recent organic matter inputs increase microbial activity by 80 to 400%, but in the long-term the organic matter input reduces microbial communities [26]. The increased activity and diversity of fungal communities in compacted soil might also be associated with either the moist condition of soil or the presence of soil carbon. A previous finding showed that fungal diversity was greater in the surface of no-tillage plots which had higher bulk density. It is presumably associated with the lack of disturbance and the greater stocks of soil organic matter derived from excess crop residues [27] on the surface of no tillage soil, lower temperature and the improvement of soil moisture and oxygen concentration in the surface layer of no tillage soils. Soil moisture and soil carbon availability supports the activity of fungal community growth [28] and therefore can also potentially boost fungal pathogen density and its ability to survive [29].

Furthermore, bacterial and fungal communities showed a different characteristics. The decrease in bacterial communities at day-80 can be linked to the compaction effect, where soil bacterial communities were lower in compacted soil treatments than those in uncompacted soil treatments. On the contrary, despite being lower at day-80 than at day-20, fungal communities remained higher in compacted soil treatment than in uncompacted soil treatment. This becomes an indicator to the ability of fungal communities including pathogenic species to survive under such an environment.

IV. Conclusions

The addition of organic matter to compacted soil increased the availability of soil carbon and therefore enhanced soil microbial biomass, activity and diversity within a 20-day period, but the effect was reduced over a longer timeframe which was most likely related to increased compaction. Changes in soil microbial diversity in compacted soil over time were associated with the differentiation in C-substrate utilisation. Higher soil bacterial

diversity in uncompacted soil with added OM within 20 days was indicated by a greater utilisation of various types of carbohydrates and carboxylic acids, whilst fungal diversity was higher in compacted soil with added OM. The reduction of soil microbial diversity within 80 days was indicated by lower utilisation of C-substrates which were dominated by their preference to carboxylic acids and amino acids. The presence of carboxylic acids and amino acids dominantly in the soil was presumably associated with increased soil acidity.

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