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Full Length Research Paper

Potential and limitations of soil organic matter build-up in dry areas

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Semi-arid areas comprise a large portion of the world's agricultural crop land. These areas are characterised by high temperature and low rainfall which hinders soil organic matter accumulation. The reported experiments were designed to study the effect of soil organic matter (SOM) from green manure crops on soil physical properties in two contrasting soils, sandy clay loam and loamy sand under the severe conditions of high temperature and low rainfall that exist in the eastern wheat belt of Western Australia. To remove soil physical and chemical constraints, the soils were deep ripped to 0.4 m after the application of 2.5 t/ha of gypsum. Basal fertilizers were applied according to soil tests to remove possible nutrient deficiencies. Cereals and legume crops were incorporated by disc cultivation into the soils as green manure for four consecutive years. Two plant groups, cereals and legumes were used to provide green manure. Oat (*Avena sativa*) as a cereal with high C:N ratio (95) and either faba bean (*Vicia faba*), field pea *(Pisum sativum)* or lupin *(Lupinus angustifolius)* were used as legumes with low C:N ratios (12 -18). These crops were arranged in three treatments for each soil type consisting of different crop sequences. A total of between 14 and 20 t/ha of green material was incorporated into the top soil over four years. All treatments increased soil organic matter significantly compared to the initial soil values but no significant differences between treatments (crop sequences) were observed. Water stable aggregates and soil bulk density were significantly improved by all treatments but no significant differences were observed between treatments. Soil water infiltration was not significantly increased by the green manure treatments after ripping and gypsum addition, though it was significantly different between treatments. The SOM increased from around 1.28 to 1.96%, well below the critical value suggested in the literature for more humid areas to sustain healthy soil, and not as high as expected from the high quantity of green material returned to the soil. However, the levels of organic carbon increase were comparable with those predicted from a CSIRO carbon model. These results point to the dominant role of soil and weather conditions in the low rainfall cropping zone of Western Australia in limiting the build-up of soil organic matter content, regardless of amount or composition of green manure applied.

Key words: Green manure, soil organic matter, water infiltration, water stable aggregates.

INTRODUCTION

Although, soil organic matter (SOM) is usually a small portion of soil mass, it is one of the most important components of ecosystems. The SOM strongly modifies soil organism habitat and provides the food and energy source for much of the soil biota. When soil micro-organisms feed, they change the form of SOM and in the process release inorganic nutrients, especially nitrogen, phosphorus and sulfur. Because soil micro-organisms are continually consuming the organic portion of their habitat, it must be continuously replenished to maintain soil quality.

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Green manuring is the practice of turning fresh green plant tissue into the soil before plant maturity in order to increase soil organic matter content. An additional benefit can be a reduction of seed set of weeds and incidence of some plant diseases. The practice can thus also be a tool to manage herbicide resistant weeds and crop root diseases (Condon, 2000; Casini and Pasten, 2004; Caporali et al., 2004; Miko et al., 2005).

Land owners for many hundreds of years have observed that addition of fresh organic material to soils improves soil physical and chemical properties and increases grain yield (Warman, 1981; Chan et al., 2003). Green manuring provides food and energy for the soil micro-organisms to decompose and ultimately to form soil humus. Soil micro-organisms function as consumers and decomposers of SOM, binding soil particles into aggregates. Bacteria are the most important group of these micro-organisms, performing specific functions such as N immobilization and mobilization. Fungi are the most important group in decomposing resistant compounds such as lignin. Their hyphae grow extensively through soils, helping bind soil particles into aggregates. Some specialized fungi grow symbiotically with plant roots, increasing nutrient and water uptake and decreasing disease incidence.

Beside bacteria and fungi, a host of other micro and macro-organisms contribute to the decay of SOM. Actinomycetes produce compounds that give soil its distinctive aroma; protozoa and arthropods help acelerate decomposition when they graze on bacteria, fungi and plant residues.

Soil organic matter is a complex mixture which influences a number of soil properties and nutrient cycling, and is determined by soil type, climate and vegetation. However, SOM is not a major binding agent because the binding substances are either water-soluble or transient, or both (Tisdall and Oades, 1982; Loveland and Webb, 2003). Therefore, SOM must be replenished continuously with fresh new materials such as plant residues or green manure. “Fresh” or “active” SOM, such as green manure, has a much more positive impact on soil health as compared to old or inert SOM.

For example, Tisdall and Oades (1982) reported that only fresh or active SOM with relatively large concentrations of mono- or poly-saccharides stabilizes soil aggregates. The ratio between less resistant (short-lived, several months) SOM and more resistant (long-term, several years) organic matter is important in determining SOM equilibrium. Establishing such equilibrium can take decades and the process can be subject to considerable short-term disturbance by agricultural activities (Loveland and Webb, 2003).

The positive effects of green manuring on soil physical, chemical and biological properties have been reported by many workers in more humid environments (Datt and Sharma, 2006; Mandal et al., 2003). Organic matter does not add any ‘new' plant nutrients but releases nutrients in a plant available form through the process of mineralisation. In order to maintain this nutrient cycling system, the rate of addition from crop residues and manure must equal the rate of decomposition. Soil organic matter will decline if the rate of addition is less than the rate of decomposition and conversely, soil organic matter will increase if the rate of addition is greater than the rate of decomposition. The term steady state has been used to describe a condition where the rate of addition is equal to the rate of decomposition. Loveland and Webb (2003) indicated that it is widely believed that a threshold of about 2.0% organic carbon (ca. 3.4% SOM) is appropriate for most regions. However, the extent to which organic matter in semi-arid areas can be raised to adequate levels is not known nor are adequate levels for low rainfall areas agreed on.

Patterns of decomposition and nutrient release from green manures and their benefits for nutrient availability in soil and crop uptake, have been discussed by many researchers (e.g. Yadvinder et al., 1991, 1994). However, few workers have researched the possibility of increasing soil organic matter content in arid areas such as the low rainfall parts of the Western Australian cropping zone, through green manuring (Hoyle, 2001) or other means. The extreme environmental conditions in such areas make increasing soil organic matter through stubble retention difficult, even after removing soil constraints such as compaction (Hamza and Anderson, 2002, 2003, 2005).

The experiments that discussed here were designed to examine the possibility of increasing the SOM levels found in cropped soils in this semi-arid region. Green manure crops (oat and legumes) were grown for four consecutive years and SOM, along with some other physical properties of the soil, were recorded and analysed. It was also of interest to observe whether an equilibrium level of SOM would be reached. Whilst it is not an economically viable practice to incorporate green plant material into the soil for consecutive years, it was more practical and realistic in the experimental sense than importing many tonnes of organic material from an external source.

The main source of organic material on commercial farms in the region is crop residues (stubble) which can be added at perhaps 2 - 3 t/ha annually. However, returning green manure crops to the soil can add much higher annual amounts, enabling a faster assessment of the potential for increased SOM to improve soil physical and chemical properties. In the areas where these experiments were conducted, the daily maximum summer air temperatures often exceed 35℃ and daily maximum soil temperatures often exceed 45℃ in summer and rainfall over December to March period averages is less than 60 mm. As a consequence of these extreme environmental conditions the SOM is very low at 0.5 to 1%, rarely exceeding 2%, and is accompanied by degraded soil and low crop yield (Hamza and Anderson, 2002, 2003). It

Table 1. Some of the soil properties in 1997 after ripping the soil at Merredin and Tammin sites.

Site	Texture	pH_{CaCl_2}	$EC_{1:5}$	CEC	ESP	Bulk density	OM	Soil strength
			dS /m	$Cmol_c$ /kg	%	Mg/m^3	%	Mpa
Merredin	SCL*/CL	5.50	0.09	11.40	0.66	1.30	1.30	1.10
Tammin	LS**/SL	6.30	0.07	8.47	0.66	1.35	1.35	0.80

29% clay, 22% silt and 49% sand, *12% clay, 3% silt and 85% sand, EC = electrical conductivity, CEC = Cation exchange capacity, ESP = exchangeable sodium percentage, OM = organic matter, Mpa = megapascal.

seems that physical rather biological breakdown of organic matter has caused most of the SOM to rapidly disintegrate and released to the atmosphere (mainly as CO_2) preventing an appreciable increase in SOM.

The objective of the experiments described in this paper was to test how much the SOM could be increased in a hot, dry cropping environment through the addition of green manure crops grown *in situ*.

Hypotheses

Soil organic matter build up in the soil under hot and dry environment is low regardless of amount or type of organic matter that is added to the soil. However, this low increase in soil organic matter is vital in maintaining and some times improving soil physical properties.

MATERIALS AND METHODS

The soils

The experiments were conducted over a period of four years (1997 to 2001) on two different types of soils, sandy clay loam (Merredin) and loamy sand (Tammin) in Western Australia. At the Merredin site (31° 35' S, 117° 34' E) the soil is classified as Haplic, Mesotrophic, Brown Chromosol; medium, non-gravelly, sandy clay loam/clay loam, moderate (Isbell, 1996). The soil type is Merredin sandy clay loam (Bettenay and Hingston 1961) locally called Salmon Gum/ Gimlet soil, the surface layer comprising 29% clay, 22% silt and 49% sand. It has a duplex profile in which an abrupt texture contrast commonly occurs at about 100 - 300 mm consisting of a greyish brown to reddish brown sandy clay loam overlying a brown to reddish brown heavy clay loam. Before ripping the soil was compacted, massive and structure-less.

At the Tammin site (31° 34' S, 117° 35' E) the soil is classified as Bleached, Calcic, Brown Chromosol; medium, non-gravely, loamy sand/sandy loam, deep (Isbell, 1996). The surface layer consists of 12% clay, 3% silt and 85% sand. It has a duplex profile in which an abrupt texture contrast commonly occurs at about 150 - 300 mm consisting of grey loamy sand overlying a massive, brown to reddish brown sandy loam. The soil before ripping was massive and compacted.

Both sites had been used in a winter legume/cereal rotation with sheep grazing in summer for many years. The soil compaction was associated with grazing by sheep and with farm machinery operations used in the cropping phase. To remove soil compaction and create a good environment for soil micro-organisms, both sites were ripped to 400 mm depth using a standard Agroplow® with straight shank and 300 mm shank spacing, about 27 days before seeding. Commercial grade gypsum at 2.5 t/ha, was applied before ripping and left for about two weeks to leach down the soil profile. Gypsum was applied to target a level of exchangeable calcium adequate to maintain soil structure (Hamza and Penny, 2002). Table 1 shows some properties of the soils after ripping. Fertilisers based on soil tests prior to sowing were applied each season at seeding at the following rates (kg/ha) (Halvorson et al., 1987): For cereal: 30 N, 20.2 P, 40.7 S, 2.5 Mg, 2.5 Cu, 3.0 Zn, 3.0 Fe, 0.09 Mo, 0.5 Co. For legumes: 8.5 N, 8.2 P, 18.4 S, 1.9 Mg, 1.5 Cu, 2.0 Zn, 1.1 Mn, 0.5 Mo, 0.2 Fe, 0.03Mo, 0.4 Co. Potassium was not applied because the soil test showed that the level in both sites was adequate (>500 mg/kg).

Treatments

Two plant groups were used to provide green manure, oats (*Avena sativa*) as a cereal with high C:N ratio (95) and either faba beans (*Vicia faba*), field peas (*Pisum* sativum), or lupin (*Lupinus angustifolius*) as legumes with low C:N ratios of 12, 18 and 12 respectively. Each site had three manure treatments consisting of different crop sequences: one treatment consisted of two cereal and two legume crops in 4 years while the other two treatments consisted of one cereal and three legume crops in 4 years (Table 2).

The treatments were designated: Mc, M1, M2 and M3 at Merredin and: Tc, T1, T2 and T3 at Tammin, where the subscript c refers to the control treatment. The treatments were laid out as a complete factorial in randomized blocks with 4 replications. Plot size was 1.8 x 20 m. Crops were slashed shortly after anthesis to make sure that no seeds would be returned to the soil, and incorporated into the top 5 cm of the soil using disc harrows to reduce exposure to direct sunlight and high temperature, and to prevent losses from wind erosion.

The control treatments were contained in experiments immediately adjacent to the experiments described here. They had the same soil and weather environments and the same land use history and were used to monitor changes in SOM where only the residues from annual cropping were retained each year as is the case on farms in the area.

Measurements

Rainfall was measured at the sites; values quoted for rainfall in the growing season are from sowing until crop maturity each year. Soil temperature was recorded by the meteorological unit at Merredin Research Station at 5 cm depth. Air temperature, solar radiation and open pan evaporation were obtained for each site from the Department of Agriculture and Food Automatic Weather Station network (http://agweb/Biosecurity-Research/Research/Ag_systems/climate/index.htm). Soil samples were collected after deep ripping and before sowing in the first year. Subsequently they were collected shortly before sowing each year. Visible plant remains were removed from the soil samples which were air dried before analysis. The soil was sampled from 0 - 10

Table 2. Faba bean (FB), field peas (FP), oat (O) and lupin (L) dry matter yields in t/ha from 1998 to 2001 for Merredin site (M) and Tammin site (T). Note the crop sequence from 1998 to 2001.

Treatment	1998	1999	2000	2001
Mc	3.04(W)	2.23(FP)	4.93(W)	1.4(FP)
M1	2.5(FB)	6.2(FP)	3.1(O)	4.79(FP)
M2	3.3(FP)	6.29(O)	2.54(FB)	1.97(FB)
M3	2.25(O)	3.93(FB)	2.31(FB)	5.73(O)
Tc	4.53(W)	1.53(CP)	5.32(W)	1.1(FP)
T1	0.75(L)	7.16(FP)	3.90(O)	5.52(FB)
T2	3.75(FP)	8.15(O)	2.81(FB)	3.97(FB)
T3	4.44(O)	5.41(FB)	2.64(FB)	7.44(O)

cm. Changes in physical and chemical properties measured were as follows: - bulk density, 3 measurements/plot using a 55 mm core (Blake and Hartage, 1986); water stable aggregates (wet-sieving method, Kemper and Rosenau, 1986); water infiltration at three places per plot using a disk permeameter (unsaturated method) at -40 mm potential (Zhang, 1997); soil strength using a penetrometer at 3 locations/plot, 3 readings/location (Rimik CP20 Ultrasonic, cone diameter = 12.8 mm, (Davidson, 1965) soil organic carbon by the Walkley Black method (Rayment and Higginson, 1992). The average yield of green material was determined from three 0.5 m^2 quadrates per plot, harvested manually and oven dried at 80°C to constant weight.

Comparison with a carbon model

The measured soil values of organic matter were compared with values predicted using a carbon model ("How much carbon can your soil hold?" constructed by Jan Skjemstand and Jeff Baldock, CSIRO, Australia). The model inputs were: yield (t/ha), clay content (%), soil pH_{water}, initial soil organic carbon, soil management, soil properties and weather data.

Statistical analyses

The statistical design was randomized blocks and all results were analyzed using Genstat® (VSN International, UK) and the 5% level of significance is used throughout in assessing significance. Analysis of variance was used to analyse the yield data and other soil parameters and changes over time were analyzed by regression.

RESULTS

The summer period between incorporating the green manure crop (around the end of October) and sowing a new crop (around late April to early May), is likely to be the most critical period for the soil micro-organism activities in Western Australia because the air and soil temperatures are at their highest and soil moisture is at its lowest. In these months of dry and hot weather, it is expected that the soil micro-organism activities (which are responsible for soil organic matter decomposition) is minimal and hence, the build up of SOM is at its minimal. The average values of solar radiation during the summer months (December, January and February) were 26.35 and 27.25 MJ/m^2 for Merredin and Tammin, respectively (Figure 1).

The maximum and minimum air temperatures for the Merredin and Tammin sites from 1997 to 2001 and Figure 2 shows the corresponding soil temperatures for Merredin only (Tammin site has a similar pattern). The maximum and minimum average air temperature for the hottest three months, December, January and February of the years 1997 to 2001 at Merredin, were 33.4 and 16.5°C respectively. The corresponding average values for Tammin were 33.2 and 16.0°C respectively. The average maximum and minimum soil temperatures for the December - February period at Merredin were 41.8 and 25.0°C respectively. Figure 3 shows the rainfall and open pan evaporation for Merredin and Tammin sites from 1998 to 2000. Table 2 shows the dry matter incorporated into the soil each year (M1, M2, M3, T1, T2 and T3) and the residue retained in the soil from the adjacent control treatments (Mc and Tc). Figure 4 shows the cumulative dry biomass yield incorporated into the soil and the crop residue retained at the end of the 2001 season (total biomass returned to the soil for four seasons). Soil organic matter was analysed each year from 1997 to 2000. The 1997 values represent the original value of SOM before the start of the experiment (Figure 5). Figure 6 shows the SOM versus the cumulative green yield incorporated into the soil. The average value of water stable aggregates (WSA) before ripping the soils was 24% for Merredin and 22% for Tammin. After ripping the WSA value was only 9% at both sites (Figure 8, data for M1 and T1 only, other treatments were not significantly different from this). Soil bulk density values are shown in Table 9 for both Merredin and Tammin sites and Figure 10 shows the water infiltration rate for M1 and T1 treatments for the years 1997 to 2001.

DISCUSSIONS

Weather and soil

Weather and soil data show that the maximum air and

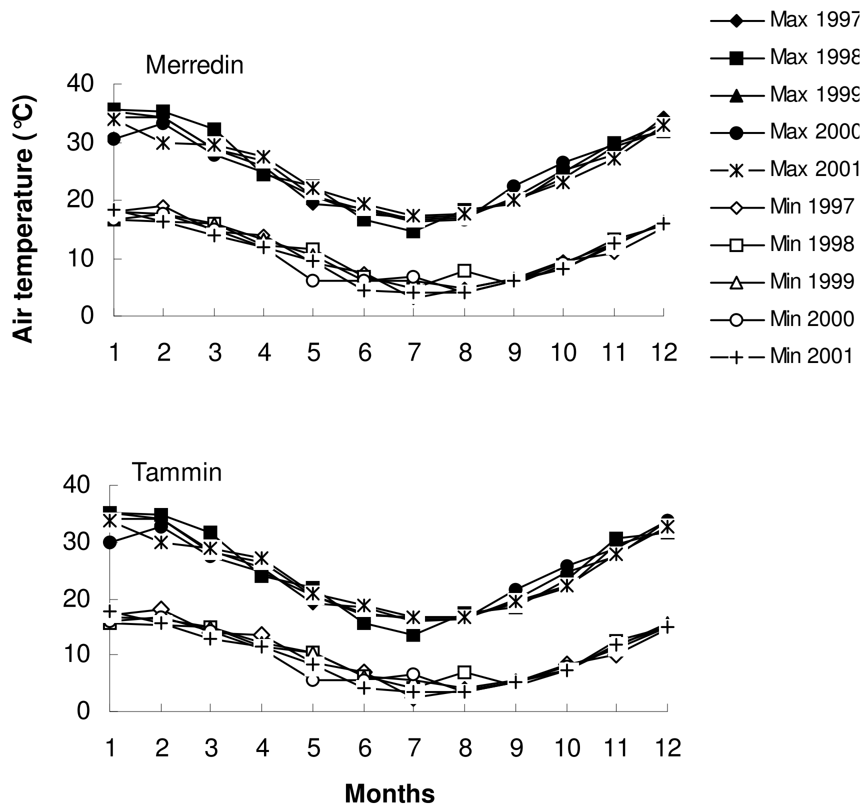

Figure 1. Mean monthly maximum and minimum air temperature for 1997 to 2001 for Merredin and Tammin sites.

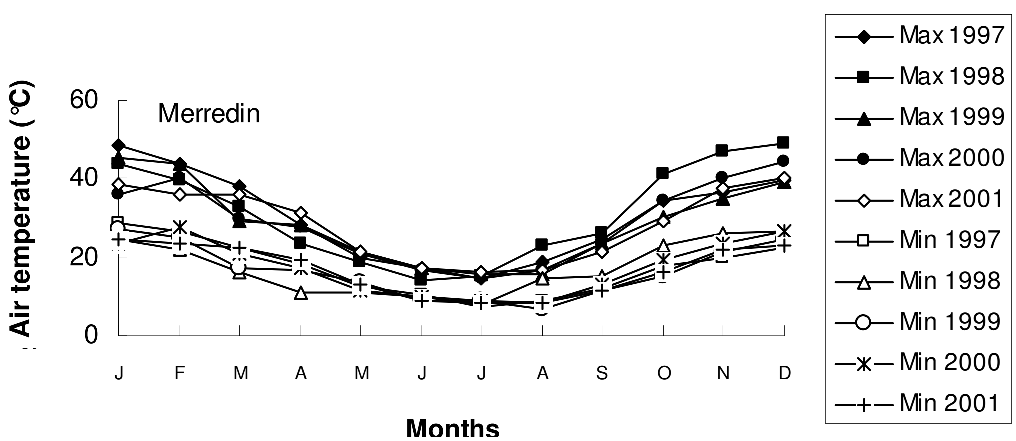

Figure 2. Mean monthly maximum and minimum soil temperature at 5 cm depth from 1997 to 2001 for Merredin.

soil temperatures were too high for ideal microbial activities (Xu and Qi, 2001) and that the differences between maximum (day) and minimum (night) temperatures were also high at 16.5°C (Merredin) and 17.2°C (Tammin) for air temperature and 16.8°C for the soil temperature in Merredin. These high temperatures and large daily fluctuations in temperatures are expected to severely restrict growth of micro-organisms during the summer months. Consequently, we assume that most of the biological decomposition and hence the SOM build up occurs in the wetter and cooler months of the year, that is in winter from May to October.

The annual pan evaporation at both sites (Figure 3) was 4.7 to 6.9 times higher than rainfall. The excess of

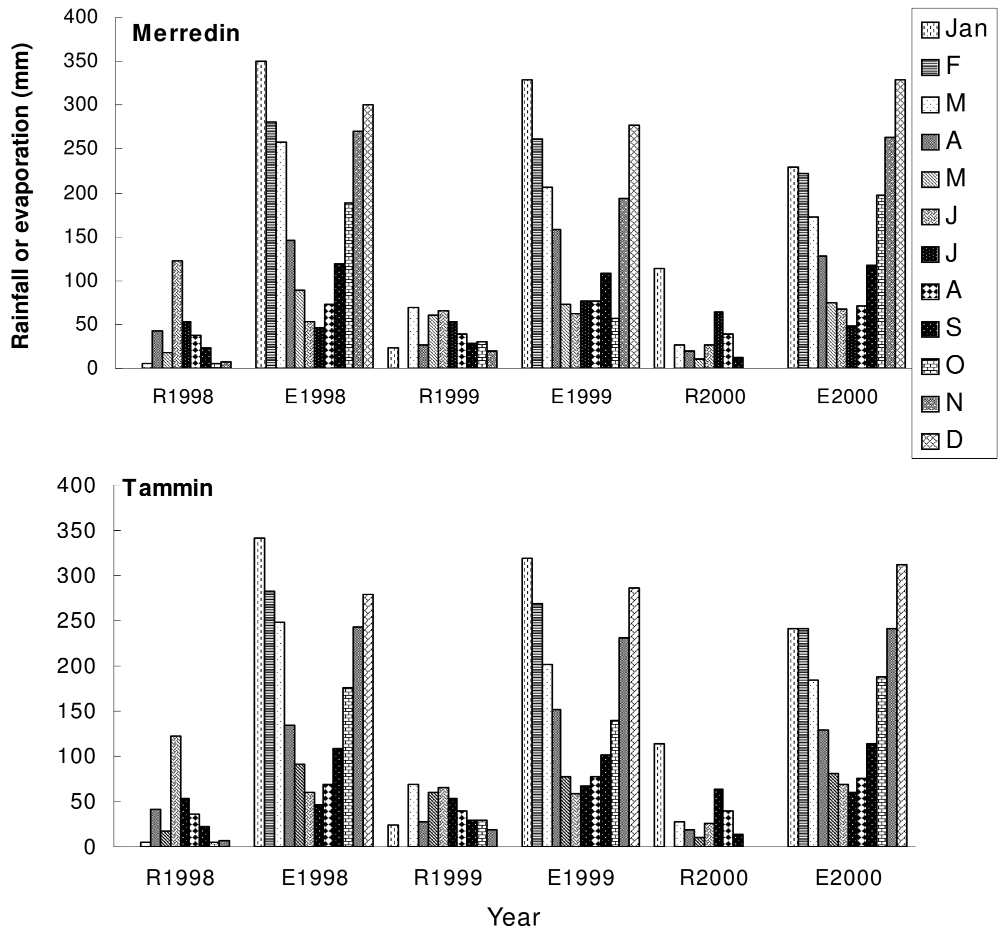

Figure 3. Monthly rainfall (R) and open pan evaporation (E) for Merredin and Tammin sites from 1998 to 2000.

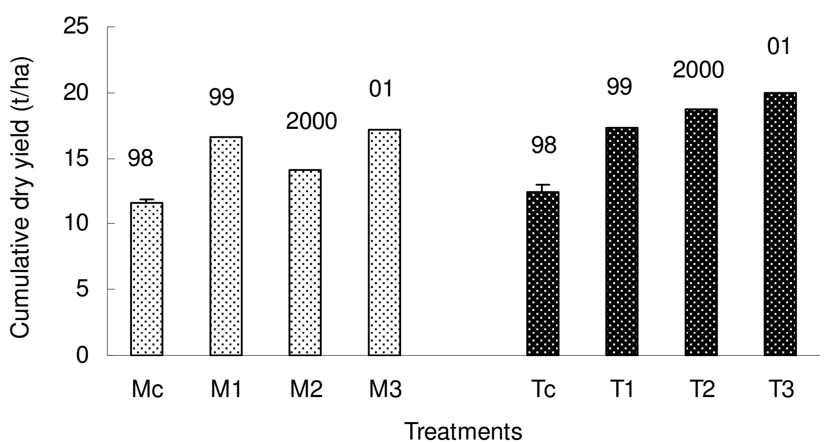

Figure 4. Total dry biomass yield incorporated into the soil. Treatments, M1, M2, M3 at Merredin 1997 - 2001, treatments T1, T2 and T3 at Tammin 1998 - 2001, see Table 2. The bars represent least significant difference (5%).

evaporation over rainfall is largest during December to April where it was more than 230 times higher in December and more than 11 and 6 times higher in January and March respectively. The moisture deficit

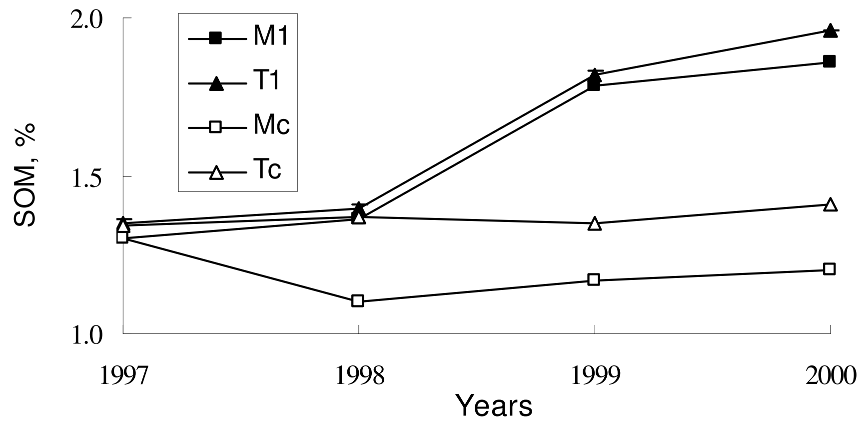

Figure 5. Soil organic matter (SOM) from 1997 to 2000 for Merredin and Tammin sites. Average standard error of the means = 0.012%.

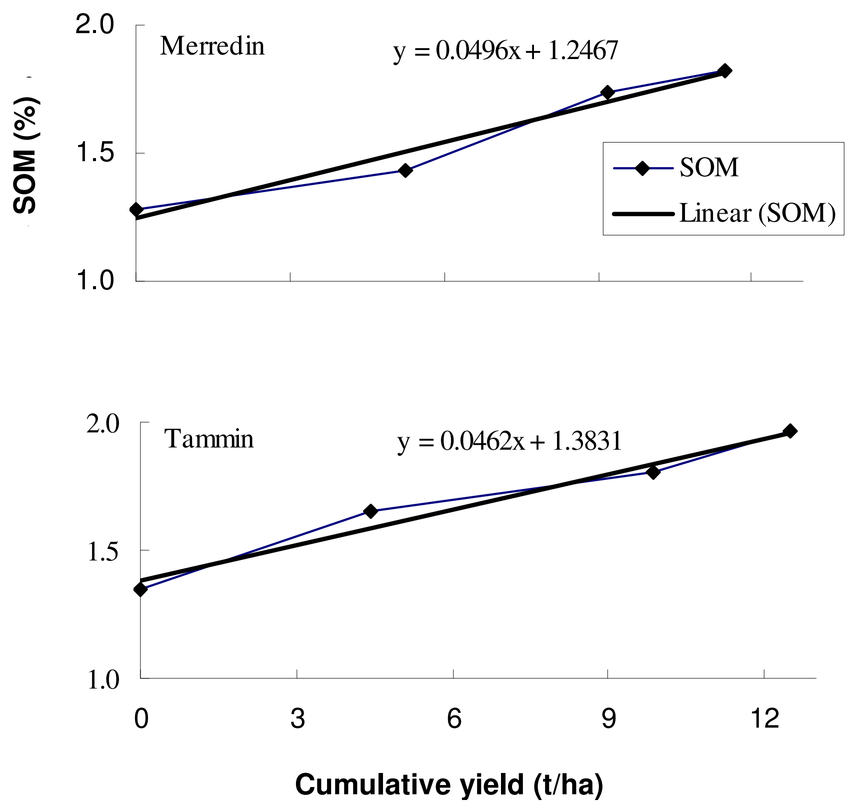

Figure 6. Cumulative dry biomass yield versus soil organic matter (%) for treatment M3 (Merredin) and T3 (Tammin).

leaves the soil profile dry, severely inhibiting the micro-organism population and slowing down the decompose-tion of the plant residue. Summer rain is a sporadic event in this environment, and is often followed by high temperatures and soil evaporation. While it does not have a major impact on biological activity for more than short periods, at the high temperatures during summer, respiration rates are high.

Green manure yields incorporated into the soil

Differences between the cumulative yield of each treatment were significant (lsd = 0.25 t/ha for Merredin and 0.52 t/ha for Tammin) at both sites. The treatments, M3 and T3 showed the highest yield at 17.2 and 19.9 t/ha at Merredin and Tammin sites respectively. These treatments were a sequence of oat in the first season

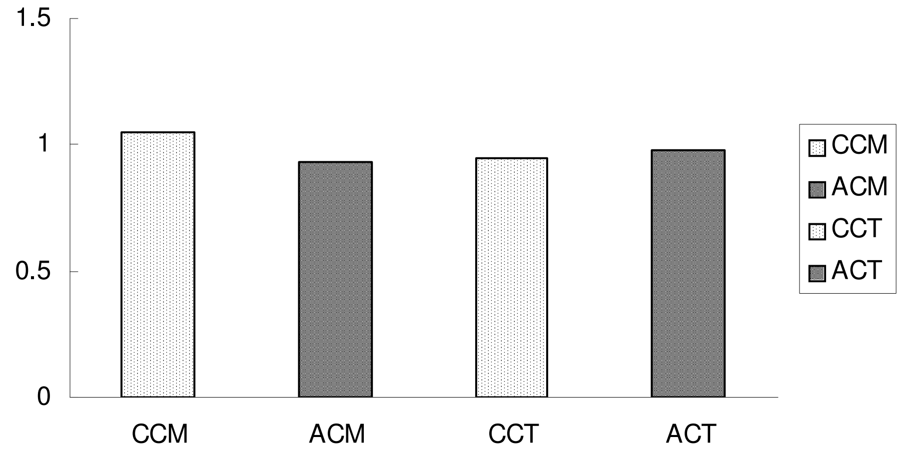

Figure 7. Actual soil organic carbon in Merredin (ACM) and Tammin (ACT) and soil organic carbon estimated by a carbon model in Merredin (CCM) and Tammin CCT).

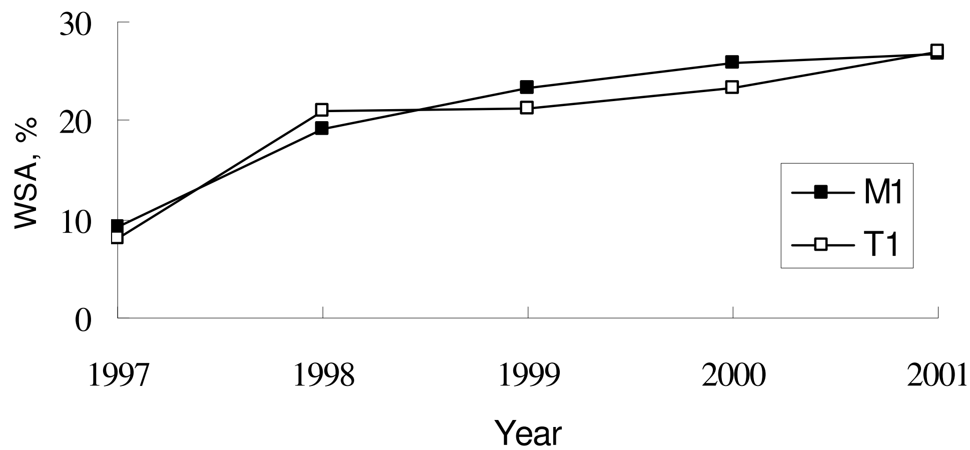

Figure 8. Water stable aggregates (WSA) from 1997 to 2001 for M1 (Merredin) and T1 (Tammin) treatments. Average standard error of the means = 1.12%.

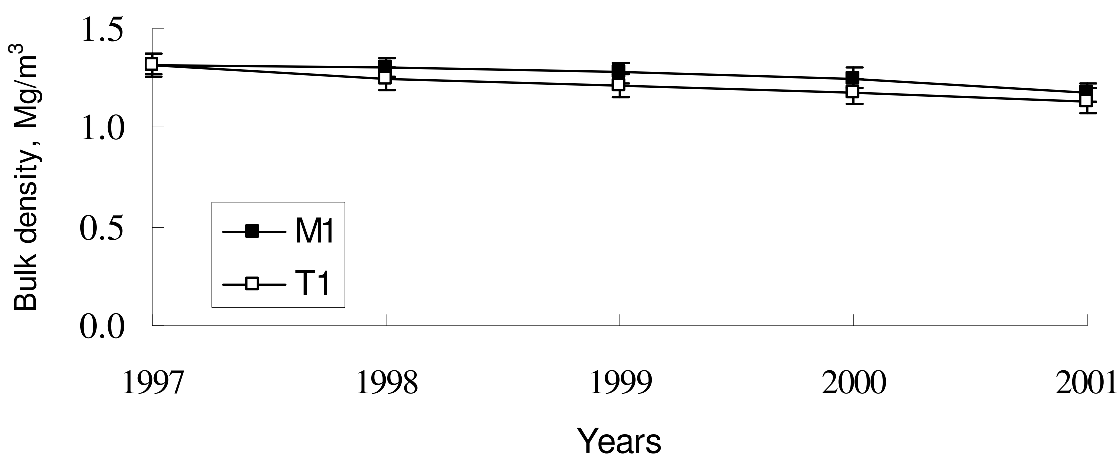

Figure 9. Soil bulk density from 1997 to 2001 for treatments M1 (Merredin) and T1 (Tammin). Average standard errors of the means = 0.013 Mg/m^3 .

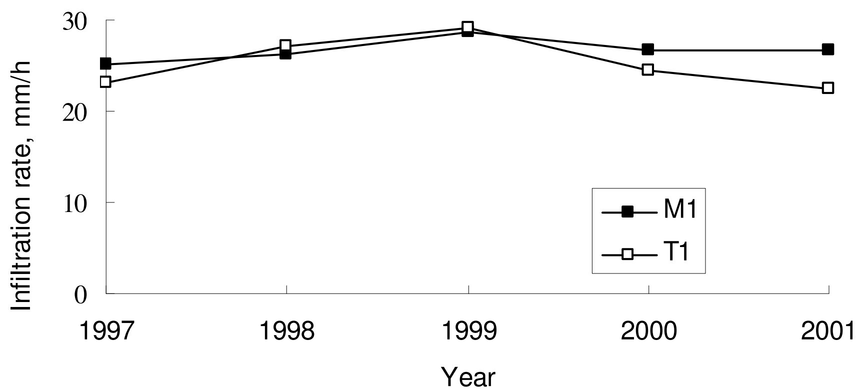

Figure 10. Soil water infiltration rate from 1997 to 2001 for treatments M1 (Merredin) and T1 (Tammin). Average standard error of the means = 0.88 mm/h.

followed by two consecutive seasons of faba beans, followed by another oat in the fourth year (O – FB – FB – O). The lowest cumulative biomass yield after the control treatments was produced by M2 in Merredin and T1 in Tammin at 14.1 and 17.3 t/ha respectively. The reason why T1 gave the lowest yield was because in the first season the lupin yield was severely reduced by the gypsum and lime applied to the soil (Hamza and Anderson, 2001).

Soil organic matter accumulation

SOM increased significantly for all treatments and for each year, including the final year (Figure 5), in both sites indicating that the potential for SOM accumulation due to green manuring was not reached and might be increased further if more green manure was added to the soil. On average, by the year 2000 the soil organic matter contents increased due to green manuring from 1.30 to 1.84% in Merredin and from 1.35 to 1.96% in Tammin. These represent around 42 to 45% increase respectively over the original values in 1997 before incorporation of the green manure. The increases in the control treatments over the same four year period were much lower. In fact the Merredin soil showed a decrease in SOM in 2000 by 8%, from 1.30% in 1997 to 1.20% in 2000, while in Tammin the SOM increased only by 5% from 1.34 to 1.41%.

The SOM increases in the first 20 cm soil layer due to green manuring can be converted to 28 and 30 g m^{-2} $year^{1}$ soil carbon or 14 and 15 g m^{-2} $year^{-1}$ soil organic matter for Merredin and Tammin sites respectively. These are low increases in SOM and are not proportional to the large amount of organic matter that was added to the soil. This suggests that the harsh environment in summer restricted the growth of soil micro-organisms which lead to a significant decrease in biological decomposition of green manure. Under such dry and hot conditions most of the green manure is lost through chemical and physical breakdown. When compared to the soil organic carbon input from crop residues in other environments with different temperature and rainfall regimes, these increases look small. For example, in southern Canada (sandy loam, average annual temperature 7.2°C and mean annual precipitation 820 mm), the average annual accumulation rate for the first 20 cm depth was 179 g m^{-2} $year^{-1}$ while that in Costa Rica (clay soil, average annual temperature 21.7°Ca and mean annual precipitation 2648 mm) was 30 g m^{-2} $year^{-1}$ (Oelbermann et al., 2006).

The low rainfall, high transpiration and high air and soil temperatures at Merredin and Tammin in summer leads to sharp decreases in populations of soil micro-organisms each summer and hence, low soil organic matter accumulation. Although, the amounts of green manure incorporated into the soil by each treatment were significantly different, the associated increases in SOM between treatments were not; suggesting that under the harsh summer conditions of dry areas there is a limit for organic matter accumulation imposed by the harsh environment regardless of quality or quantity of the SOM.

Green yield versus soil organic matter

The slope of the relationship between SOM and the cumulative green yield incorporated into the soil (Figure 6) indicates that each tonne of green yield increased the SOM by about 5%. The verage conversion rates over three years were close to each other for both sites, indicating similar rates of increases in SOM. However, even though the average conversion rates in Merredin and Tammin over three years were similar; the annual rates were different, varying in apparent relation to the type and amount of material added. In addition, the sites differ in their soil type (SCL for Merredin and LS for Tammin) with potential for a possible influence of soil type on accumulation of SOM. Since soil texture can effect soil aeration (Plante et al., 2006) and physical protection of SOM, it can influence accumulation of SOM (less accumulation in sandy soils than clay soils). However, relative to the amount of green material added each year the rate of accumulation of organic matter had not yet reached a plateau as indicated in Figure 6, and more SOM accumulation may have resulted if more green manure was added. A simple calculation may shed some light on the efficiency of green manuring in increasing soil organic matter in the dry areas. Between the years 1998 and 2000 a total of about 11.8 and 13.0 t/ha of dry organic matter was incorporated into the top soil (5 cm depth) as green manure in Merredin and Tammin respectively. If we assume that only one third of this organic matter stayed in the soil (3.93 t/ha for Merredin and 4.33 t/ha for Tammin, here we chose one third arbitrarily as a low value) then this will equal to 0.60 and 0.66% of the weight of the top soil per hectare based on the average bulk density values measured after ripping the soil. Since the original organic matter contents of the top soil were 1.30 and 1.35% for Merredin and Tammin respectively, the total amount of organic matter (original plus incorporated) by the year 2000 would be around 1.90 and 2.01% (if only one third of the added organic material was converted directly to SOM). The measured values of organic matter in the year 2000 were 1.84 and 1.96% for Merredin and Tammin, respectively, which is very close to the calculated values. This shows that a significant portion of the added organic manure, almost two thirds of the incorporated green manure, was not retained by the soil.

Using a carbon model to estimate organic carbon build up

The data of organic carbon obtained in this experiment were compared with organic carbon estimated from using a carbon calculator constructed by Jan Skjemstand and Jeff Baldock, CSIRO, Australia (Figure 7). Using yield (t/ha), clay content (%), soil pH_{water}, initial soil organic carbon, soil management, soil properties and weather data for each location (site) the model predicts, after incorporating all green manure into the soil, 1.05 and 0.95% organic carbon for Merredin and Tammin respect-tively. Comparing these predictions with the actual data of 0.93 and 0.98% organic carbon (1.86 and 1.96% organic matter for Merredin and Tammin respectively) we find the differences are really very small indicating a good simulation, and some confidence in the model predictions. Thus the model was used to estimate likely accumulation of organic carbon in the future. It showed that after 10, 20, 30, 40 and 50 years of 3.9 t/ha/y of green manuring, the organic carbon would be 1.34, 1.75, 2.07 and 2.55% for Merredin and 1.16, 1.45, 1.68 and 2.03% for Tammin. This means that we have to add around 4 t/ha of fresh organic matter every year for 50 years to get the soil organic matter to around 5.1% in Merredin. This is unlikely given the current cropping systems prevalent in this hot and dry environment. For example, the average grain yield for wheat in Merredin from 1996 to 2006 was 1.56 t/ha (Cooperative Bulk Handling, Ltd), a yield that would have resulted in only about 2 t/ha of straw (at a harvest index of 0.4). This figure is less than half the amount required to increase the SOM to around 4% in 50 years time according to the carbon calculator model.

The effect of the small increase in SOM described in the aforementioned on some parameters of the soil physical fertility such as water stable aggregates, soil bulk density and soil water infiltration will be discussed as follows.

Water stable aggregates

WSA values were substantially restored to the original levels after the first year of green manuring and steadily increased thereafter to about 25% at Merredin and 28% at Tammin (Figure 8). Decreases in WSA after ripping due to breakdown of soil structure have been reported previously for similar soils (Hamza and Anderson, 2002, 2003). This increase in WSA at both sites indicates that a relatively stable structure was re-established in a reasonably short time after ripping and gypsum application. There were no significant differences between treatments on WSA indicating that different species of green manure had a similar influence on WSA.

The increase in WSA at both sites after incorporation of green manure in the first season was much more rapid than previously reported for plots treated with gypsum and deep ripping alone (Hamza and Anderson, 2003). This suggests that the processes of restoring soil structure were further assisted by incorporating green manure into the soil. The data and the trend of WSA discussed here agrees with the suggestion made by Loveland and Webb (2003) that there is a growing body of evidence that ‘fresh’ or ‘active’ plant residues are important in determining soil aggregation and related properties, and the proportion of these residues in the total soil organic carbon pool is more important than the size of the pool itself. We assume, even though we did not measure the various pools of organic matter, that the increases we measured in total SOM were largely in the more labile or active fractions because the soil organic matter was measured a short time after incorporation. Improvement in water-stable aggregates by green manuring has been reported by several other researchers (Jiao et al., 1986; Liu, 1988)

Soil bulk density

Soil bulk density before deep ripping was 1.65 Mg/m^3 for Merredin and 1.5 Mg/m^3 for Tammin (Figure 9). It decreased to about 1.31 Mg/m^3 after deep ripping at both sites, and to 1.17 and 1.14 Mg/m^3 at the end of the experiment in 2001 after incorporating the green yield into the soil each year. Other researchers have reported similar decreases in soil bulk density after manuring (Liu 1988; Sood, 1988). The initial decrease in bulk density was greater at the sandy soil at the Tammin site in the first year than at the loamy site at Merredin, where the main decrease occurred in the second year. This might indicate that sandy soils are more responsive in their interaction with organic matter and may require less organic matter than heavier soil to improve their physical properties. This may be because sandy soils possess less surface area and hence, require less organic matter to improve. No significant differences between treatments were observed, indicating again that the quantity rather than quality was important in stabilising soil structure.

Soil water infiltration rate

Before ripping the soil, the water infiltration rate was quite low at 8.9 mm/h at Merredin and 9.1 mm/h at Tammin, and increased after ripping to 25.2 and 23.1 mm/h respectively. For the next four years (1998 - 2001) and in spite of incorporating the green manure every year into the soil, the water infiltration rate did not further increase significantly at either site (Figure 10). Improvements of soil water infiltration after green manuring have been reported by some researchers (Padma and Deb, 1970).
However, at the Tammin site the water infiltration rate did increase ($p=0.059$) for treatment 3 (O-FB-FB-O) during the first two years of green manure incorporation (1998 and 1999) from 27.9 mm/h just after ripping to 33.4 mm/h and after the first year of green manure incorporation to 35.9 mm/h in the second year. However, it decreased to 30.0 and 29.1 mm/h in the next two years making the overall improvement insignificant.

Conclusion

Incorporating green manure at around 14 to 20 t/ha of cereal and legume as green manure over four consecutive years increased soil organic matter significantly. However, though the increase was statistically significant, it did not increase the SOM to a level proportional to the large amount of material incorporated into the soil. The most likely reason for the low rate of accumulation of organic matter is the low rainfall and high temperatures experienced in the experiments, factors that almost certainly restricted the activity of the soil micro-organisms. However, this low addition of SOM annually to the soil is of great importance because the increases in soil organic matter and the improvement of soil physical properties associated with it, such as soil bulk density, water stable aggregates and water infiltration rate, indicate that green manure can play a vital role in improving and maintaining soil physical fertility under the arid conditions of these experiments. Differences in green manure plant types did not result in major differences in the SOM content or soil properties measured, leading to the conclusion that the hot and dry conditions of these experiments imposed a greater limitation on bacterial activity and organic matter accumulation than the quantity or quality of organic material added to the soil. The values of organic carbon in the soil predicted by a soil carbon calculator were very close to the measured data.

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