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Evaluation of greenwaste mulch to control runoff quality from landfill sites during frequent storms

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Abstract

This paper describes a preliminary evaluation of two types of greenwaste (fresh and aged) used as a mulch layer to control runoff from disturbed landfill areas. Fresh greenwaste refers to woody and herbaceous garden waste that has been recently collected, chopped and shredded. Aged greenwaste is greenwaste which has been stockpiled for 18 months. We used rainfall simulator tests to investigate two aspects: (1) the performance of greenwaste mulch in reducing runoff during designed storm events with a high frequency of occurrence and (2) the release of pollutants via runoff as total suspended solids (TSS) and total organic carbon (TOC) during rain. Rainfall of <5-year average recurrence interval (ARI) was generally applied, consistent with stormwater compliance requirements for many Australian landfills. TOC released from fresh greenwaste material was higher in concentration than from aged greenwaste. However when used as a 10cm-deep mulch layer, fresh greenwaste was able to completely prevent runoff, even when tested under rainfalls up to 50 year ARI duration. An equivalent mulch layer of aged greenwaste was also effective in reducing runoff volume and TSS concentration compared with the bare soil during a 3.5-year ARI rainfall, but mean TOC concentration was higher. Based on these preliminary results, fresh greenwaste mulching of bare soils is an attractive option to control runoff and erosion from areas subject to intermittent landfill operations and worthy of further investigations.

KEYWORDS Stormwater; landfill; runoff, erosion, mulch; runoff quality; sediment control

1. Introduction

Municipal landfills used for the disposal of solid waste present considerable ecological and human risks unless there is effective landfill cover that minimises erosive runoff and isolates contaminants in the landfill from the nearby environment (Breshears et al., 2005). Physical disturbance due to landfill activities can cause loss of vegetation and exposure of the surface soil within the active parts of the site. Disturbed areas are also subject to compaction by heavy machinery reducing infiltration which increases runoff. Low vegetative cover combined with reduced infiltration may predispose landfill sites to excessive erosion during storm events. As a consequence, effective erosion control of these disturbed areas is critical in reducing turbid runoff generated from landfill sites.

For sustainable management of agricultural, urban and industrial landscapes, establishment of full vegetative cover with grass is typically the most preferred method to reduce sediment loss from sloping, disturbed soil surfaces (Adekalu et al., 2007; Gyasi-Agyei, 2004). Revegetation is often used to rehabilitate inactive areas of landfill which are no longer part of landfill operations for long-term erosion prevention (Athy et al., 2006). However, for areas subject to intermittent landfill operations, a temporary control measure is often preferred over full rehabilitation as these areas may need to be reactivated in the future.

Municipal landfill sites typically receive significant amounts of woody and herbaceous garden waste (referred hereafter as ‘greenwaste’) that is suitable for recycling. Greenwaste includes all material derived from the general maintenance of parks and gardens, tree pruning and residential garden activities which is shredded and chipped to produce a mulch material. This material could be used as a convenient and economic method for short term erosion control on land fill sites as it is similar to woody waste which is known to be beneficial for erosion control (Buchanan et al, 2002; Demars et al., 2004 and Benik et al., 2003), especially for short term prevention of erosion from disturbed areas of construction sites (e.g. USEPA, 1993; QDMR, 2002). The performance of greenwaste could also be similar in the erosion control of highway embankments using yard waste compost (Persyn et al., 2004). These applications indicate that more specific information is required to test the suitability of greenwaste mulch as a short-term erosion control to reduce offsite impacts associated with sediment-laden runoff from disturbed landfill areas.

The performance of mulch to control runoff and erosion is often evaluated with simulated rainfall. Using a simulated rainfall intensity of 95 mm h^{-1}, tests by Iowa Department of Transportation indicated both runoff and erosion rate from areas treated with yard waste compost to be 22% and 4% of bare soil, respectively (Persyn et al., 2004). In their study, superior performance of yard waste compost over other compost treatments involving biosolids and industrial wastes was due to the coarse nature of the material. This indicates that surface roughness and detention or storage capacity of the mulch may be key properties which could be important in reducing runoff and erosion.

Biophysical mechanisms of runoff and water erosion over land surface is reasonably well known and modelled (e.g. Nearing et al., 1989; Misra and Rose, 1996; Van Dijk and Bruijnzeel, 2004), but the interaction of mulch with both these processes are relatively complex and not as well understood. Early work of Kramer and Meyer (1969) found that the rough surface created by mulches lowers runoff velocity, provides greater water storage and allows water to percolate into the soil. There are also indications that soil crusting occurs less often when mulch is present on surface due to the dissipation of energy associated with the raindrop impact and runoff (Risse and Faucette, 2003). Demars et al. (2000) reported an increase in water infiltration and water holding capacity due to improvements in soil structure when composted wood mulch was used to prevent erosion.

Although mulching directly affects runoff rates and erosion, the concentration of soluble and sorbed chemicals in runoff are not necessarily affected in the same way. This is well illustrated in the studies of Glanville et al. (2004) which showed significantly higher concentration of soluble zinc, ammonium, nitrate and phosphorus in runoff from plots treated with the yard waste compost than the untreated, bare soil plots. Marques (2007) sampled stormwater runoff from different areas at one landfill site in southern Sweden and found the highest concentration of total organic carbon, biochemical oxygen demand and nutrients were associated with composting stockpiles.

These studies indicate that an improved understanding of the interaction between runoff, erosion and water quality is required to evaluate greenwaste mulch performance as a temporary measure to reduce erosion and offsite water quality impacts. A preliminary evaluation using simulated rainfall tests on small landfill plots is described herein.

2. Materials and Methods

All runoff experiments were conducted at the main municipal landfill site of Toowoomba city, a regional centre located in south east Queensland, Australia. The landfill is operated by the Toowoomba City Council (TCC) and is designated as an ‘Environmentally Relevant Activity’ (ERA) under the authority of the Queensland Environmental Protection Agency. All ERAs need to comply with a number of licensing conditions including containment of pollutants so that stormwater discharge from the landfill site does not exceed a critical concentration of total suspended solids (TSS) and total organic carbon (TOC). Consistent with these licence requirements, TSS and TOC were adopted as the water quality determinants in our study. Furthermore, it is generally a licence requirement to monitor runoff quality from the landfill site to check compliance during several representative storm events over the course of a year, so runoff control in response to relatively minor, but frequently occurring storms is of critical interest.

At this landfill site, TCC chips, shreds and stockpiles approximately 40,000 m^3 yr^{-1} of greenwaste. Degradation of the greenwaste material increases temperature within the stockpiles and reduces the viability of weed seeds. This onsite activity produced two types of material for use in our tests: fresh greenwaste as a mulch that was chipped and shredded 3 weeks prior to tests, and aged greenwaste which had been stockpiled for a longer period of 18 months. Fresh greenwaste was lighter in colour and coarser than the aged greenwaste. Based on visual observation, the aged greenwaste contained a relatively higher proportion of fine particles as it was partially decomposed during storage.

2.1 Experimental Strategy

A rainfall simulator designed for soil erosion and infiltration research (Loch et al., 2001) was used in all experiments. The rainfall simulator consisted of a tubular steel frame to support a boom containing a series of nozzles. Alternating clockwise and counter clockwise rotation of the boom allowed rain to be applied over test plots by a sweeping action. The rainfall rate was controlled by stopping the boom at the end of sweep by a pre-set time. Details of rainfall rate control as a function of pre-set time used to overcome direct rainfall measurement during specific experiments is given in Loch et al. (2001). The nozzles of the simulator were designed to provide a water droplet kinetic energy similar to natural rainfall, which for the conducted tests was approx. 0.275 J m^{-2} s^{-1}.

The simulator is designed to be easily transported by a 2-tonne trailer fitted with a 4 kVA petrol generator used to supply power to operate the equipment, including a pump and control systems. It is designed to be erected and operated by a fieldwork team of 2 to 3 persons and is able to apply simulated rainfall to an overall test area 2.0 by 1.8m in size. A plastic canopy was attached to the A-frame of the simulator to provide a windbreak and to reduce the advection of applied rain from the target plot. The rainfall simulator has been widely used in Queensland for studies of soil infiltration properties and nutrient mobilisation (Loch et al., 2001).

Previous erosion studies with simulated rainfall have often used high intensity rainfall (e.g. 100-118 mm h^{-1} used by Misra and Rose, 1996 and Teixeira and Misra, 2005) that coincides with infrequent storm events. Past studies have also a tendency to measure total sediment loss in preference to suspended solids in stormwater (TSS) and have tested the capacity of mulch to reduce sediment loads rather than its potential to contaminate stormwater runoff. In our experiments, we selected a base rainfall intensity of 40 mm h^{-1} that has a high frequency of occurrence and more representative of rainfall events likely to occur during stormwater compliance monitoring at landfill sites. At this intensity, 30 minute duration of rainfall application is equivalent to 1-year ARI (Average Recurrence Interval) storm magnitude (Figure 1). The duration-ARI curve in Figure 1 is based on the design storm estimation procedures as described for Australian Rainfall and Runoff (Pilgrim, 1987).

Simulated rainfall was applied for a period sufficient to provide at least a 30 minute duration for runoff sampling. A few recent erosion studies (e.g. Grismer and Hogan, 2004; Gyasi-

Agyei, 2004) have used a similar approach of allowing a fixed duration of runoff. As runoff commenced at different times depending on the mulch treatment, the duration of rainfall and hence equivalent ARI also varied between tests. However, the rainfall applications of the tests generally remained less than 5-year ARI, significantly less in magnitude than of the order 100-year ARI simulated rainfalls used in various erosion experiments cited earlier.

2.2 Runoff plots and mulch treatments

A portion of a closed waste disposal cell at the Toowoomba landfill was cleared of vegetation 1 week before setting up the test plots. Onsite vegetation consisted of shallow-rooted grasses which were scraped from the surface. The surface soil of the test plots is described as a self mulching, black vertosol (Isbell, 1996). Macroporosity associated with surface roots was considered to be minor, compared to that inherent within this soil type. The gravimetric moisture content of the surface soil was 12%. The slope of all test plots (after surface clearing) was 8.5°. The water used for the simulated rainfall study was obtained from a groundwater bore and transported to the testing site. A grab sample of the bore water indicated low TSS and TOC concentrations at less than 2 mg L^{-1}.

The simulator is designed to apply rainfall simultaneously onto two rectangular plots positioned side by side. Each duplicate plot is 1 m wide and 1.6 m long defined by a steel frame hammered into the soil surface to a depth of 75 mm. Although the size of each test plot was small, border effects on runoff due to preferential flow and loss of sediment due to splash was negligible. An open drainage pipe was fitted to the downslope end of each plot frame to collect runoff by gravity to a central sample collection point.

Five plot treatments were used (Table 1). To facilitate the rainfall tests, five pairs of duplicate plots (i.e n = 2) each of identical treatment were established at the landfill site. Greenwaste treatments were not randomly allocated to test plots in order to minimise spatial variation. Each pair was separated by a distance of approximately 2 m so they could be tested individually using the moveable rainfall simulator. The plots were positioned along the contour so test conditions at each plot site would not be affected by downslope runoff generated from other sites. A total of five rainfall tests were conducted during January 2007; one for each pair of duplicate plots. More testing to increase the number of treatment replicates was restricted by site access and time constraints.

As greenwaste may be a source of contaminants, two treatments were designed to quantify the TOC (and TSS) released directly from greenwaste during rainfall. These are referred to as ‘greenwaste characterisation’ tests which were conducted by placing fresh or aged greenwaste over plastic sheets. Additional ‘mulch performance’ tests were conducted to investigate the effectiveness of greenwaste in controlling runoff when placed as a mulch over bare soil. Greenwaste was spread within the plot frames and lightly tamped to an even depth of 0.1 m. The selected mulch depth was based on Queensland erosion and sediment control guidelines (QDMR, 2002). Both fresh and aged greenwaste was tested. The placement densities ranged from 16 kg.m^{-2} for the fresh material to 50 kg.m^{-2} for the denser, aged greenwaste. A bare soil plot was used as a control to determine its contribution to runoff and water quality.

2.3 Sampling and measurements

For each treatment, duplicate plots were exposed to simultaneously applied rainfall at a constant rate of 40 mm h^{-1}. Runoff samples were collected using a methodology illustrated in Figure 2 and were also taken simultaneously from both duplicate plots. After the start of runoff, grab samples of runoff were collected at 5 min intervals for 30 min, after which rainfall was stopped. Runoff was collected over a fixed time period of 1 min to obtain a flow-weighted grab sample. This approach ensured samples were obtained to represent an event mean concentration (EMC) of the runoff.

During the period between grab sampling, runoff was collected in a plastic measuring cylinder to measure runoff volume for each test event. Time-averaged runoff rate was estimated from runoff volume and sampling time (typically 5 min). Runoff volume estimated from the discrete grab samples was also used as an instantaneous measure of runoff rate. A runoff discharge hydrograph was generated for each test plot by combining the data from both types of runoff collection.

The first and last discrete samples (referred to as [1] and [6] in Figure 2) from each test plot were analysed in the laboratory to provide an indication of initial and steady-state runoff conditions from each test event. The intermediate samples ([2] to [5]) were combined together and analysed to provide a composite TSS and TOC determination for the middle portion of the runoff hydrograph for each test plot.

TSS concentrations were determined by laboratory analysis using the APHA (2005) test method 2540D. A Shimadzu analyser incorporating a combustion catalytic oxidation process was used to determine TOC. The runoff samples were also analysed for dissolved organic carbon (DOC) after filtering through 0.45μm glass filter paper. The DOC data was expressed as a percentage of TOC.

The data on water quality (TSS and TOC) were subject to two-factor analysis of variance (Zar, 1999) considering the type of mulch and time of sampling as two independent factors. Most analysis involved comparison of two types of mulches (FGP and AGP or AGS and BS) and three sampling times, all of which had two replicates. Statistical comparisons were also reported using the t-test between the whole-of-event runoff characteristics (runoff volume, event mean concentration, load etc.) involving only two types of mulches. However, when two types of mulches were compared with a t-test, uncertainty with statistical analysis due to the limited number of replicates means that each comparison is indicative only. As a result, the results of the tests are discussed in terms of mean runoff characteristics, with comparisons reported as being either significant ($P \leq 0.05$) or not significant (NS, $P > 0.05$).

Maximum values of selected runoff characteristics are also reported. These values correspond to the single highest observation recorded from the duplicate plots during testing.

3. Results and Discussion

3.1 Greenwaste characterisation tests

Runoff and water quality measurements for fresh and aged greenwaste over plastic (FGP and AGP) provided information on the ability of a layer of greenwaste to store and release water and pollutants during storm events without affected by the underlying soil. Discharge hydrographs for these tests are shown in Figure 3. Whole-of-event values of runoff and its quality (TSS and TOC) are presented in Table 2 and temporal variation in TSS and TOC are shown in Figures 4-5.

Runoff during the FGP and AGP tests (Figure 3) commenced fairly rapidly within a few minutes after the start of rain as water infiltration into the soil was prevented by plastic. This suggests that rain percolated quickly through the mulch layer to generate runoff and a steady state runoff condition was evident for both types of greenwaste approximately 25 minutes after rainfall simulation began. When rainfall ceased, runoff reduced gradually over a period of several minutes.

Mean runoff characteristics, including initial loss (defined as the amount of rainfall that needs to be applied before runoff is observed), runoff volume and maximum discharge for the fresh and aged mulches were of similar magnitude (NS, $P>0.05$, Table 2). Based on the volumetric runoff coefficient (total runoff/total rainfall), both mulches have the capacity to retain approximately 50% of the applied rainfall. Potential mechanisms for water retention by the mulch layer are expected to be absorption and storage of water within the voids of the mulch material and surface storage within small depressions on the plastic underlay.

Temporal variation in TSS and TOC data (mean±1 standard error) for the FGP and AGP tests are shown in Figures 4-5 as an ‘initial’ concentration (Sample 1) and an ‘intermediate concentration’ for bulked runoff (Samples 2-5) to represent the middle part of the runoff hydrograph and the ‘final’ and in some occasions ‘steady-state’ concentration (Sample 6). Other TSS and TOC statistics are also shown in Table 2 to include the maximum concentration, EMC and the mass load lost via runoff.

As shown on Figure 4, TSS concentration declined significantly over time ($P\leq0.05$) for both mulches indicating a ‘first-flush’ behaviour commonly observed in many erosion studies without mulch. However, for these mulch treatments without soil these results suggest that maximum pollutant concentrations are likely to occur during the early stages of runoff. As stormwater compliance monitoring focuses on checking that landfill runoff quality is within certain concentration targets, then management of this initial, relatively low-volume runoff phase is an important consideration. The reduction of TSS concentration over the duration of the applied rainfall suggests that the mobilisation of suspended particles in the runoff is ‘supply-limited’ and a dilution effect is present i.e. the runoff volume generated from the mulch in response to rainfall becomes proportionally larger than the particle mass washed out.

Maximum TSS concentration of runoff was found to be higher for the aged mulch than the fresh mulch (Table 2). Overall, the mean TSS load and EMC in runoff from the fresh mulch were 36% and 13% higher than the aged mulch, respectively (NS, $P>0.05$, Table 2).

Mean EMC of TOC in runoff for the fresh mulch was approx. 1.5 times higher than the aged mulch ($P\leq0.05$, Table 2). As a stockpile of aged mulch is exposed to the weather, some loss of TOC via leaching is expected prior to our testing. This leaching may have reduced the mean TOC mass load in runoff (approx. one-third) from the aged mulch than the fresh mulch (NS, $P>0.05$, Table 2). Runoff produced from both types of mulches had a dark brown, coffee colour and the TOC was predominately in a dissolved form (>94% DOC).

Temporal variation in TOC concentration was relatively constant for both mulches throughout the event with no evidence of any first flush effect (Figure 5). This suggests that TOC is not supply limited during the applied rainfall and a dilution effect that may be introduced as runoff increases was not present. The difference in runoff response between TSS and TOC could be attributed to the different kinetics that are involved i.e. TSS involves the physical mobilisation of small particles whereas TOC, being mainly DOC, involves the dissolution of organic carbon from the mulch material.

3.2 Mulch performance tests

Measurements for fresh and aged greenwaste over soil (FGS and AGS) provided an opportunity to assess the performance of greenwaste mulch in controlling runoff and its quality compared with a bare soil control (BS). Results are given in Table 3 and Figures 6-8.

In bare soil (BS) tests, runoff did not start until well after 30 minutes of rain (Figure 6) that was equivalent to a total amount of 21 mm rain. Thus, applying rain at 40 mm h^{-1} (1-year ARI rainfall) allowed most of the rain to infiltrate into the soil and increased the rainfall duration for BS tests to 62 minutes, coinciding with a 3.5-year ARI rainfall. Runoff from the bare soil was only 24% of the applied rainfall (Table 3) and it stopped quickly within a few minutes of cessation of rainfall (Figure 6). The shape of the hydrograph for bare soil suggests that runoff did not reach a steady state during the testing period although the magnitude of maximum discharge from bare soil was similar to the mulch tests on plastic (Tables 2 and 3). This suggests a reduction in infiltration towards the end of the tests for bare soil possibly due to the formation of a surface seal and development of crust under the impact of rain (Geeves, 1997).

With fresh mulch over soil (FGS), the hydrological response was very different to other test surfaces as there was no runoff even when rain was applied for 120 minutes coinciding with a 50-year ARI storm event. A few studies have reported complete infiltration of applied rain with mulches. For example, Grismer and Hogan (2005) reported complete absence of runoff from plots covered with a 0.3 m thick woodchip layer under a rainfall rate of 180 mm h^{-1}.

The coarse, open nature of the fresh mulch apparently controls percolation of water through the mulch layer into soil at a rate that matches, or remains under the infiltration rate over time to generate any runoff. The mulch is expected to physically protect the soil against the impact of raindrop to prevent surface sealing and development of surface crust. Particle size distribution of mulches suggests that fresh woody mulch is coarser than the composted mulch that helps reduce runoff when the mulches are placed over soil (Persyn et al., 2004) by possibly affecting the continuity of water flow through the mulch.

The hydrograph from the aged greenwaste over soil (AGS) showed an intermittent pattern (Figure 6). Runoff commenced within <10 minutes from the start of rain in a pattern similar to the behaviour of this mulch over plastic (AGP). During the first 20 minutes of runoff, water may have moved downslope through and/or over the mulch layer with little infiltration into soil. This first phase of runoff had an early peak and after 20 minutes, runoff became negligible but re-established 35 minutes after the start of rainfall. The second phase of runoff was relatively steady at a rate of 3 to 5 mm h^{-1}. The unusual pattern of runoff for AGS seen in Figure 6 suggests that the hydraulics and storage properties of this material placed on soil are complex.

Due to the sporadic nature of runoff from the aged mulch (AGS) tests, an additional sample (referred to as Sample 0) was collected during the first 30 minutes of rainfall to represent the early runoff phase. The total duration of rainfall for AGS tests (including the early runoff phase) was 60 minutes that corresponded with a 3.5-year ARI storm similar to that used for the bare soil tests. Based on the volumetric runoff coefficient (Table 3), mean runoff from AGS plots was 13% of the applied 3.5-year ARI rainfall and its volume was approx. half of that generated from the bare soil (NS, $P>0.05$, Table 3). Maximum runoff discharge from AGS plot was also lower than the discharge from bare soil (Table 3).

The quality of runoff indicated a substantial reduction of 98% in mean TSS EMC from AGS plots compared with the bare soil (BS) plots ($P \leq 0.05$, Table 3 and Figure 7). Thus, a 10-cm layer of aged greenwaste is an effective method in reducing the turbidity of stormwater generated from landfill surfaces.

The TSS EMC in runoff from AGS was of similar magnitude to that for the aged greenwaste over plastic (AGP in Table 2), with the indication that the TSS in AGS tests may have originated from the mulch itself, rather than from the soil. Total TSS load from the aged greenwaste plot was <1% of that from the bare soil (NS, $P > 0.05$, Table 3).

TOC concentration in runoff from the bare soil (BS) during the 3.5-year ARI rainfall test was in the range of 10-50 mg L^{-1} (Figure 8) with an average EMC of 26 mg L^{-1} (Table 3). Approximately 40% of the total organic carbon was in a dissolved form, but it varied considerably between runoff samples (11-86%). With a 10 cm layer of aged mulch on soil (AGS), TOC concentration (both maximum and EMC) increased at least two fold over TOC from the bare soil (NS, $P > 0.05$, Table 3). In addition, the temporal pattern of TOC in runoff showed first flush effects for AGS but not for BS (Figure 8). Due to a reduction in runoff volume from AGS, the mass load of TOC from the aged mulch was similar to BS (NS, $P > 0.05$, Table 3). Runoff from the AGS plots had a higher mean dissolved organic carbon (DOC) than from the bare soil (NS, $P > 0.05$, Table 3). The nature of greenwaste to export carbon in dissolved form was consistent with that observed from the mulch characterisation tests (AGP, Table 2).

The initial runoff phase for the AGS tests corresponded with a 1-year ARI rainfall duration. Runoff generated during the first phase was 3 mm or 13% of the applied rain (Table 3). During the same period, the 1-year ARI rainfall fully infiltrated into the bare soil (BS) plot. This indicates that aged mulch on bare soil may contribute to TSS and TOC pollution during minor storms when no runoff is occurring from bare soil.

4. Conclusions

A series of simulated rainfall tests were conducted at a landfill site in Toowoomba, Australia to obtain a preliminary assessment of the TOC and TSS released from the greenwaste (aged and fresh) material when it is exposed to rain and the performance of these waste materials as a mulch to control turbid runoff. Storm events of high frequency of occurrence (generally <5 year ARI) were adopted in our tests to represent actual rain events likely to occur during stormwater compliance monitoring at landfill sites. This contrasts with previous studies which tend to focus on large, less frequent rainfall intensities of approx. 100 year ARI.

The mulch characterisation tests on plastic indicated that both fresh and aged greenwaste have the capacity to retain approximately 50% of the 1-year ARI applied rainfall. This water storage ability moderates the amount of water released during minor storms, either infiltrating into the ground or appearing as surface runoff. TOC and TSS were mobilised from the greenwaste material as the applied rainfall passes through it. Fresh greenwaste released a higher EMC of TOC compared to aged greenwaste. TSS release exhibited a ‘first flush’ behaviour of peak concentration at the commencement of runoff, whereas the temporal variation in TOC concentration was small. TOC was predominately in a dissolved form (>94% DOC).

Although fresh greenwaste had the highest potential to release TOC when subjected to rain, as a 10 cm-deep mulch layer placed on bare soil, it prevented the occurrence of runoff even under a 50-year ARI storm event. The ability of this material to limit runoff appears to be due to its open, porous nature that not only allows water storage within the mulch layer but also maintains infiltration into soil possibly by protecting soil from raindrop impact and prevention of soil surface sealing.

Aged greenwaste was less effective than fresh greenwaste in restricting runoff; however, it reduced the mean volume of runoff by >50% and TSS mass load and concentration to <1-2% of these quantities in runoff from the bare soil during a 3.5-year ARI storm. The effectiveness of aged greenwaste in reducing runoff turbidity was offset by an increase in mean TOC EMC, predominantly in a dissolved form. Repeated testing of greenwaste over time and with larger number of replicates is desirable to determine the full potential of aged greenwaste in modifying runoff and its quality.

Overall, our preliminary research indicates that application of fresh greenwaste over the soil surface is an attractive option to control runoff and erosion from areas subject to intermittent landfill operations. Long-term benefit from mulch application can be sustained if the fresh greenwaste is replaced before it ’ages’. Aged greenwaste has reduced capability in controlling runoff during frequent storm events (~1-year ARI) as it tends to generate small volumes of runoff when no runoff is produced from bare soil. Under these conditions, aged greenwaste is a potential source for off-site export of organic carbon. It is suggested that when fresh greenwaste naturally deteriorates into aged greenwaste over time, it may be incorporated into soil with tillage before recovering the surface with fresh greenwaste.

As our experiments were based on relatively small plots with limited number of replicates to overcome spatial variation, further studies are needed to examine how variation in the thickness and placement density of the mulch layer contributes to water quality in runoff. Long-term runoff plot studies are difficult to conduct on landfill sites as these are subject to intermittent operations. Future studies in this area need to focus on a range of soil types, slopes, rainfall intensity and duration, greenwaste age and thickness to extend the importance and application of our results. Since there is a potential for mulches to add nutrients, pesticides and other contaminants to runoff, the range of pollutants assessed for water quality in these studies need to be broadened.

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Table 1. Description of plot treatments used for simulated rainfall experiments.

Purpose of test	Plot treatment	Test run
Greenwaste characterisation	Fresh greenwaste over plastic	FGP
	Aged greenwaste over plastic	AGP
Mulch performance	Fresh greenwaste over soil	FGS
	Aged greenwaste over soil	AGS
	Bare soil (control)	BS

Table 2 Runoff, total suspended solids (TSS) and total organic carbon (TOC) for 'greenwaste characterisation' tests during a 1-year ARI rainfall application. Mean values and standard errors of duplicate test plots are shown. Mean values shown **bold** indicate significant difference with a t-test (*n*=2, P≤0.05).

Parameters	Fresh greenwaste on plastic (FGP)	Aged greenwaste on plastic (AGP)
Runoff Characteristics		
Initial loss (mm)	3.3 ± 0	2.0 ± 0
Runoff volume (mm)	11.9 ± 1.5	10.3 ± 0.9
Runoff coefficient	0.50 ± 0.06	0.46 ± 0.04
Max. discharge (mm h^{-1})	27.2	25.3
TSS Characteristics		
Max. TSS (mg L^{-1})	272	320
TSS EMC (mg L^{-1})	133 ± 47	118 ± 6
TSS Load (g m^{-2})	1.65 ± 0.75	1.21 ± 0.04
TOC Characteristics		
Max. TOC (mg L^{-1})	457	246
TOC EMC (mg L^{-1})	**436 ± 0.9**	**177 ± 3.8**
TOC Load (g m^{-2})	5.2 ± 0.6	1.8 ± 0.1
%DOC	**93.8 ± 0.4**	**98.0 ± 0.9**

Table 3 Runoff and its quality for 'mulch performance' tests during 1 and 3.5-year ARI rainfall applications[1]. Mean values and standard errors of duplicate test plots are shown. Mean values shown **bold** indicate significant difference with a t-test (*n*=2, P≤0.05) between BS and AGS for 3.5-year ARI rain.

Parameters	Bare Soil (BS) 3.5-year ARI rain	Aged greenwaste on soil (AGS) 3.5-year ARI rain	Aged greenwaste on soil (AGS) 1-year ARI rain
Runoff Characteristics			
Initial loss (mm)	**21.3 ± 0**	**4.7 ± 1.3**	4.7 ± 1.3
Runoff volume (mm)	9.9 ± 1.4	5.0 ± 0.5	3.1 ± 0.6
Runoff coefficient	0.24 ± 0.03	0.13 ± 0.01	0.13 ± 0.03
Max. discharge (mm h^{-1})	26.9	11.5	11.5
TSS Characteristics			
Max. TSS (mg L^{-1})	8300	246	164
TSS EMC (mg L^{-1})	**7228 ± 91**	**132 ± 16**	154 ± 29
TSS Load (g m^{-2})	71 ± 11	0.63 ± 0.21	0.25 ± 0.05
TOC Characteristics			
Max. TOC (mg L^{-1})	48	103	103
TOC EMC (mg L^{-1})	26 ± 12	74 ± 4	95 ± 7
TOC Load (g m^{-2})	0.27 ± 0.15	0.34 ± 0.03	0.16 ± 0.03
%DOC	38 ± 20	79 ± 10	83 ± 17

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[1] No runoff was generated from fresh greenwaste over soil (FGS) plots for all tests including 50-year ARI rainfall. No runoff was generated from bare soil plots (BS) for the 1-year ARI rainfall.

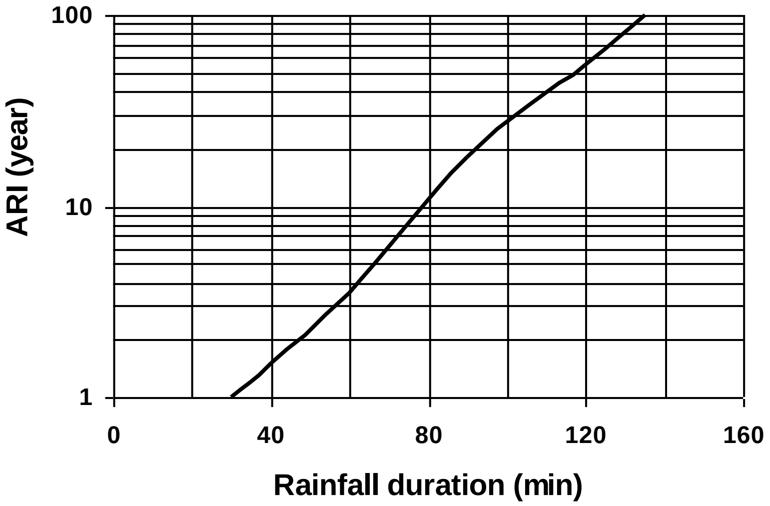

Figure 1. The relationship between rainfall duration and its average recurrence interval (ARI) for a constant rainfall intensity of 40 mm h^{-1} in Toowoomba.

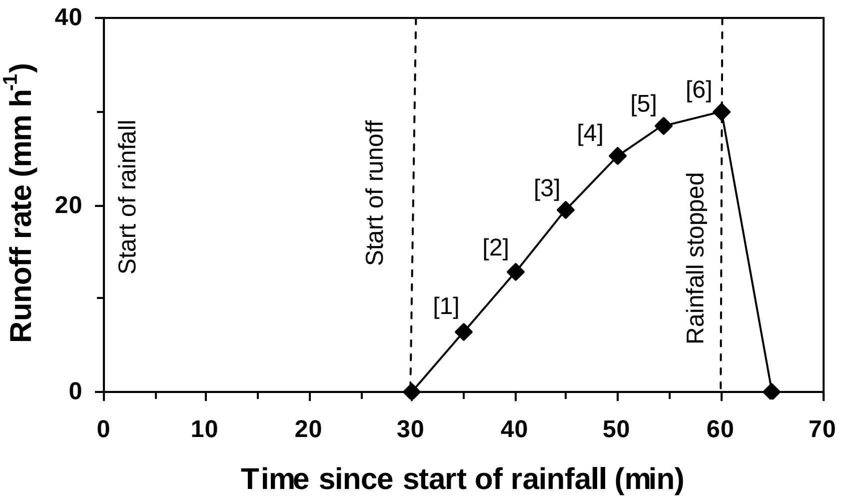

Figure 2. A schematic diagram of runoff sampling procedure used by accumulating runoff samples over time marked as [1] to [6].

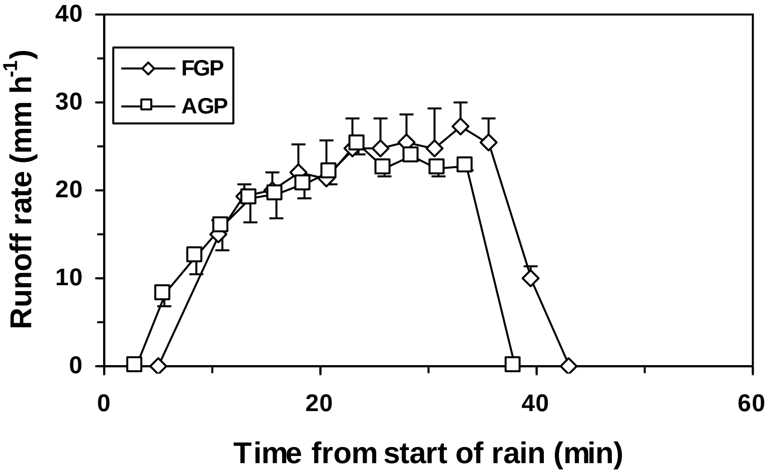

Figure 3. Temporal variation in runoff rate during the greenwaste characterisation tests. FGP and AGP respectively refer to a layer of fresh and aged greenwaste placed over plastic. Vertical lines over mean values denote standard errors (SE), shown in one direction only for clarity.

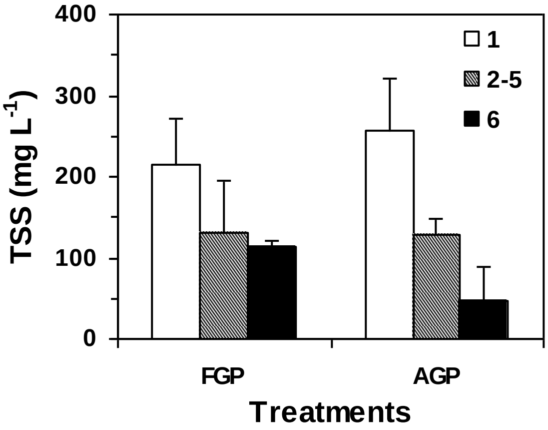

Figure 4. Temporal variation in TSS during greenwaste characterisation tests. Treatment descriptions are given in Figure 3. Initial sample is represented as 1, intermediate sample as 2-5 after combining runoff samples 2 to 5 and final sample 6 to represent steady state concentration.

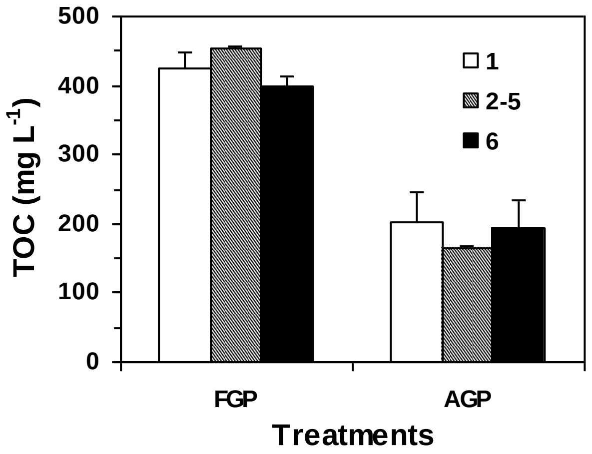

Figure 5. Temporal variation in TOC during greenwaste characterisation tests. Treatments and sample numbers as described in Figure 4.

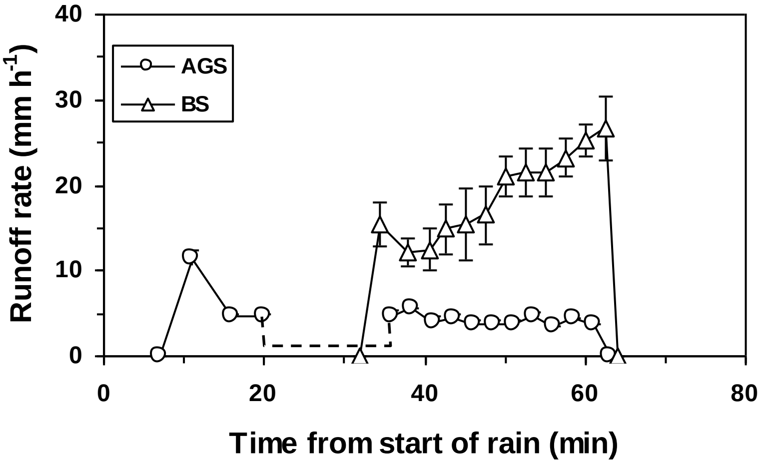

Figure 6. Temporal variation in runoff rate during the mulch performance tests. AGS refers to a layer of aged greenwaste placed over the soil surface and BS represents bare soil. Vertical lines over mean values denote standard errors (SE). Dashed line shows period of negligible runoff observed during AGS test.

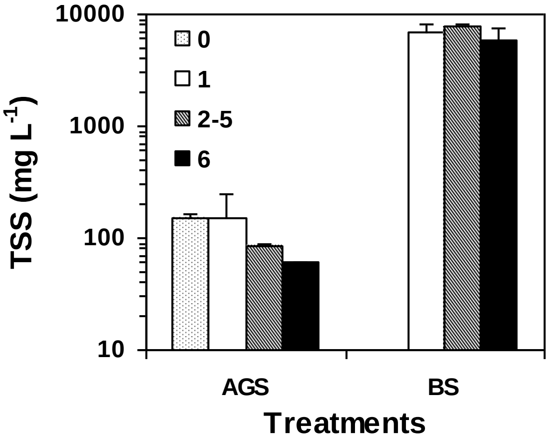

Figure 7. Temporal variation in TSS during mulch performance tests. Treatment description as given for Figure 6. Initial sample for both treatments is represented as 1, intermediate sample as 2-5 after combining runoff samples 2 to 5 and final sample 6 to represent steady state concentration. Sample 0 for AGS treatment refers to concentration for early sporadic runoff phase.

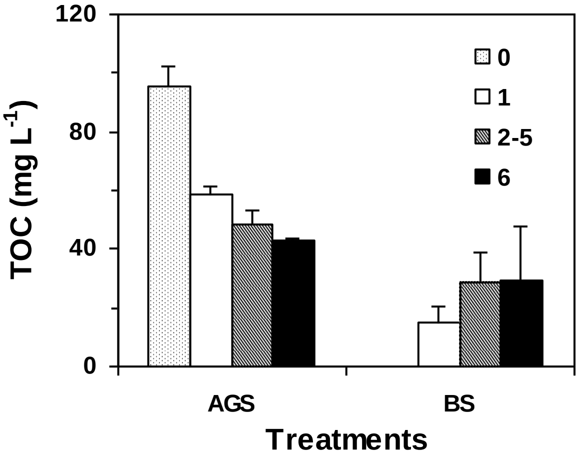

Figure 8. Temporal variation in TOC during mulch performance tests. Treatments and sample numbers as described in Figure 7.