Mulch Specification for Stormwater Bioretention Devices

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Mulch Specification for Stormwater Bioretention Devices

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Contract Report LC1656

Executive summary

Many raingarden and bioretention construction guides specify placement of a mulch layer over the surface of bioretention devices. Mulch is specified to protect the medium from erosion, suppress weed growth, and increase water availability for plants during establishment. However, some organic mulches are prone to floating. Floating mulch can expose and erode the underlying growing medium, block overflows, and contaminate receiving waters. Auckland Council contracted Landcare to identify bioretention mulches used in New Zealand and overseas, and their characteristics, both positive and negative. The key objective was to identify mulches that have a low potential to float and achieve the required functions. This would enable industry to develop or extend the range of suitable raingarden mulches. A second objective was to 'industry test' interim results and recommendations with major mulch producers. The research has four parts: a literature review, a review of available mulches in the Auckland market, the testing of available mulches, and recommendations.

A reasonably wide range of organic and inorganic mulches are available in Auckland. Organic mulches are based on radiata pine bark, green waste, or recycled, untreated wood waste (e.g., packing cases). A range of mulches specifically designed to bind on erosion-prone slopes, and two products supplied as non-floating mulches for raingardens, are available. In the USA organic, non-floating mulches are commonly based on the fibrous bark of hemlock or redwood (sequoia) trees. These mulches are not available in Auckland.

A range of organic and inorganic mulches were tested in the laboratory and glasshouse. A floatation test was developed. Mulches were tested at moisture contents ranging from air dry to a maximum moisture content achieved by three cycles of saturation and drainage, simulating three raingarden ponding and drainage events. Results were presented and discussed at a meeting with three major mulch manufacturers. Manufacturers considered the small volumes of mulches used for bioretention in Auckland restricted both investment in, and availability of, specific non-floating products. One, non-floating, organic mulch is widely available but needs to be pre-ordered (and specially mixed). However, some non-floating, organic mulches are manufactured for large, individual contracts.

Three methods can be used to supress floating of organic mulches. First, 25%v/v compost or crushed shell can be added. The method is most effective with wood chip (reharvest). Adding compost to double shredded bark does not consistently reduce floating to low levels, largely because compost can wash through large gaps in coarse bark mulch. Second, mulches can be composted to a level that increases both the wet bulk density and speed of wetting. The impact of a higher proportion of fines, as a result of either adding compost, or particle break down during the composting process, on the effectiveness of weed suppression was not quantified. However, adding compost or using composted mulch enhances nitrogen (N) and phosphorus (P) levels. This helps reduce plant N stress, which can temporarily impact plant growth as organic mulches with low N concentrations decompose. N stress is most likely for raingarden media with low organic matter contents. The third method of supressing floating is to optimise the shredding (mulching) process and feedstock properties to produce particles with suitable size range and shape. Feedstock properties include plant species, particle density and moisture content. Stringy mulches bind most effectively. As the raingarden market grows, industry may explore feed stocks from timber mills that process redwoods and stringy-bark eucalyptus species.

Industry has indicated that specifications based on the existing NZ4454 (2005) or AS4454 (2012) standards for organic mulches would be more practical than a standard exclusive to organic raingarden mulches. If NZ4454 (2005) is to be used, mulch metal concentration values and proportion of mulch particle sizes may need amendment. It would probably be necessary to apply the particle-size specification before blending with compost or fines used to reduce floating. Alternatively, it may be feasible to specify a target wet density.

All tested mulches conformed to the NZ4454 Compost standards for copper (Cu) and zinc (Zn); however, the lower concentrations required for Grade A biosolids are probably more suitable for raingarden mulches. This is because raingardens receive Cu and Zn in road and some roof runoff and are installed to reduce the concentration of contaminants in discharged stormwater. Cu levels in some mulch may approach Grade A biosolids level. Specifying a minimum pH and maximum P concentration would also help reduce the potential for metal mobilisation and P leaching respectively.

In addition to specifying non-floating mulches, a survey of raingardens identified three additional practices or guidelines that would reduce the risk of organic mulches floating.

- Thoroughly wet organic mulches at installation (irrigation)
- Design raingardens with sheet flow, or reinforce areas of concentrated flow with stone
- Ensure a dense cover of plants is achieved within 24 months so re-mulching is unnecessary. This reduces the risks of decorative bark being used to fill in gaps between plants. Avoiding re-mulching also reduces the risk of over-deep mulching, which can reduce raingarden ponding depth.

Where the energy of inflowing stormwater is high, placing inorganic mulch around inlets or over the raingarden surface should be considered. Inorganic mulch should resist physical breakdown, contain very few fines (particles <2mm diameter), and preferably be in the particle size range of 4 to 20 mm. Literature reports inorganic mulch can effectively supress weeds at 50 mm depth. Because inorganic mulch does not break down, it is important the installed depth ensures the design volume (ponding depth) is achieved. Further information on the influence of organic mulch on pH, metals, and nutrient availability in raingardens would be valuable, particularly when significant decomposition is complete. Landscape architects and engineers may find a decision tree useful to help them match the optimum mulch to site characteristics and specific treatment priorities.

Raingarden mulch can achieve a variety of functions that enhance the performance and aesthetics of raingardens. Mulch helps conserve soil moisture, and moderate soil temperature. To reduce the risk of surface sealing (inadequate infiltration rates), inorganic mulch should have a very low proportion of fines. When applied to a suitable depth, mulch supresses weed germination and establishment, hence reducing maintenance costs. Stone and crushed shell mulches do not float. Organic mulches manufactured from shredded wood waste, shredded bark, arborist pruning and green waste have minimal floatability when moisture contents and wet bulk density is above about 0.5 Tm^{-3}. However, decorative bark, particularly bark nuggets, are not suitable for use in raingardens because they generally have a high proportion of floating material.

Table of contents

List of figures

List of tables

1.0 Introduction

1.1 Raingardens and mulches

The placement of a mulch layer over the surface of bioretention devices is specified in most raingarden and bioretention construction guides, to protect the underlying media from erosion, suppress weed growth, and increase water availability for plants during establishment. However, some organic mulches are prone to floating. Mountford (2006) surveyed 41 young raingardens at 29 sites in the Auckland region. In excess of one third of the sites (39%) had mulches that were considered prone to floating. This increases the risk of mulch being flushed down, or blocking, the bypass structure (Figure 2). Mulch flushing down the bypass structure can pollute receiving waters or cause blockages in the piped network and flooding of the surrounding area. Auckland Council requested research to identify non-floating mulches, other than stone, because organic mulches can provide a range of benefits over inorganic mulches.

This report identifies bioretention mulches currently used in Auckland and overseas, and their characteristics. Non-floating mulches are identified and practices suggested that maximise the likelihood that mulches will not float. This information will help industry develop a range of suitable raingarden mulches, if they are not already available. The research has four parts: a literature review; a review of available mulches in the Auckland market; testing of available mulches; and discussion with recommendations.

Figure 1 Auckland raingardens, tree pits and bioswales.
LEFT: Waitakere Civic Centre in Henderson, CENTRE: Albany Town Centre near Oteha Valley Road, RIGHT: Bucklands Beach

Figure 2 Floating organic mulches in two Auckland bioretention devices.
LEFT: mulch adjacent to bypass structure, RIGHT: mulch collecting against a filter of rocks surrounding the overflow.

1.2 Literature review

1.2.1 Method

Literature was searched for terms ‘bioretention’, ‘raingarden’ and ‘mulch’. Few peer-reviewed, scientific papers investigate the characteristics of mulch used in raingardens or bioretention devices. Most of these papers focus on the influence of mulches on chemical attenuation of contaminants in stormwater runoff. Very few papers mention floating characteristics or provide physical characteristics of mulches used in the devices. However, there is literature on the use of organic mulches to protect soil surfaces of swales during vegetation establishment. This information is of some value; however, two factors limit the application to raingardens on a broad scale. Firstly, mulches used for swales need to resist significant horizontal flows as water is transported through the device. In contrast, raingarden mulches generally experience a low energy environment, with the exception of raingardens where inflows are concentrated into small areas, creating localised areas of high energy flows. Secondly, most of the organic mulches in swales are bound as rolls or mats. This means they are expensive to purchase and install compared with most unbound (or loose) mulches typically used for raingardens.

There is also literature on the use of organic mulches to protect erodible slopes during vegetation establishment. The characteristic of resistance to floating – so important in raingardens – is not considered in soil stabilisation and erosion literature, although features that enhance binding of mulches may also enhance resistance to floating. The main body of literature on mulches lies in the landscaping, horticulture and arboriculture industries. These industries focus on the roles of mulches in weed suppression, soil moisture conservation, buffering of soil temperatures and protection of soil from erosion. The effects of different mulches on soil chemistry, plant nutrition and plant growth are also widely reported in horticultural and forestry studies.

1.2.2 Definition of mulch

For the purposes of this project the definition of mulch is an organic or inorganic material suitable for placing on soil (not mixing into soil) that has a particle size distribution that ensures rapid permeability of water and air into underlying soil. Organic mulches are differentiated from soil conditioners and composts primarily by particle size, level of pasteurisation (or composting) and suitability for seedling germination. Mulches are coarse, may not be composted, and are generally hostile to seedling germination.

The New Zealand standard NZ4454:2005 defines mulch as 'any pasteurised organic product (excluding polymers which do not degrade such as plastics, rubber and coatings) that is suitable for placing on soil surfaces. Pasteurisation is defined as 'a process whereby organic materials are treated to significantly reduce the numbers of plant and animal pathogens and plant propagules'. Mulch is defined having at least 20% by mass of material that has passed through a 20 mm sieve. Coarse mulch is defined as having less than 20% by mass that passes through a 20 mm sieve, i.e. at least 80% by mass is particles more than 20 mm diameter. Composts, in contrast, are defined as having at least 95% by mass of material less than 20 mm diameter. The revised AS4454 2012 Australian Standard for composts, soil conditioners and mulches has an additional clause to ensure not more than 20% by mass of fine particles in a fine mulch pass through a 5mm sieve. Australian soil scientist Pittaway (2013) notes the amendment is important to ensure water penetration and air exchange, even with the presence of waxy coatings on twig and leaf fragments.

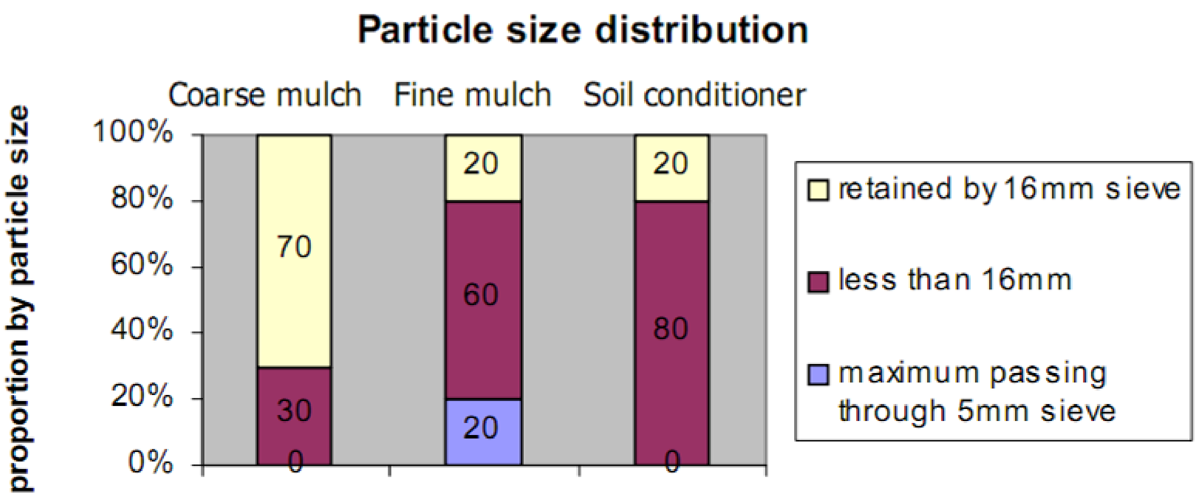


Figure 3 Particle size criteria for mulches in AS4454 2012 (Recycled Organics Unit, 2012)

1.2.3 Uses of mulch

Organic and mineral (rock or shell) mulches are primarily used in the landscaping industry. Placed over the root zones of plants, mulches play an important role by replacing the natural litter layer. Mulches protect the soil surface from physical impacts of rain and hail. Mulches also reduce water loss by evaporation and buffer soil temperature. Iles and Dosman (1999) report soil temperatures at 100 mm depth were significantly higher in unmulched soil and under inorganic mulches (9 mm diameter pea gravel, 38 mm diameter river rock and 19 mm diameter crushed brick) than under bark or woodchip mulches. However, the elevated temperatures did not reduce growth of the red maple trees studied. In the same study, soil moisture levels were increased under all mulches compared to the unmulched control. Fine-textured inorganic mulches (pea gravel) and organic mulches that meshed together were more effective barriers to evaporation than coarser mulches, and therefore more effective at conserving greater soil moisture. Depending on applied depth and particle size distribution, mulches also inhibit weed germination and supress weed growth (Duryea et al., 1999).

The New Zealand mulch industry has developed special-purpose mulches to meet the specific requirements of individual clients. These requirements include altering physical properties to achieve surfaces suitable for children's playgrounds or equestrian arenas. Requirements for plant nutrition have resulted in mulches with added compost. Compost addition is also reported to enhance water retention, thus reducing runoff volume and rate (Faucette et al., 2007). Compost has also been added to mulches to reduce floatation. Different colours are applied to match landscaping. The reflectivity of glass mulch has been used to enhance productivity in some vineyards. With knowledge, suitable processing machinery, and feedstock, a very wide range of organic mulches can be tailor-made to meet individual requirements (Ted Yates, pers. comm.). Table 1 summarises the priority placed on the different roles of mulches in Auckland.

Table 1 Priority of roles for mulches in three applications

Mulch Property **++ = highest priority, o = low priority**	**Raingarden/ Swale**	**Landscaping**	**Motorway**
Supress weed growth to decrease maintenance and enhance/provide short-term aesthetics until plants grow	+ Substrates may be weed-free	+	++
Maintain infiltration rate into soil by reducing crusting, reducing blocking of the surface by fine sediment and protecting soil surface from compaction	++ Critical until plants grow	+	++
Store and absorb water = reducing runoff and erosion control (organic mulches)	+	o/+	++
Feed plants – short /long term	o/+	++	o/+
Conserve moisture and reduce soil surface temperatures	o/+ for summer plantings	+	o
Absorb, immobilise or buffer contaminants: (filter, chemically bind or complex)	+	O[1]	o/+
Do not contribute contaminants: floating material, metals (particularly Cu & Zn), pathogens, etc.	++	o/+	+/o
Ease of spreading around plants	++ (Dense planting)	Depends on plant spacing	+/o (wide spacing)

1.2.4 Specifications for raingarden mulches

Healy et al. (2010) identified the key functions of raingarden mulch (in Auckland) are to prevent weeds and retard media drying. They also noted *'wood mulches can aid in capture of oil and grease'* and *'pebbles are not recommended where nitrogen removal is required'*. In Auckland, raingarden mulches are typically spread over the surface of raingardens and bioswales at 50 mm depth to a maximum of 75 mm depth (Figure 4, Auckland Council, undated). The aforementioned raingarden construction guide specifies mulches should not float, be well-aged, and free of other materials (weed seeds, soil, roots, etc.). The beneficial values of mulches and undesirability of floating mulches is noted in many international bioretention guidelines.

Particle size is an important characteristic as it influences the effectiveness of supressing weeds and depth of application. A higher proportion of fine organic material is more likely to allow seeds to germinate, reducing the effectiveness of supressing weed establishment. Auckland Council and international bioretention guidelines do not specify a particle size for organic mulches; however, in North Carolina, USA, finer (double- and triple-shredded) mulches are preferred over coarser, less-processed mulches. The terms double- and triple-shredding refer to particle size, not necessarily to extent of processing '*Single-shredded mulch has the longest strands of mulch, with pieces as long 10 inches. Double-shredded mulch ranges in size from 4 to 6 inches in length. Triple-shredded mulch is the shortest and most compact ranging in size from 1 to 3 inches. The finer the shred, the better the mulch locks together to hold it in place after it is applied*.'[1] Hinman (2007) recommends use of coarse compost over the base of raingardens rather than chipped wood due the former's greater resistance to floating.

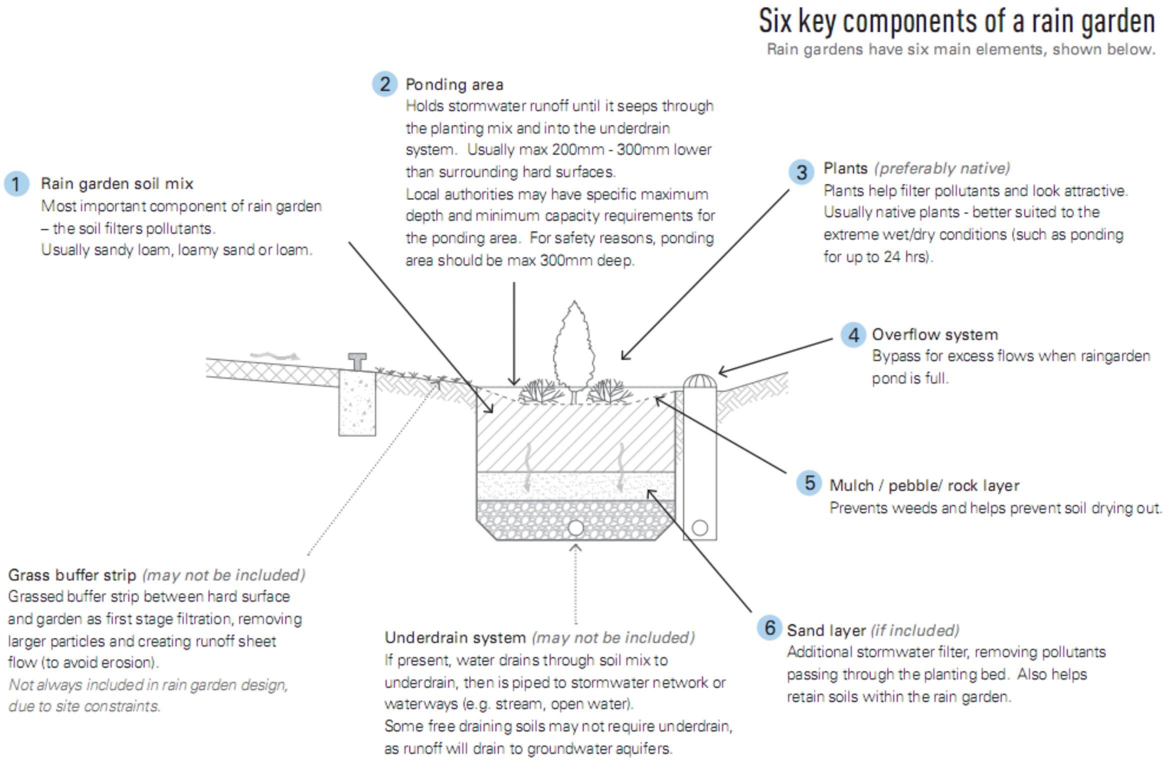


Figure 4 Key parts of a raingarden, Auckland Council Raingarden Construction Guide (Auckland Council, 2011)

For inorganic mulches, however, a size range is specified in some guidelines and reports. Somes and Crosby (undated) based their raingarden mulch recommendations on a survey of 22 raingardens in Melbourne. They recommended a 50 to 75 mm layer of clean, 5 to 13 mm diameter gravel or stone to control weeds and aid moisture retention. They identified unwashed gravel and sand mulches as one of several factors implicated in formation of impermeable crusts and clogging of some surveyed raingardens. Low infiltration rates are undesirable as treatment capacity is reduced and risk of

[1] http://www.ehow.com/list_7391452_shredded-hardwood-mulch-specifications.html

overflows increased. In Auckland, washed or screened gravels and rock from 4 to 8 mm or 50 to 200 mm diameter are typically used as raingarden mulches (see Section 3).

None of the international bioretention guidelines examined specify the chemical properties of mulches, despite raingarden media being required to have specific pH, metal, nitrogen, and phosphorus characteristics to increase the capture of nitrogen and phosphorus. Research indicates materials such as grass clippings and alfalfa (lucerne) hay consistently release nitrogen due to a combination of high initial N content and rapid decay rates (Valenzuela-Solano and Crohn, 2006). Hinman (2007) in 'The Raingarden Handbook for Western Washington Homeowners' identifies grass clippings as unsuitable for raingarden mulches due to nutrient concerns, and mushroom compost unsuitable as an organic amendment for the same reason. Woods-Ballard et al. (2007) also specifies lawn clippings as not suitable for use as raingarden mulch. Materials with high nitrogen concentrations are unsuitable for use as mulches in areas where nitrogen is a stormwater contaminant of concern. In contrast, organic mulches with low N contents and slow decay rates tend to immobilise N, at least in the short to medium term. This includes pine 'straw' or needles harvested from the forest floor. Pine needles are the most common landscaping mulch in North Carolina where forest landowners receive income from contractors who harvest the straw (Bill Lord, North Carolina State University, pers. comm.). However, pine needle mulch lowers the pH of soils to a greater extent than other organic mulches (Duryea et al., 1999). A single application of pine needles in a raingarden where either the raingarden soils were well buffered (indicated by a high Cation Exchange Capacity) or the pH was circum-neutral is likely to have little effect. Most organic mulches slightly lower soil pH as they decompose, releasing organic acids (Iles and Dosman, 1999). Very sandy mixes with a low buffering capacity could be expected to be more vulnerable to pH reduction.

Few bioretention guidelines identify the secondary values that some mulches provide. These values include maintaining the infiltration rate of the underlying soil, and removing or buffering chemical contaminants (extending the life of the raingarden). Mulches can help maintain infiltration rates of underlying soil by intercepting sediment inflows. This reduces surface clogging. Hsieh et al. (2007) ran stormwater with 150 mg l^{-1} TSS though bioretention columns with and without a mulch layer. They reported a layer of mulch 'prevented the column from clogging over 12 cycles', whereas in unmulched columns infiltration rates were compromised. In an earlier study, Hsieh and Davis (2003) also reported '*most TSS was filtered by the top mulch layer*'.

Mulches can cushion the raingarden surface from compaction, with elastic mulches, i.e., those that bounce back from compactive forces, being most effective. Many organic mulches are elastic. This can be important where raingardens are planted when the media are wet and highly vulnerable to compaction. The absorption, microbial processing, and filtration processes depicted by Brix (1993) (Figure 5) as occurring in raingarden media, also occur to some extent in the mulch layers.

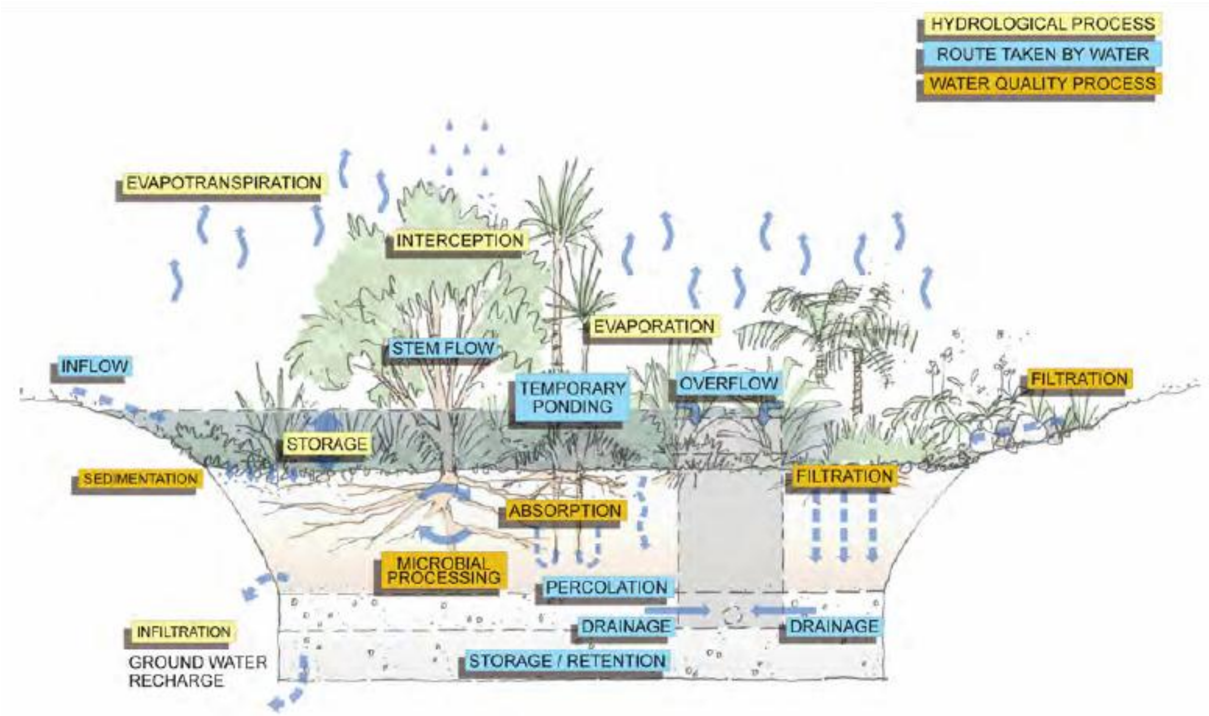


Figure 5 The processes attenuating stormwater volume and quality that occur in a raingarden, Brix (1993)

Organic matter (aged compost, peat or shredded wood) has been identified as a key component of biofiltration media used to reduce contaminants in stormwater (Clar et al., 2007, Hunt and Lord, 2006). The removal or buffering of chemical contaminants by organic mulches can be quantified by measuring the accumulation of contaminants in the mulch layer. In Auckland, such accumulation was monitored. A non-floating arborist mulch, processed in a Vertical Compost Unit (VCU), was coarsely shredded, and placed over a raingarden to about 70 mm depth (Trowsdale and Simcock, 2011). Zinc concentrations in the mulch increased over time as the mulch removed this contaminant from road runoff (Figure 6).

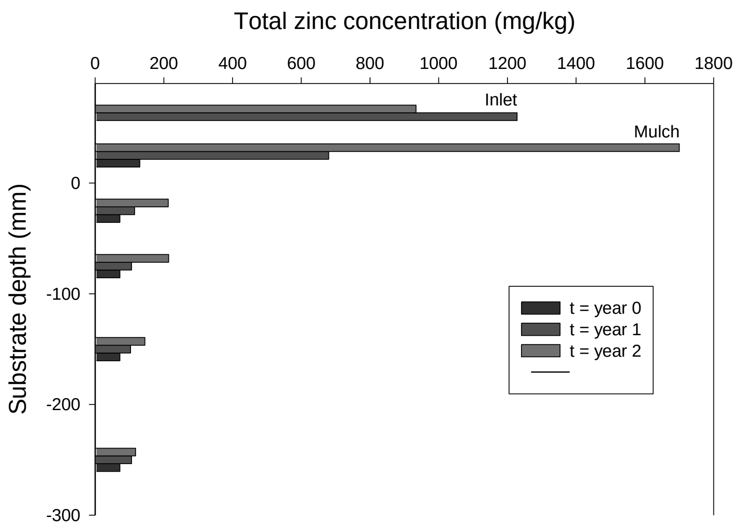


Figure 6 LEFT: The build-up of zinc in mulch and soil of a raingarden RIGHT: the raingarden receiving runoff with no evidence of floating organic mulch

The catchment for this raingarden included a road conveying 16,000 vehicles per weekday. Inlet samples are road-derived sediment accumulated adjacent to the three t-shaped inlets shown in the photo.

Mulches can be a sink and/or source for nitrogen and phosphorus depending on balance of carbon to nitrogen and the speed of decomposition (Duryea et al., 1999). High ratios of lignin: N, Carbon:N or phenolic substances tend to result in slower decomposition rates and greater N removal in the short to medium term by soil micro-organisms. Where soils are low in nitrogen, this can create short-term nitrogen stress for plants. However, as mulches decompose, nitrogen is released. If decomposition occurs slowly, leaching losses are low because the raingarden plants are able to intercept and uptake the nitrogen.

Mulches containing humified organic matter can also stabilise metals and PAHs. The most efficient organic materials are those with high humic and fulvic acid contents. These organic acids chemically bind with metals to form stable soluble or insoluble complexes. These stabilise contaminants such as zinc (Zn), lead (Pb) and copper (Cu) making them less prone to leaching and/or less toxic to aquatic organisms. Laboratory experiments show peat, compost, and activated carbon, are efficient at removing organic and metal contaminants from stormwater and retaining these contaminants when flushed with clean water (Clark et al., 2006). Other materials that have been successfully used include tree barks, sawdust and wood mulches (Ray et al., 2005). However, some organic materials can have a 'first flush' effect (Figure 7), as dissolved organic material and very fine organic material are washed from the filter matrix (Trowsdale et al., 2006).

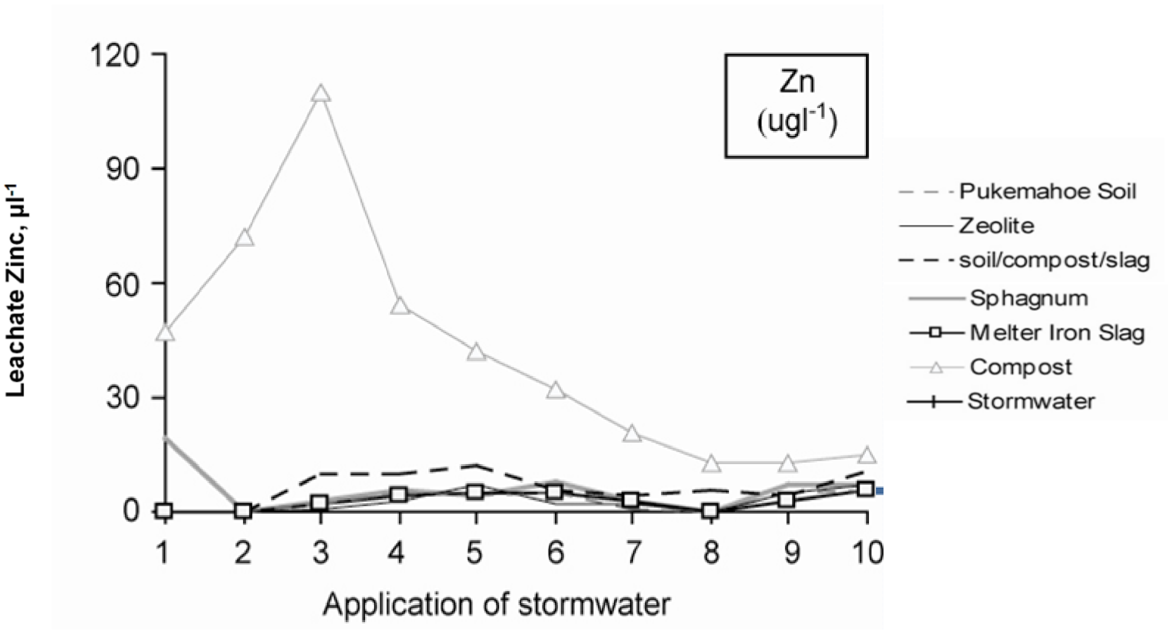


Figure 7 Percentage removal of zinc by different filter media in a laboratory (Trowsdale et al., 2006). Removal of zinc from 10 sequential applications of road runoff in a laboratory leaching experiment. Upper grey line is fresh compost (Trowsdale et al., 2006).

The longevity of benefits achieved by contaminant binding depends on the stability of the organic material and chemical bonds. Shell and limestone mulches may provide an alkaline modifier that buffer against potential acidification caused by acidic stormwater. Maintaining a pH above 6 is particularly important where zinc is a contaminant, as at pH values less than about 6, zinc becomes much more mobile. C. and M.J.A. (2010) reported a five-fold reduction in leachate zinc from road-derived sediment (catch pits and street sweepings) when the pH increased from 6.5 to 7.5 (Figure 8).

Values higher than about pH 8 would further reduce leachate zinc concentrations; however, such high pHs may induce plant phosphate and some micronutrient deficiency.

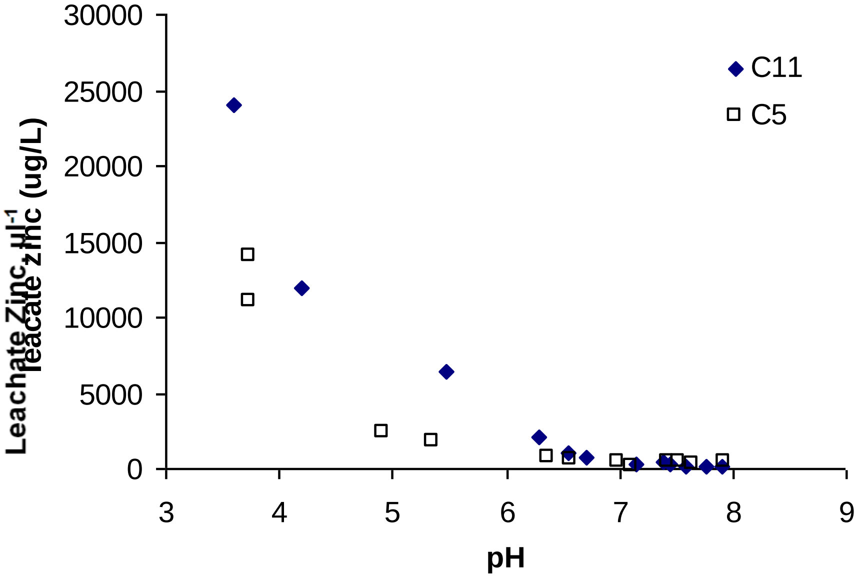


Figure 8 The effect of leachate pH on solubilisation of zinc (C. and M.J.A., 2010)

Mulches can be selected that have chemical properties that facilitate precipitation or the binding of pollutants, thus reducing their bioavailability, and also provide nutrients for plant growth. The longevity of organic mulches is determined by such characteristics as surface area, resistance to microbial degradation (presence of inhibitors such as phenols and tannins found in bark), and availability of nitrogen in the mulch itself, in the runoff entering the raingarden, and in the raingarden substrate. Longevity is influenced both by mulch depth and by local environmental conditions such as moisture content (required for decomposition) and temperature.

In summary, the four most important characteristics of mulches used in bioretention devices are that they have an equivalent or higher infiltration rate than the underlying media at all times, so that infiltration into the media is not compromised; they do not float; they supress weeds; and they enhance water supply to young plants. The potential for some mulch to float, and the difficulty in specifying non-floating mulches, are the main drawbacks associated with the use of organic mulches.

The major advantages of organic mulches over many inorganic mulches are that they are relatively inexpensive, use recycled waste materials (wood, bark and green waste) that can be locally sourced, improve short-term removal of some contaminants (particularly Zn, Pb and PAHs), and, on breaking down, stimulate microbial processes and infiltration into underlying raingarden media. The potential benefits of different mulches are influenced by inherent mulch characteristics, depth of application, raingarden substrate, and local site environmental conditions.

2.0 Methods

2.1 Mulch characterisation

The range of mulches available in Auckland was assessed by visiting landscape suppliers and surveying raingardens, tree pits, and bioswales built throughout Auckland. A range of organic and inorganic mulches were purchased from five landscaping suppliers. Bark nuggets were known to be unsuitable due to floating. Stone and shell mulches were certain to be non-floating (Section 2.2). These three mulches formed the upper and lower boundaries against which the floating potential of mulches was assessed. Results of the field survey, in which performance of mulches installed at sites around Auckland was visually assessed, can be found in Chapter 3.

The particle size of mulches was quantified (section 2.3). A floating (or floatation) test was developed in which each mulch was wetted to moisture contents, ranging from air dry through 'as delivered' (field moist) to maximum moisture content (section 2.4) before testing. Phase One floating tests showed one commercially available mulch did not float at the 'as delivered' moisture content'. Several organic mulches did not float at maximum moisture content, but floated at the 'as delivered' moisture contents. A second phase of floating testing therefore investigated the effectiveness of different pre-wetting durations, and adding 25% v/v of compost or shell to reduce the susceptibility to floating (section 2.4). The impact of four mulches on water availability was quantified in a glasshouse trial (Section 2.5), and representative samples of mulches were submitted to chemical testing (Section 2.6).

Figure 9 Tree Pit, Potaka Crescent, Panmure, shortly after establishment

2.2 Available mulches

Twelve mulches were considered for testing. These represented a wide range of potential mulches (Table 2). The majority selected were organic mulches, as these have the potential to float, and floating was the research focus. Most mulches were sourced in Auckland, with the exception of some mulches mixed with compost – these were manufactured in the laboratory. Commercial shredded bark and compost were available in Palmerston North, the location of the soil physics laboratory, where all floating tests was carried out.

Table 2 Potential raingarden mulches selected for testing in Phase 1 and Phase 2

Mulch	Rationale for testing
Arborist Mulch (fresh)	Widely available, low cost, and the base of many composts. Floats without pre-soaking on installation. Highly variable when produced in small volumes, depending on leaf: wood ratio and plant species. When made from garden waste it can contain soil, plastic, and noxious plants. Tree mulch may also include tree weed seeds (e.g., privet and acacia).
Arborist mulch (part-composted)	The degree of composting is variable. Resistance to floating increases with the extent of composting as material becomes denser and absorbs more water.
Arborist mulch & compost	Not commercially available at retail level. Retains the potential to introduce weeds, depending on source material for arborist mulch.
Bark nugget 20 mm	Not suitable as for raingardens. Included because this product is widely used (by mistake), and because it provides an upper boundary for float tests.
Double-shredded Bark	This is the closest to American triple-shredded mulch on the market. Triple-shredded mulch has been made in Auckland in the past. Small piece size and thin shape is influenced by the moisture content of the bark or wood and method of shredding (Ted Yates, pers. comm.)
Double-Shredded Bark & Compost	Not commercially available in Auckland. Tested as potential non-floating mulch using 20% v/v compost.
Shredded Bark & Compost	Product similar to non-floating, shredded, arborist mulch processed in Vertical Composting Units (VCU) successfully used on raingardens at Paul Matthews Road and Waitakere Civic Centre in 2006 and 2007. As the VCU plant in Henderson is closed, this product was sourced from Palmerston North.
Reharvest (Black)	Variable particle-size and shape depending on producer and location in stockpile (for bagged product). A variety of dyes are used with a range of colourfastness. Iron oxides have previously been used to colour the mulch, but not in Auckland; some are vegetable dyes (Ted Yates, pers. comm.).
Reharvest (Black) & Compost	Commercial product identified as being non-floating and suitable for raingardens.
Crushed Shell	Shell probably has lower thermal mass and higher reflectivity (where white) than dark-coloured stone so may be a more favourable option where heat may damage near-surface roots and inorganic mulch is wanted.

Mulch	Rationale for testing
Crushed Waste Shell	Crushed, processed, waste mussel shell. Trials have shown crushed mussel shells from processing plants increase pH and decrease soluble metals in stormwater; Product chemically tested but not included in float testing because it smelt 'rotten' so could not be used on a raingarden surface.
Limestone chip	Limestone has been shown to have a beneficial impact on acidic stormwater by raising pH until a rind forms on the limestone. Unlikely to contribute to plant nutrition.
Other inorganic mulches, Not tested	Non-reactive or weakly reactive mulches include all the main pebble and stone mulches used in raingardens and bioretention devices, and recycled glass.

The following listed mulches were tested in Phase One. Photographs of mulches, with coins for scale, are given in Figure 10.

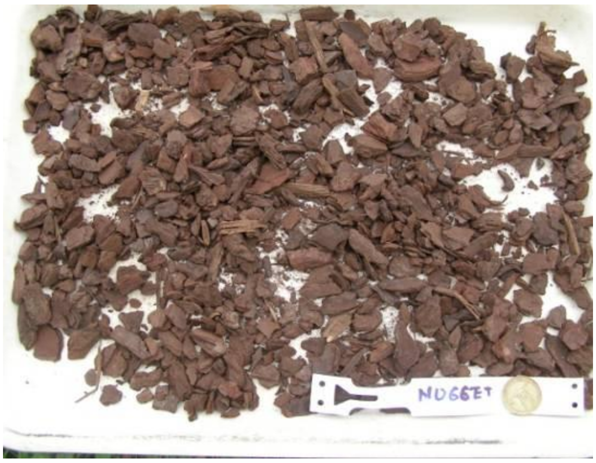
- Fresh Arborist mulch
- Aged Arborist mulch
- Bark nuggets
- Double-shredded bark (supplier A)
- Double-shredded bark (supplier B)
- Shredded bark and compost
- Reharvest Black
- Crushed shell
- Limestone chip

The following combinations of bark, or arborist mulches with 25% additional material were tested in Phase Two:

- Fresh Arborist mulch and 25% compost
- Double-shredded bark and 25% compost (bark based)
- Double-shredded bark and 25% compost (green waste-based)
- Reharvest and 25% compost 'as commercially delivered'
- Reharvest and 25% compost 'lab mixed'
- Double-shredded bark and 25% crushed shell

Double-shredded Bark mulch

Crushed shell (7 to 13 mm)



Bark nuggets (20 mm)

Arborist mulch ‘composted 8 weeks

Reharvest wood chip with 25%v/v compost

Arborist mulch with 25% v/v crushed shell

Figure 10 Inorganic and organic mulches characterized in this study.

2.3 Particle size

Mulch samples were taken from stockpiles or at least three bags of mulch were purchased. Where mulch samples were taken from stockpiles, samples were taken from four or five positions in the stockpile, excluding the drier, outside 200-mm layer, and shovelled into sacks. Two mulches were subsampled from 0.25 to 0.5 m^3 trailer-loads taken from stockpiles, and subsampled into sacks that were then sealed and sent to the laboratory.

In the laboratory, mulches were spread onto tarpaulins and thoroughly mixed. Three, 1-litre samples were oven dried at 105°C for 24 hours, and bagged for particle-size analysis. Stones in organic mixes were removed where observed. Sieve sizes represented ½ phi intervals from 45 mm to 63 microns. AS4454-2012 requires square sieve sizes with 5 and 16 mm grades used to define cut-offs for mulch and compost. Samples were sieved on a vibrating shaker using an 'intermittent' setting at amplitude of 1.5 mm for 5 minutes. Shell and limestone samples were sieved by hand to prevent sieve overload due to very narrow particle size range. Results for replicates were averaged for each mulch, then graphed as a line graph and a stacked bar graph of 'percent passing' sieve sizes. Error bars represent one standard deviation.

2.4 Floating tests

Floating tests were carried out in two stages. In the first stage, tests were carried out on air-dry, field-moist, and maximum moisture-content mulches. A second block of tests were carried out on mulches wetted to two intermediate moisture contents defined by hours of applied irrigation.

In stage one, mulches were tested at three moisture contents: field moist (as received), air dry, and maximum moisture content. Air-dry samples of between 5 and 10 kg were prepared by laying mulch to a depth of 80 mm in large trays and placing the trays in a forced-air oven at 35°C until moisture loss was less than about 50 g per day. This took 2 weeks for drier samples such as Reharvest and fresh arborist mulch, and up to 8 weeks for the wetter samples. Maximum moisture content was achieved by placing mulch in large, shallow trays, adding water to the level at which all mulch was submerged for approximately 14 hours (overnight), then draining for about 8 hours before re-soaking the following night. This was repeated over 3 consecutive nights. The aim was to mimic a raingarden being filled with runoff before draining. Raingardens are designed to pond (submerging mulch) for 12 to no more than 48 hours following a rainfall event. As inorganic mulches (shell and limestone) exhibit low variability in moisture content and have little ability to hold water they were only tested at the 'as delivered' moisture content.

Stage 1 testing showed that the moisture content of organic mulches was a critical factor influencing the extent of floating. Well-composted mulches had higher moisture contents and hence higher density. Stage 2 testing was therefore designed to explore each of these mechanisms further by float-testing five additional mulches, four of which contained added compost:

- Fresh Arborist mulch and 25% v/v compost
- Double-shredded bark and 25% v/v compost (bark based)
- Double-shredded bark and 25% v/v compost (green waste-based)
- Reharvest wood chip and 25% v/v compost 'as commercially delivered'
- Reharvest wood chip and 25% v/v compost 'lab mixed'
- Double-shredded bark and 25% v/v crushed shell

In stage two, mulches were tested at two moisture contents. The moisture contents were based on measuring the change in moisture content with increasing length of irrigation. Two mulches were tested, double-shredded bark and Reharvest wood chip. Each had 25% v/v compost added. Duplicate samples of approximately 100 mm depth were packed into cylinders (150 mm diameter), then irrigated for either 30 minutes or for 3 hours. Another set of duplicate samples were packed into cylinders (100 mm diameter), then soaked and drained in 8–16 hour cycles over 3 days, simulating ponding and drainage conditions in a raingarden. At the end of each treatment, mulch samples were allowed to drain freely for 2 hours before being weighed to determine water contents. Stage 2 floatability tests were then carried out on other mulches that were irrigated for 3 hours or for 6 hours. Six hours was considered a maximum practical irrigation duration.

Floating tests began by placing three representative samples of each mulch into three replicate crates. Each crate was 330 mm square, and contained 8–9 litres of mulch (75–80 mm depth). An overhead sprayer irrigated the mulch at 0.2 to 0.3 l min-1 (approx.140 mm hr-1) in a cone-shaped spray pattern that was not precisely even across the square crate, but wetted all areas of the mulch. Crates were then left for 7 minutes to drain before a subsample of mulch was removed from each crate to calculate oven dry mass. Crates were given a 'settling' by plunging fingers into the mulch to simulate a raking. After flattening the surface, the mulch mass and depth (target 80 mm depth) were measured. Water was then delivered by hose (at about 7 l min-1) over the whole sample for 30 seconds, then to one corner of the crate. The crate was allowed to overflow until no more material floated (1 minute). Any floating material was collected (this took up to 8 minutes) and weighed. Where large amounts floated (1–2 kg oven dry equivalent), a subsample was taken (about 1 kg wet weight) and oven dried to calculate the oven dry mass of material. Material that floated and spilled with the overflowing water was collected and oven dried. This was always a very small amount (usually < 1g).

2.5 Impact of mulch on moisture availability

A key reason mulch is used in landscaping is to conserve water during plant establishment by reducing evaporative losses from the soil surface. This increases the amount of water available for plant uptake. The impact of three mulches on water loss was quantified in a glasshouse experiment.

Individual mulches were placed into 10-litre buckets (170–200 mm base diameter, 250–260 mm top diameter, 10 litre capacity) to a depth of 80 mm. A single layer of coarse coco-fibre cloth was put at the bottom of each bucket to prevent fine particles washing through the pot base-holes. Mulches were placed either directly onto the cloth, or onto 150 mm of proprietary raingarden mix. The controls were two buckets with no mulch, i.e., just raingarden mix on coir mat. The buckets were saturated for 1 hour, drained for 2 hours, then weighed and placed in a glasshouse. The weight of each bucket was recorded every 1–3 days for nearly 3 weeks. The weight of two 'controls', a bucket with 80 mm of water, and a similar-sized 100-mm-deep container with 80 mm of water was also measured. A temperature probe was placed in one mulched bucket and ambient air temperature above this bucket also monitored. The mulch treatments were:

- Double-shredded bark
- Crushed beach shell 7/13 mm
- Reharvest 'Black' wood chip with 25%v/v compost
- Reharvest 'Black' wood chip (no compost)

All but the Reharvest ‘black’ treatment had two matching replicates of the same mulch placed over raingarden mix.

2.6 Mulch chemistry

Representative samples of each mulch were sent to the Environmental Chemistry Laboratory, Landcare Research. Each mulch was dried, and sieved, and the <2mm fraction ground for analysis. This fraction has the greatest biological and chemical impact, as it has the greatest surface area and is generally the fastest to break down. Analyses were chosen to allow comparison with earlier samples and to identify the primary characteristics that influence mulch breakdown and contribution to contaminant removal. Results are reported on a dry mass basis. The majority of soil chemistry test methods (pH, Total P, Total Cu and Total Zn) are after Blakemore et al. (1987), and briefly described on the Landcare Research website. Methods for testing Total Carbon and Total Nitrogen are after Leco (Laboratory Equipment Corporation, undated), also briefly described on the Landcare Research website: http://www.landcareresearch.co.nz/services/laboratories/eclab/eclabmethods_soils.asp.

3.0 Case studies

3.1 Mulch

The use of mulches in early Auckland raingardens was summarised by Mountford (2006). Raingardens were surveyed in this study to confirm the range of mulches used in raingardens constructed since Mountford's survey. Most sites had multiple raingardens, tree-pits or bioswales (vegetated swales used for infiltration and stormwater conveyance) over an extensive area. Different designs were sometimes present within a single site, e.g., Waitakere Civic Centre (now Auckland Transport). The raingardens ranged from new (under construction, e.g., Long Bay) to several that were over 5 years old. Some of these older raingardens had been re-mulched as part of on-going maintenance. Seven general findings can be drawn from the survey:

A wide range of mulch types and sizes are used in Auckland, from large stones and fine gravels to composted and non-composted organic materials. No sites used erosion fabrics or shell mulches. Most raingardens were initially constructed with non-floating or with minimally floating mulches (Figure 11, Figure 12 and Figure 13).

Raingardens with low plant cover or high weed cover after 24 months are vulnerable to being re-mulched with floating mulches. This risk is highest for raingardens located within larger landscaped areas in which decorative bark mulch is used, and for older raingardens where ownership or maintenance contracts have changed providers (Figure 13). Decorative bark typically has a high proportion of small, rounded pieces (minimal binding). This finding indicates that it is important to minimise the need for remulching. This can be done by achieving full plant cover within 24 months. The finding also indicates maintenance contracts need to identify, and differentiate raingardens from amenity landscaping and stipulate use of non-floating mulches in the raingardens.

Figure 11 New Lynn Town Centre bioswales are mulched with fine gravel and planted with jointed rush (Apodasmia similis), ōiōi.

The potential for mulch to move and/or float is reduced when runoff enters the raingarden as sheet flow (e.g., Potaka Crescent, Panmure, and Wynyard Quarter) or where many inlets and low gradients achieve low energy stormwater inflows (e.g., New Lynn Town Centre, Figure 11). Conversely, where runoff enters through inlets that create high energy inflows, even fine gravel mulches will move. Mulches that resist floating by binding weakly together, such as shredded fresh arborist mulch, are 'undermined' at inlets that concentrate water flows. Concentrated flow appears most common where only one or two inlets do most of the 'work', where inlets are narrow, or where inlets are poorly shaped so the flow is not evenly spread across the entire inlet.

A range of mulch depths was present, both within and between raingardens, but was generally <100 mm in depth in new raingardens. The greatest variability was associated with organic mulches, rather than with stone mulches. Stone mulches were rarely over 70 mm depth. Organic mulches tended to be deepest in older raingardens that had been re-mulched due to low plant cover. In cases this reduced the actual ponding volume below the design volume. Where plant cover was high, mulch had not been reapplied. In these cases mulch had completely decomposed as it had been incorporated into the raingarden media, e.g., Paul Matthews and the larger, linear Waitakere Civic Centre raingardens.

Figure 12 LEFT: Large rounded river-stone mulch in St Luke's bioswale. RIGHT: Crushed volcanic rock mulch in a bioswale, Stonefields.
Note the adjacent landscaping mulched with fine decorative bark mulch)

Large stone mulches do not appear to have a negative impact on plant growth (Figure 12). However, planting density was generally lower in raingardens that had large stone mulches, so development of full plant cover was delayed compared with raingardens that were more densely planted. The ability of *Apodasmia similis* to extend rhizomes through large stone mulches was not quantified, although rhizomes may be physically restricted.

Mulches were generally not visible over the majority of densely planted raingardens older than 24 months, as full plant cover had been achieved.

Weeds were generally concentrated in areas of sediment deposited at inflows and areas where mulch was thin or absent. Such areas were most common adjacent to edges, especially where raingardens had sloping sides.

The following table summarises the observations of mulches at the main raingardens and bioswales that were visited between November 2012 and May 2013 (Table 3).

Table 3 The mulches used in raingardens and bioretention swales surveyed in 2013

Raingarden Location	Mulch	Comment
Jellico Street Wynyard Quarter Raingardens	Fine gravel (c.4-8 mm), c.50 mm depth. Non-floating	Constructed August 2011. Highly urbanised area with high maintenance: weekly plant upkeep, daily litter removal and road sweeping. Mulch in isolated edge or corner areas has been covered with sediment or removed.
Waitakere Civic Centre, Waitakere Tree pits and raingardens	Composted shredded green waste. Non-floating.	Constructed about 2007. Office blocks with moderate maintenance: weekly removal of deciduous leaves from grates, removal of sediment at inlets, and annual trimming of shrubs and oioi along paths. VCU shredded green-waste spread to about 70 mm depth to supress weeds. Edges re-mulched in 2012 with decorative bark over-filled the raingardens. Bark mulch has floated and moved in places.
Waitakere Civic Centre, Waitakere Raingardens	Large rounded stones, 50 to c. 300 mm diameter	Stones placed in the larger raingardens, over the organic mulch. Now largely covered with plants.
Mountain Road Panmure Tree pits	Reharvest (+ compost?)	Constructed 2013. Variable depth. Mulch has washed away from inlets and steep sides towards centre, but minimal movement of mulch over majority of tree pit.
Potaka Crescent, Panmure Raingardens	Shredded bark	Constructed 2011/12. Thin layer of mulch (<30 mm) now present over majority of raingardens. Mulch has washed off raised root balls (c. 450 mm diameters) of large trees (and/or media has settled). Over most areas mulch is stable.
Talbot Park Estate, Tamaki Raingardens	Variety of organic mulches, some floating	Floating (decorative bark) and non-floating mulches used over 5 years in areas where ground-cover plants have not established. Movement of bark into bypass structures.
Stonefields Estate, St Johns Vegetated Swales	Large 70 mm+ crushed rock, non-floating	2010–2011. In many areas rock is now largely covered with groundcover (*Muehlenbeckia spp*).
St Kentigern School, Shore Road Raingardens	Variety of organic mulches, some floating	Constructed about 2010. Many small raingardens planted with pohutukawa. Decorative bark mulch applied to areas with poor plant growth. Small areas of bare media.
Judges Bay, Parnell Raingarden and swales	Angular rocks 20 to 150 mm diameter	Constructed about 2011. Six-cell raingarden with timber retaining walls. Low aesthetics due to uneven rock size, low planting density, plant selection and weed growth.
Morning Star Estate, St Luke's Raingarden	Rounded stones, 50 to c. 300mm diameter	Constructed about 2007. Terraced raingarden receiving water from grassed swales and permeable paving. Now reasonably well-covered with plants (*Apodasmia similis*, oioi) but has taken a long time as planting density was very low (0.5 plants m^{-2}). Organic wood-chip mulch has washed into the raingarden from adjacent landscaping and has moved.

Raingarden Location	Mulch	Comment
New Lynn Town Centre Raingardens and bioswales	Fine 4-8 mm diameter gravel, c.50 mm depth	Constructed 2012. Highly urbanised area. Minor movement of mulch and inflow of sediment near some inlets.
New Lynn Raingardens	Organic Mulch	Mulch no longer visible in the four large, terraced raingardens separated by gabion retaining walls due to dense ōiōi cover. Sediment and leaf inflow in second raingarden supports weeds. Decorative bark used in landscaping around upper raingarden has spilled/washed into edges of the raingarden but is trapped by plants, so unlikely to move.
Auckland Botanic Gardens, Raingarden and swale	Coarse-shredded green waste, gravel, coarse arborist mulch	Coarse-shredded green waste did not float but required handpicking to remove plastic contamination. Gravel spread on swale and coarse arborist mulch spread on adjacent landscaping area enter edges of swale but dense cover of plants prevents mulch movement.
Albany Bus way swales	Reharvest (possibly with compost)	Some movement of mulch down swales towards bypass structures where it was retained by erosion logs. The same mulch is used in large raingardens adjacent to Lucas Creek, where a small proportion has accumulated adjacent to the bypass structure.
Long Bay Subdivision	'Premium Forest Floor', non-floating when wet	Part-composted, shredded arborist mulch and 'fines' which binds when wetted (T. Sherson, pers. comm.). No floating observed in flooded raingarden.

Figure 13 LEFT: Waitakere Civic Centre raingardens with non-floating, shredded VCU mulch (2008). RIGHT: Tree pits remulched with floating, decorative landscaping bark (2013)
Note that the decorative bark prevents entry of stormwater

4.0 Results and discussion

4.1 Mulch

The potential mulches identified through visits and discussions with landscaping suppliers are summarised in Section 4.2. The rationale for selecting mulches for physical and chemical characterisation is given in Section 2.0. The results of particle-size analysis are given in Section 4.3; Section 4.4 reports results of float testing as the percentage of each mulch sample that floated at specified moisture contents. Results confirmed that a range of available options exist to minimise the potential for organic mulches to float. The impact of four mulches on water availability, as measured in a small glasshouse trial, is presented in Section 4.5. Results of a limited range of chemical analyses are given in Section 4.6. These include screening for potential metal contaminants.

4.2 Available mulches

The most common mulches in New Zealand landscaping are organic mulches derived from green waste, pine bark and recycled timber. Green wastes include arborist mulch. These are tree prunings that are generally free of soil, grasses and herbaceous plants. Green waste includes 'yard waste' which typically includes a higher proportion of leaves than wood together with roots, soil and weed contaminants, plastics (plant pots, labels and bags) and paper waste. In areas with a high proportion of deciduous trees, autumn green waste can be relatively consistent and clean. Such mulch is usually mixed with other green waste in Auckland, but may be available in large quantities in parts of the South Island, and specific areas, e.g. Christchurch Botanic Gardens.

The bark used in New Zealand and Auckland mulches is predominantly radiata pine, a by-product of the plantation timber processing industry. Bark is stripped before logs are milled, and broken off during log marshalling. This bark is collected at large marshalling areas such as major ports and railway yards, sold as a 'budget bark' product with a large, uneven individual piece size, or further processed. Processing can include shredding, grinding, composting, and/or sieving. High-quality ornamental mulches and specialised potting mixes based on processed bark are produced and exported by New Zealand companies. Pine needles are not commercially sold in New Zealand (Figure 14).

Figure 14 Mulches in North Carolina
LEFT long-needle pine 'straw' (photo courtesy Bill Lord) RIGHT triple-shredded hardwood bark, which is recommended for raingardens

Recycled untreated timber, i.e., wood chip, is the third common organic mulch used in New Zealand and overseas. The products from recycled timber such as packing cases are lightweight, and can be dyed a range of colours; red and black being most popular (Ted Yates, pers. comm.). The weight of recycled timber mulch favours application by blowing and this material has been used in large quantities on some Auckland Motorway Capital projects. Potential contaminants in recycled wood can include galvanised nails (zinc) and, to a lesser extent, plastics, depending on the source material; however, processing technologies are available to remove these contaminants and are used by some suppliers. Treated timber is unsuitable for use in raingarden mulches as the common preservatives are copper, chromium, and arsenic – all toxins to aquatic ecosystems.

Organic mulches produced as rolls or mats, living mulches or very short-lived mulches were not considered in this project. Mats or fabrics are generally used on only a small proportion of sites, or specific areas of a site with higher erosion risks. Mats and fabrics are expensive to purchase relative to loose mulches, and slow to plant through (adding cost). Fabrics need to be manually cut or separated to allow planting of nursery-grown plants. Some fabrics contain seed within the mulch, usually grass seed – these may be more cost effective to use as additional planting is not required. The permeability, resistance to clogging (by sediment) and erosion, weed suppression, and longevity of these products vary with the organic source (e.g. wool, felt, coco fibre, straw, paper fibre), weight, weave, and thickness. The wide variety of available mats, their cost, and the small volume used in raingardens mean they have not been included in this review. Large quantities of short-lived straw and hay mulches are used in earth-works for erosion control but are not used in raingardens.

Living mulches – also known as green or standing mulches – are usually annual plants (e.g., lupins, mustard). Living mulches may also be seeded grasses. Green mulches may be treated with herbicide or dug into the surface to provide temporary erosion control and suppression of weeds. They are common in some market gardening and revegetation projects. Living mulches have mainly been used in raingardens in the form of pre-grown turf mats. Such mats provide a temporary cover that protects underlying raingarden media and provides an aesthetically acceptable look prior to planting with the long-term plants.

Inorganic mulches are used for raingardens in Australia, where gravel and pebble mulches are common. The most common inorganic mulches used in Auckland raingardens are aggregates produced by the quarrying industry. Aggregates range from 4 mm diameter washed gravel to >200 mm diameter rocks, and include basalt, scoria, alluvial gravels (typically ex Waikato River deposits), and greywacke/argillites. Although limestone mulches have not been used in many Auckland raingardens to date, limestone chip was used in a gold-award-winning display garden at the Ellerslie International Flower Show in 2007, when the show was held at the Auckland Botanic Gardens (Figure 15). Recycled brick can also be used as mulch. Depending on the source of clay, its porosity and volume of attached mortar (which is alkaline), recycled brick can be chemically active mulch. It too has been used at an Ellerslie International Flower Show exhibit in 2012.

Figure 15 Raingarden with limestone chip mulch
Ellerslie International Flower Show 2007 designed and installed by Unitec landscape architecture students.

Common types of mulches sold by landscape suppliers in Auckland are given in Table 4. Products from different manufacturers are usually subtly different, particularly with respect to particle size; with arborist mulches having the highest variability. The moisture content (and therefore weight) of most organic mulches also varies through the year with weather conditions and product, even in bagged products. Aggregate prices are generally higher for products that are processed to achieve an even size and/or low proportion of fines.

Table 4 Description and cost of common mulches sold in Auckland (February 2013)

Mulch	Description	Approx. cost, $ m^{-3}
Arborist Mulch, Forest Floor	Not composted. Density, particle size and shape depend on machinery, vegetation species, moisture and leaf content	30–50
Composted Green waste Mulch	Finer particle size, although can be sieved to remove fines (compost), or compost may be added to increase plant nutrition	80
Wood chip, Reharvest	Dyed red, black or brown, or undyed	90
Wood chip and compost	Mixture of two recycled materials with compost providing plant nutrition	110
Bark nuggets (Decorative bark)	Rounded, even fragments available in a variety of grades and sizes (15–50 mm)	90
Shredded fine bark	Linear fragments, often with a higher fines content, also decorative	80

Mulch	Description	Approx. cost, $ m^{-3}
Coarse Bark or Cambium Mulch	Large piece size, not decorative at small scale	70
Crushed shell	From beaches, several grades available	160–190
Limestone chip	Quarried, several grades are available	180–200
Pebble >4 mm	Quarried; finer products are generally cheaper; South Island uniformly coloured stone can be $250–300 m^{-3}	140–170

[1] Some synonyms are given

4.3 Particle size

The tested mulches had a wide range of particle sizes. Washed or screened products, such as bark nuggets and limestone chips, had a very low percentage of material less than 2 mm diameter. Most mulches, whether based on shredded bark or arborist mulch, had between 30% and 40% by weight comprising particles <4 mm diameter, when dry. The two Reharvest wood chip samples from different manufacturers had a similar proportion of particles in the <4-mm range, but one had a higher proportion of coarse particles, with nearly ⅔ of particles being 8–16 mm in diameter compared with ⅓ in the other sample (Figure 16, Table 5).

All mulches tested are fine mulches based on AS4454 (Australian Standard, 2012), as all had more than 80% by mass <16 mm diameter). Only bark nuggets and limestone chips had less than 20% by mass <4 mm diameter. Both arborist mulches and Reharvest wood chips had about 20 % by mass (17 to 21%) comprising particles <2 mm. The three shredded bark products had a broadly similar size distribution and the highest proportion of fines, between 26 and 32% by mass. In general, a high fines component creates a moister, more favourable growing environment and reduced effectiveness at supressing weeds.

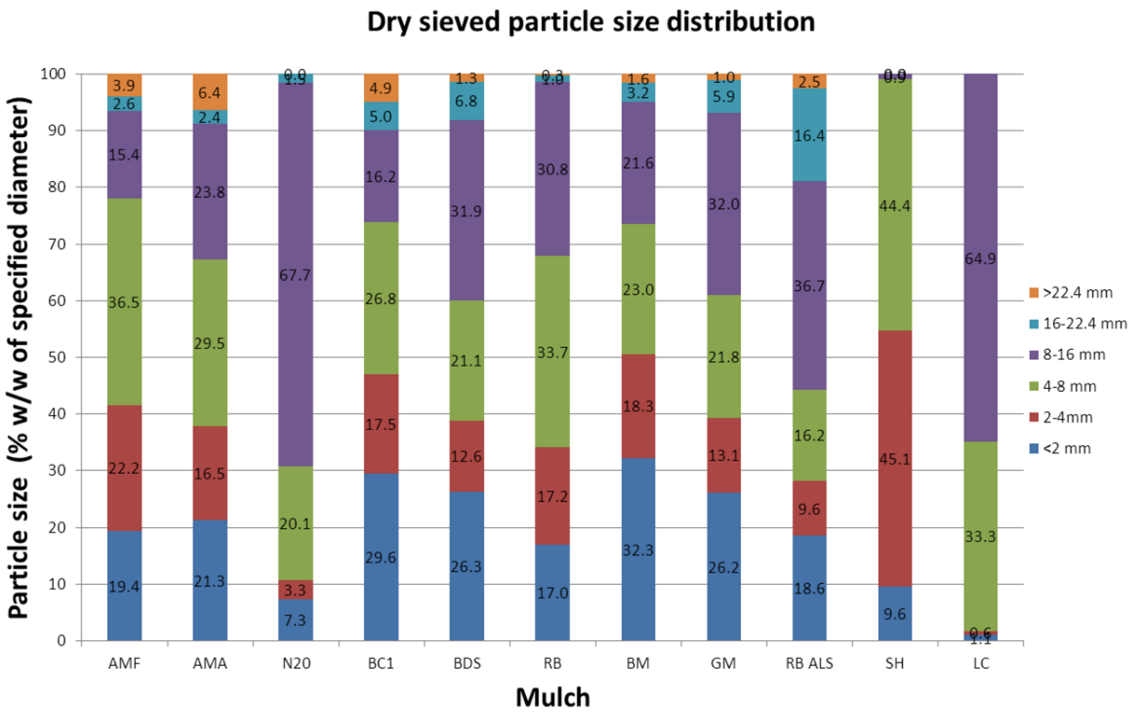


Figure 16 Dry-sieved particle distribution for tested mulches (% w/w, mass).

Note: AMF – Fresh Arborist Mulch, AMA – Aged Arborist Mulch, N20 – 20 mm diameter Bark Nugget, BC1 – Composted Shredded Bark, BDS – Double Shredded Bark from manufacturer 1, RB – Reharvest from manufacturer 1, BM –Double Shredded Bark from manufacturer 2, GM - Garden Mulch from sieved, composted green waste, RB ALS – Reharvest from manufacturer 2, SH – Crushed Shell, LC – Limestone Chip)

Table 5 Dry-sieved particle distribution for tested mulches (% w/w, mass)

Mulch	**Particle Size Distribution (% mass. dry sieved)**					
	<2 mm	**2–4 mm**	**4–8 mm**	**8–16 mm**	**> 16 mm**	**<4 mm**
Fresh Arborist Mulch	19.4	22.2	36.5	15.4	6.5	41.6
Aged Arborist Mulch	21.3	16.5	29.5	23.8	10.8	37.8
Bark Nuggets (20 mm)	7.1	3.3	20.1	67.7	1.5	10.4
Composted Shredded Bark	29.6	17.5	26.8	16.2	9.9	47.1
Double Shredded Bark M1	26.3	12.6	21.1	31.9	8.1	37.9
Double Shredded Bark M2	32.3	18.3	23.0	21.6	4.8	50.6
Reharvest M1	17.0	17.2	33.7	30.8	1.3	34.2
Reharvest M2	18.6	9.6	16.2	36.7	28.9	28.2
Crushed Shell	9.6	45.1	44.4	0.9	0	54.7
Limestone Chip	1.0	0.6	33.3	64.9	0	1.6

4.4 Float testing

Stage One float testing confirmed that two factors control the potential of mulch to float – the most important factor being bulk density. Mulches with a bulk density greater than 0.5 Tm^{-3} generally had a low proportion of floating material (Figure 17). Inorganic mulches such as shell and limestone chip have high bulk densities that are independent of moisture content because they absorb very little water, so they never float. In contrast, the bulk density of organic mulches varied with moisture content (Table 6).

All organic mulches tested (fresh and 8-week composted arborist mulch, shredded bark, and Reharvest wood chip) floated when air-dry (8–14% w/w/ moisture content, Table 6) and when 'as received' bulk density was <0.5 Tm^{-3} (moisture content <100% w/w). The shredded-bark and compost product had a bulk density of 0.51 Tm^{-3} 'as received' and did not float. When the organic mulches were soaked overnight for three consecutive nights, to achieve moisture contents >180% w/w, the proportion of floating material dropped to between 0.3 and 8% v/v. Although decorative bark nuggets (20 mm diameter) reached a bulk density of 0.61 Tm^{-3} after three nights of soaking, 20% v/v floated. This product has an oval piece size that minimizes the potential for binding.

Materials that are more decomposed, or contain decomposed material, can generally hold more moisture, so have a higher moist bulk density and are less prone to floating. These materials also took a longer time to dry, i.e. in the field they would be expected to stay within a 'non-floating bulk density' for longer. Field observations indicate the risk of an organic mulch floating is greatest in the first few storms after spreading (Bill Lord, pers. comm.). This is consistent with a relatively rapid increase in bulk density due to an increase in moisture content. In addition mulches containing finer materials with lower C: N ratios (such as the leaf component of arborist mulch) will more rapidly decompose. The rate at which organic mulches dry should be slower when pore spaces are smaller and less continuous; finer mulches are likely to be more resilient to floating than coarser mulches due to a higher moisture content. Thinner, smaller shapes are also more likely to compress or compact over time, hence maintaining a higher moisture content (i.e. higher bulk density) and also increasing resistance to scouring and floating. Mulches must, however, maintain a higher permeability than the underlying raingarden media.

Thinner, stringy particle shapes also bind more effectively than short, rounded particle shapes. However, if the binding is disrupted, for example, around by high-energy raingarden inflows, sections of mulch may be broken away and float. Physical locking is important for raingardens and bioswales in which significant horizontal water flows (energy) occur. In most of these situations an inorganic mulch or erosion fabric would be specified. The binding of organic mulches to underlying soil is increased by creating a rough, underlying surface and/or 'by crimping' (pressing long-fibred mulches such as straw into the surface in a herring-bone pattern) (Smets et al., 2008).

Table 6 Phase 1 Results of float testing organic and inorganic mulches at three moisture contents.

Mulch **Dry bulk density,Tm^{-3}**	**% Floating at 'air dry' moisture content**	**% Floating at 'as received' moisture content**	**% floating at 'fully wetted' moisture content[1]**
Crushed Shell ***1.00 ± 0.3, n=3***	n.a.	***0 (4% moist)***	n.a.
Limestone chip ***1.43 ±0.01, n=3***	n.a.	***0 (1% moist)***	n.a.
Arborist Mulch (fresh)[2] 0.20 ± 0.01, n=9	100 ± 0.2 (8% moist)	91 ± 5 (59% moist)	***0.6 ± 0.2 (184% moist)***
Arborist mulch (composted) 0.21 ± 0.01, n=10	96 ± 5 (14% moist)	81 ± 2 (88% moist)	***2 ± 0.8 (193% moist)***
Bark nugget 20 mm 0.26 ± 0.01, n=9	95 ± 1 (10% moist)	77 ± 2 (85% moist)	20 ± 6 (154% moist)
Double-shredded Bark (commercial) 0.25 ± 0.01, n=9	85 ± 3 (15% moist)	84 ± 5 (58% moist)	***8 ± 5 (181% moist)***
Shredded Bark & compost (commercial) ***0.17 ± 0.01, n=9***	91 ± 1 (13% moist)	***0.4 ± 0.1 (200% moist)***	***0.3 ± 0.1 (275% moist)***
Reharvest (Black) 0.19 ± 0.01, n=9	99 ± 0.5 (10% moist)	86 ± 5 (76% moist)	***4 ± 1 (194% moist)***

[1] 3 days saturation

[2] Tends to form a mat that can release more floating material if disturbed

[3] ***Bold font and italics*** indicate results where a low proportion of mulches floated;

[4]n.a. indicates the test was not carried out as inorganic mulches show minimal variation in moisture content

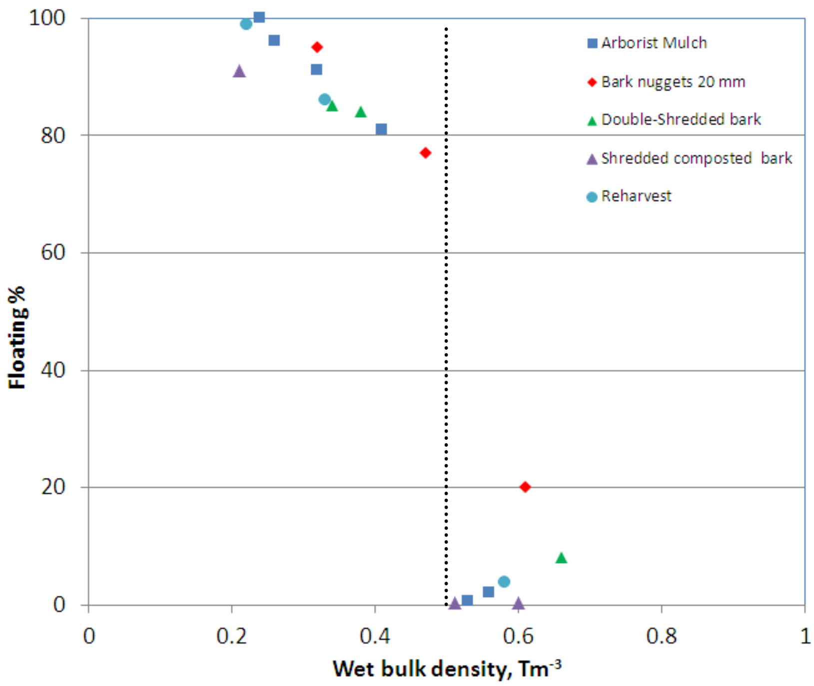


Figure 17 Results of Stage One mulch testing.

The dotted line indicates a critical bulk density at which floating is minimized. Each point is the mean of three replicate.

Stage Two testing compared the floating potential of organic mulches to which 25% v/v compost was added to quantify to what extent this mitigated floating. Compost was added to the each of the generally available mulches: arborist mulch, Reharvest wood chip, and double- shredded bark. A Reharvest/compost blend commercially available in Auckland was tested in addition to a laboratory-mixed blend. The efficacy of crushed shell was compared with compost. Floating tests were conducted at two moisture contents achieved by irrigating each mulch blend for three or six hours. Non-composted arborist mulch was selected for this test because it is the cheapest organic material (c. \$30–40 m^{-3}), and shell is one of the most expensive mulches (c. \$200 m^{-3} retail); a 4:1 mix therefore brings the cost to within the range of more highly-processed bark and Reharvest products.

The addition of 25% shell to arborist mulch prevented floating (Table 7, Figure 18). However, evenly mixing shell through the organic mulch by hand took time (10 minutes), and it was noted that over time the shell appeared to settle to a greater degree than did the arborist mulch. This may increase the risk of floating material in the short term if the arborist mulch is slow to wet to bulk density >0.5 Tm^{-3}. It may be as cost-effective, and more aesthetic (see Figure 9), to spread a thin sheet of shell (or other heavy inorganic material) over an organic mulch than to blend the products. Adding shell to organic mulch is likely to benefit the chemical performance, and could be useful to buffer the more acidic bark mulches.

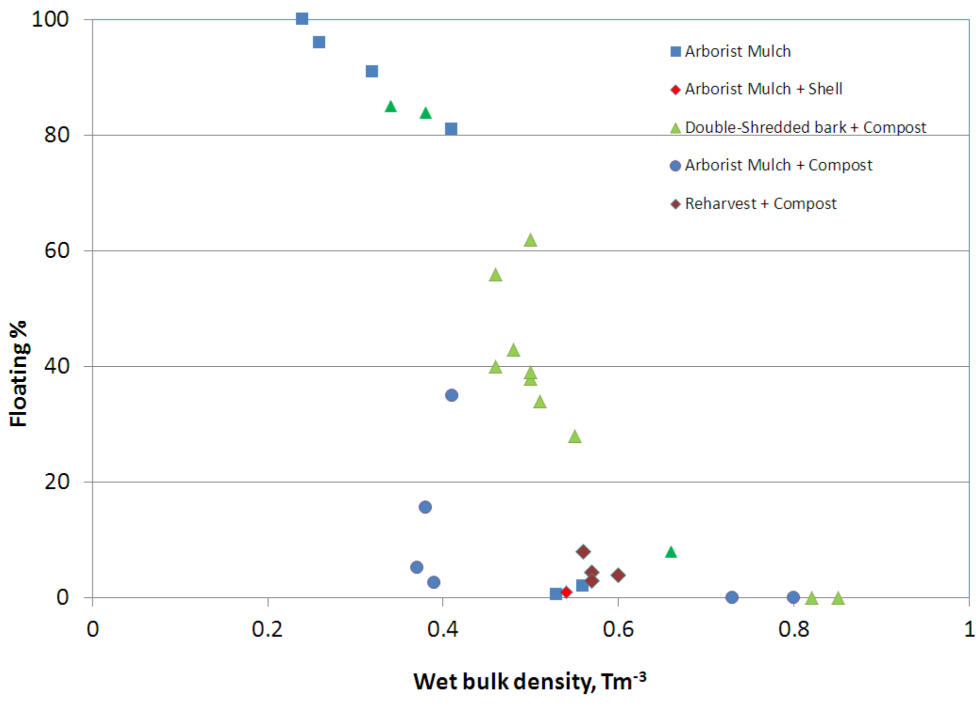


Figure 18 Results of Stage Two mulch testing.
Each replicate of mulches with added compost are given as the variability was relatively high for two mixes (double-shredded and arborist mulches with compost)

Adding 25% v/v compost to Reharvest wood chip or Arborist mulch and irrigating for six hours reduced the proportion of floating material to between 4 and 9 % v/v on average (Table 7, Figure 18). The primary mechanism increases the maximum water holding capacity (density) of the mulch. The addition of compost probably also increases the rate of wetting (and increase in density). The effects of adding compost were consistent for Reharvest wood chip but unacceptably variable for the Arborist mulch.

The effect of adding compost to shredded bark was also unacceptably variable. In addition a longer soaking time was required, as neither three, nor six hours wetting of both bark/compost mixes was sufficient to prevent an unacceptable proportion of the material floating. Both the variability and overall effectiveness of adding compost was probably influenced by the architecture of the bark. The double-shredded bark was still coarse enough to create many paces into which compost could wash to the base of the layer where it is less effective. It is likely that finer shredded bark would be a more suitable base material. Part-composted, shredded bark mulches are also likely to be less prone to floating and more responsive to compost, as they would have higher initial moisture content and wet more quickly.

Table 7 Phase 2 Results of float testing at three moisture contents.

Mulch	**% Floating at 3 hrs spray' moisture content**	**% Floating at 6 hrs spray'**	**Maximum = 'fully wetted' moisture content[1]**
Arborist Mulch (fresh) + 25% compost (lab)	20 ± 21 (155% moist)	***9 ± 9 (156% moist)***	184% (maximum content without compost = 262%1)
Reharvest + 25% compost (commercial)	***6 ± 3 (136% moist)***	***4 ± 1 (141% moist)***	239% (maximum content without compost = 194%)
Double-shredded bark + 25% compost A (lab)	33 ± 7 (160% moist)	37 ± 4 (154% moist)	287% *uneven wetting* (max content without compost = 181%)
Double-shredded bark + 25% compost B (lab)	51 ± 16 (164% moist)	50 ± 10 (176% moist)	255% *uneven wetting*
Crushed Shell	***n.a.***	***0 (4% moist)***	n.a.
Arborist Mulch (fresh) + 25% shell (lab)	n.a.	***1 ± 0 (31% moist)***	166%

[1] as this test took place three months after the original tests, maximum moisture content is different from the value in Table 6 as fresh arborist mulch was collected.

[2]***Bold font and italics*** indicate acceptable results. (lab) identifies mixes created by hand in the laboratory.

4.5 Impact on moisture availability

The trial was carried out in late February and March 2013, which was a warm summer. The mean daily ambient shade house temperature at midday was 24.8°C (range 21–28°C), and the mean temperature of the mulched raingarden mix was 19.9°C at midday (range 17–22°C). Under these conditions in the shade house, evaporation from the open containers was 1.51 mm day^{-1} in the bucket and 1.58 mm day^{-1} in the shallow tray, representing the 'mulch-only' treatment.

A shade house location was required to prevent any rainfall entering pots during the experiment. In a shade house, evaporation was likely reduced compared with outdoor conditions. This is due to lower radiation, lower temperatures and less air movement (a larger boundary layer above the mulch). The performance of mulches is reported as a percentage of the maximum evaporation values as measured in the water-filled containers (Table 8, Table 9).

All mulches reduced evaporative losses from the raingarden media (Table 8). The most effective mulches over the whole 18 days and 2–18 days period were shell (45% of maximum) and double-shredded bark mulch (50% of maximum). Reharvest + compost was slightly less effective (66% of maximum). This was probably due to its finer texture allowing 'wicking' movement of water from the moist raingarden mix up into the mulch, combined with the high moisture-holding capacity of this mulch. However, over the first two days the coarse-texture of the shell and bark mulches provided greater surface area from which evaporation could occur while the mulches were still moist – under these conditions the Reharvest has lower evaporative losses.

Table 8 Average water loss as a proportion of evaporation from open water (%) for mulched raingarden media.

Treatment	Unmulched Mix	Double Shredded bark	Reharvest + Compost	Shell
Total over first 2 days	152	168	119	232
Loss over 3–18 days	81	36	60	23
Total, 1–18 days evaporated	88	50	66	45

[1] As there were only two replicates, standard deviations are not provided

Removing the raingarden media showed how the mulches dry without the potential upward movement of moisture from the raingarden media (Table 9). The impact of water-holding fines is shown by comparing the two mulches containing Reharvest. More than twice the volume of moisture is retained in a 3–18-day period in the absence of compost. Shell, Reharvest, and Bark mulches are similarly moisture conservative.

Table 9 Average water loss as a proportion of evaporation from open water (%) for raingarden mulches

Treatment	Reharvest	Double Shredded bark	Reharvest + Compost	Shell
Total over first 2 days	105	85	77	44
Loss over 3–18 days	18	25	41	15
Total, 1–18 days evaporated	25	20	45	18

[1]As there were only two replicates, standard deviations are not provided

4.6 Mulch chemistry

Representative mulch samples were analysed. Tests were performed on the <2 mm-fraction of the compost which formed about 20–30% of each organic mulch, other than bark nuggets (7% w/w). , The <2mm fraction has the greatest impact on chemistry in the short term. All mulches had 40–50% total carbon and organic carbon. Most mulch had low concentrations of nitrogen (Table 10), as is typical of products based on bark and wood that are designed to supress weeds. The arborist mulch has moderate concentrations of N due to the leaf content. This speeds the decomposition rate of mulch, shortening its life.

When shaken with water, both bark mulches, and particularly the coarsest bark, had low pH values and could potentially contribute to acidification of raingarden media, particularly to media with a low buffering capacity (low percentage of clay and silt and/or low organic matter content). Crushed beach shells, crushed mussel waste, and green waste compost were alkaline (pH >7.5), so would act to neutralise and mitigate acidification. A circum-neutral pH is valuable as it reduces the solubility of metals, particularly zinc. The crushed mussel waste also contributes significant nitrogen and phosphorus compared with the clean beach shell; however, the drawback is an unpleasant odour, at least in confined spaces, while the proteins decompose.

When compost is added to mulches to increase resistance to floating, the pH and concentration of available nutrients (N and P) increase. This is because composts have higher concentrations of nutrients and pH than the mulches. This is likely to speed decomposition of organic mulches and reduce or avoid plant nitrogen stress that can occur when microorganisms that break down mulch extract nitrogen from soils with low N levels. If raingarden substrates already contain moderate to high nutrient levels, or decomposing carbon, the addition of more N may result in N leaching.

Table 10 Basic chemical properties of a representative range of mulches.

Mulch	**pH**	**Total C (%)**	**Organic C (%)**	**Total N (%)**	**C/N ratio**	**Total P (mg/kg)**	**Total Cu (mg/kg)**	**Total Zn (mg/kg)**
Double-shredded bark	4.10	42.2	42.3	0.30 UR	141	400	***15***	69
Reharvest Black + compost	***7.64***	27.7	25.9	1.87 UR	14	3730	68	190
Reharvest Black	6.54	50.2 OR	49.0	0.48 UR	103	194	151	127
Arborist Mulch	6.05	49.2 OR	45.1	1.40	32	1710	***15***	85
Crushed beach shell	***8.52***	11.5	1.83	0.01 UR	127	63	***1***	***2***
Fine Shredded Bark	5.49	48.0 OR	45.3	0.34 UR	134	307	***7***	***42***
Crushed mussel waste	***7.87***	11.9	3.77	0.40	9	258	***2***	***4***
Green waste compost	***7.79***	25.2 OR	25.5	1.98	13	3830	74	193
Pine bark compost	6.12	35.7 UR	32.3	1.38	23	5560	59	143

[1]Results marked 'OR' are above the confirmed validation range of the LECO Trumac analytical machine;
[2]Results marked 'UR' are below the validation range.
[3]Although accuracy of UR and OR results cannot be guaranteed, the consistency of differences between Total C and Organic C for for organic mulches accuracy within 3%, UR results for nitrogen are very low, therefore C:N ratios are approximate. However, all the relevant C:N ratios are very high, so have similar biological impact, with the exception of Reharvest+compost..
[4]***Bold font and italics*** indicate particularly favourable properties

In Auckland, heavy metals in stormwater runoff, particularly zinc and copper (Timperley et al., 2005), have been identified as primary pollutants of concern. Raingardens have been shown to reduce these contaminants through reducing both the volume of stormwater discharged and the concentrations of contaminants, although the efficacy varies. Regardless, zinc and copper concentration in mulches used in raingardens should be low.

Three standards may be considered relevant: the New Zealand biosolids guidelines; NZ Compost Standards; and Auckland Contaminated Land Rules (Table 11). Biosolids meeting the NZ biosolids guidelines for Grade Aa ('grade a' post-2012 values) are recommended for use without resource consent. NZ4454 (Compost New Zealand, 2005) “Composts, Soils and Soil Conditioners” provides a voluntary standard for compost production to minimise the potential for “these products to present a risk to the environment or public health”. Contaminated land rules in the Proposed Auckland Regional Plan: Air, Land and Water (2001) (Auckland Regional Council, 2001)(PARP: ALW) provide a regulatory framework for management or remediation of contaminated land to a standard based on protection of human health and the environment.

Table 11 Copper and zinc guideline values and standards used in New Zealand

Metal	NZ Compost Standard 4454:2005 (mg/kg)	Biosolids Grade A (mg/kg)	PARP: ALW Schedule 10 (mg/kg)	Auckland background Soil Levels (mg/kg)
Copper	300	100	325	1–45
Zinc	600	600	400	9–179

[1]Values are for composts, biosolids, and discharges to land, compared with background Auckland volcanic soil concentrations (Auckland Regional Council 2001)

All the mulches and composts tested had Cu and Zn concentrations well below maximum NZ Compost standard values (Table 10). Zinc concentrations in most products were within the background range for volcanic soils in Auckland. Reharvest +compost (190 mg Zn kg^{-1}) and compost manufactured from greenwaste (193 mg Zn kg^{-1}) were slightly above the reported Auckland volcanic soils maxima of 179 mg Zn kg^{-1}. Bark and arborist mulches had low metal concentrations: <20 mg kg^{-1} Cu and <100 mg kg^{-1} Zn. The Reharvest Black mulch tested also had Cu concentrations that exceeded the Biosolids grade A guideline values, Adding 25% compost lowered the Zinc concentrations of Reharvest Black but could be expected to increase overall metal concentrations in mulches based on bark and arborist prunings. Further testing of Reharvest from different suppliers and of colours other than black would be useful. The >2mm fraction, should also be tested, as this formed about 80% of the product and testing would indicate if the <2mm fraction is representative of concentrations in the entire particle size range.

Figure 19 LEFT: Long Bay subdivision raingardens RIGHT: Raingardens adjacent to Lucas Creek
Long Bay subdivision raingardens are mulched with non-floating, organic mulch derived from shredded, composted arborist prunings. Organic mulch based on Reharvest (recycled wood chip) in raingardens adjacent to Lucas Creek that receive runoff from the Albany Bus way car parks.

5.0 Summary

Many raingarden and bioretention construction guides specify the placement of a mulch layer over the surface of bioretention devices for three reasons: to supress weed growth; to enhance plant moisture supply, and; to reduce the risk of short-term sealing or crusting of the media. Sealing and crusting reduces raingarden infiltration rates and may be caused by breakdown of raingarden substrate, and deposition of fine sediments. Enhancing water available for raingarden plants is particularly important during the establishment phase when plants have small root systems, and when raingardens are planted in summer. Suppression of weed establishment reduces the maintenance required to control weed competition with selected plants and retain desirable aesthetics. Mulches used in raingardens must not float, as this can expose or erode the underlying media, block overflows, and contaminate receiving waters. This report reviewed bioretention mulches used in New Zealand and overseas. The characteristics of organic mulches that confer a low potential to float were identified.

A wide range of organic and inorganic mulches are available in Auckland. Organic mulches are based on radiata pine bark, fresh green waste or wood waste. Radiata pine bark is a by-product from the plantation forestry industry. It is salvaged from timber processing plants and log marshalling areas. Pine bark is used composted, shredded, ground or sieved to various sizes, shapes, and grades. Pine bark is shredded, composted and sieved to create high-quality composts for growing media. It may be ground and sieved to create even-sized decorative bark ‘nuggets’ for landscaping, or minimally-processed and used to supress weeds over large areas of landscape (so-called ‘cambium bark’). Green waste can be divided into soil, weed, and contaminant-free, arborist (tree) prunings, and ‘yard’ waste. Both arborist mulch and yard waste are converted into a range of products using composting and sieving. Wood chip, known as ‘Reharvest’, is manufactured from recycled, untreated wood waste such as packing cases. Arborist mulches with low leaf contents can have similar properties to Reharvest wood chip. Two organic mulches have been commercially produced as non-floating mulches for raingardens. One is based on Reharvest, the other on composted, shredded arborist mulch. Non-floating, shredded, bark-based mulch was identified in Palmerston North but an equivalent product was not able to be sourced in Auckland. The fine, stringy organic mulches based on fibrous tree barks (e.g. redwood) or long pine needles used in USA raingardens are not currently available in Auckland.

A representative range of organic and inorganic mulches were tested for floating. Floating was quantified at moisture contents ranging from air dry to ‘maximum moisture content’. Maximum moisture content was achieved by three cycles of saturation and drainage over three consecutive days. It was designed to simulate raingarden ponding and drainage. Two factors control the potential of mulch to float. The most important of these is moist bulk density. The second is the extent of binding or knitting of particles. Inorganic mulches such as shell and limestone chip do not float as they have dry bulk densities of around 1 Tm^{-3}. These mulches absorb very little water. Particle shape does not impact their floating performance. In contrast, all organic mulches had oven-dry bulk densities less than 0.26 Tm^{-3} and had a high propensity to float at air-dry moisture contents. Air dry bulk densities varied from 0.21 to 0.32 Tm^{-3}. However, the proportion of floating material dropped to between 0.3 and 8% v/v and bulk densities increased to over 0.52 Tm^{-3} when most organic mulches were at maximum moisture content. This made them suitable for use in raingardens. The exception was 20 mm decorative bark nuggets. About 20% v/v of decorative bark nuggets floated at the maximum moisture content. These nuggets absorb water slowly and their round shape means they bind poorly.

Two organic products did not appreciably float at lower moisture contents. Shredded-composted bark product with added compost was the only organic product that did not appreciably float (0.4% v/v floating) at an 'as delivered' moisture content, giving a wet bulk density of 0.51 Tm^{-3}. Commercially-available Reharvest wood chip with 25% v/v added compost was also highly resistant to floating after minimal wetting (wet bulk density 0.52 Tm^{-3}) achieved by 3 hours of irrigation. A lower rate of irrigation was not trialled.

The ability of organic mulch to absorb water is linked to the extent of decomposition or composting, the type and particle size of organic matter. Absorbance varies with the organic source. Arborist mulch and wood chip absorb water more readily than coarse pine barks. More decomposed mulches, or those containing a significant proportion (20–25%) of decomposed material (such as compost) are less prone to floating when moist because they are heavier. Composted materials take longer to dry than uncomposted materials. This means they can be expected to stay within a 'non-floating bulk density' in the field for longer. Field observations indicate the risk of an organic mulch floating is greatest in the first few storms after spreading. This is consistent with a relatively rapid increase in mulch bulk density due to both an increase in moisture content and, for finer materials with lower C: N ratios (such as arborist mulch), to increased decomposition. The rate at which organic mulches dry should be slower when pore spaces are smaller and less continuous. Finer mulches, and mulches with a variation of particle sizes (allowing packing or compression) are therefore likely to be more resilient to floating than coarse, or uniformly sized mulches (e.g., bark nuggets).

Three methods can be used to supress floating of organic mulches. First, 25%v/v crushed shell or compost can be added. Adding 25% crushed shell to arborist mulch prevented floating. However, evenly mixing shell through the organic mulch by hand took time (10 minutes). Also, over time the shell appeared to settle to a greater degree than the arborist mulch. This may increase the risk of floating material in the short term if the arborist mulch is slow to wet to an adequate bulk density. It may be as cost-effective to spread a thin sheet of shell (or other heavy inorganic material) over an organic mulch rather than to blend the products. Adding shell to organic mulch, particularly the more acidic bark mulches, is also likely to enhance the mitigation of contaminants such as metals.

Adding 25% v/v compost to either Reharvest wood chip or Arborist mulch and irrigating for six hours reduced the proportion of material floating to between 4 and 9% v/v. The primary mechanism that reduces floating is increased wet bulk density by increasing the maximum water-holding capacity of the mulch. The rate at which the compost component wetted also appeared to increase. Adding compost to double shredded bark is not consistently effective. Both three and six hours wetting of both bark / compost mixes was not long enough to prevent an unacceptable 50% v/v of the material floating. This appeared to be because the architecture of the bark creates large gaps into which compost is washed away from the surface. It is therefore likely that much finer shredded barks would be a more suitable base material. Part-composted bark mulches are also likely to be more effective, as they have higher initial moisture content and wet up more quickly.

Second, mulches can be composted to a level that increases the wet bulk density and speed of wetting. The impact of a higher proportion of fines, from either adding compost or breakdown during composting process on the effectiveness of weed suppression was not quantified. However, adding compost or using part composted material enhances the nitrogen (N) and phosphorus (P) levels. This helps avoid plant N stress, which can temporarily impact plant growth as organic mulches with low N concentrations decompose. N stress is most likely if raingarden media has low organic matter content.

Table 12 Summary of Mulch Properties.

Mulch Property **+ = positive outcome, o = neutral outcome** **-- = negative outcome**	**'no-fines' Shredded Bark + F**	**Wood chip / Reharvest + F**	**Arborist Mulch + F**	**Crush Shell**	**Active Gravel (lime, scoria)**	**Inert Gravel / glass**
Do not contribute floating material Result depends on moisture content and % fines for organic materials (+ when wet, - when dry)	-- to +	-- to +	-- to +	+	+	+
Supress weed growth to decrease maintenance and enhance aesthetics	Dependant largely on depth & piece size of mulch, and weeds present – 30–80 mm adequate					
Maintain infiltration rate into soil by reducing crusting, avoiding surface degradation or blocking with sediment	+	+	+	+	+	+
reducing runoff by absorbing rain[1]	+	+	++	O	o	o
c) cushioning against soil compaction	++	++	+	o to +	o	o
Feed plants – short /long term	-	-	+	o to +	-	-
Conserve moisture and reduce soil surface temperatures	++	++	++	+	+	- to +
Absorb, immobilise or buffer contaminants : (filter, pH-precipitate, chemically bind)	++	++	++	+ to ++	+	-
Do not contribute excess/bioavailable chemical or biological contaminants Cu, Zn, pathogens	+	+ Colour?	+	- to +	+	+
Ease of spreading	+ to –[3]	++	++	+	+	+
Longevity (>12 months) influenced by piece size for organic mulches	++/+	+[4]	-	++	++	++
Consistency of product [5]	+	+	-	++	++	++

[1]absorbing water allows higher infiltration, surface evaporation and plant-available water
[2]P and Cu variable (P can act as a chemical binder); N depending on C: N and activity of micro-organisms
[3] depending on the piece size; coarse bark with long pieces is very hard to spread finely
[4] Long-life Reharvest products may be available
[5] Arborist mulch may be consistent within a specific location or source, but is highly variable across different sources, and may vary seasonally where deciduous vegetation is dominant
[6]+F = plus organic fines, achieved by back-blending composted (weed free, stabilised) material

Physical interlocking appeared to improve resistance to floating when organic mulches were at marginal bulk densities. Thinner, stringy, particle shapes bind more effectively than short, rounded, particle shapes, so the bulk density of the overall mulch, rather than individual pieces, determines the extent of floating. Stringy mulches can be achieved by managing the shredding process with expert knowledge of existing mulch feedstock moisture, density, and shredder characteristics. As the raingarden market grows, industry may explore feed stocks from timber mills that process redwoods and suitable eucalyptus species that have intrinsic ‘stringy’ qualities used successfully by overseas agencies.

If the binding of light mulches is disrupted, for example, around high-energy raingarden inflows, sections of mulch may be broken away and float. Thinner, smaller shapes are also more likely to compress or compact over time, increasing resistance to scouring and floating. However mulches must maintain a higher permeability than the underlying raingarden media. Physical locking is important for raingardens and bioswales in which significant horizontal water flows (energy) occur. In most of these situations an inorganic mulch or erosion fabric would be specified. Mulches bind best to a rough underlying surface. Crimping, in which long-fibred mulches, such as straw, are pressed into the surface in a herring-bone pattern is another method of binding mulches.

Results were presented and discussed at a meeting with three major mulch manufacturers. Manufacturers commented on the issue of limitation of the small volumes of mulches currently used by the bioretention industry, which required minimising investment and availability. Given the relatively small volumes of organic mulches currently used in raingardens, this research indicates the most cost-effective way to achieve consistently non-floating mulches is to add either 20–25% v/v compost or crushed shell to Reharvest, weed-free, arborist mulch, or suitable fine bark, and ensure mulches are wetted after installation. Back-adding fines or compost to consistent-quality mulch is more likely to achieve a consistent outcome than attempting to compost to a specified density. Manufacturers indicated that specification based on the existing NZ4454 (Compost New Zealand, 2005) or AS4454 (Australian Standard, 2012) standard for mulches would be more practical than a specific standard for raingardens. This may prevent use of suitable but non-composted materials such as arborist mulch.

All tested mulches conformed to the NZ4454 Compost standards for Cu and Zn; however, the lower Cu standard of 100 mg/kg for Grade A Bio Solids is probably more suitable, given raingardens receive more than background levels of Cu and Zn (when receiving runoff from roads or copper roofing material) and are designed to reduce the concentration of contaminants in discharged stormwater. The new generation of raingardens with sand and compost-based media may also have a lower capacity to buffer metals unless specific amendments are added. There is very little research reporting what changes in pH may be anticipated as raingardens age, however, there are raingardens in Auckland that have baseline pH measurements that could be sampled to provide some data. Some USA guidelines limits level of P in raingarden media to reduce the potential for P leaching in areas where P is a contaminant of concern. Preliminary, unpublished, research has been done in New Zealand on P leaching from raingardens, and raingarden media amendments that reduce leaching, but further work would be needed to justify a maximum P concentration in raingarden media or mulch.

In addition to specifying non-floating mulches, this survey identified three additional practices or guidelines to reduce the risk of floating mulches:

- Thoroughly wet organic mulches at installation (irrigation)
- Design raingardens to receive sheet flow, or reinforce areas of concentrated flow
- Ensure a dense cover of plants is achieved within 24 months so re-mulching is unnecessary. This reduces the risk of decorative bark being used to fill in gaps between plants and of over-mulching, which reduced raingarden ponding depth.

Further information on the influence of organic mulches on pH, metals and nutrient availability in raingardens, particularly after 3–5 years, when organic mulches have significantly decomposed, would be valuable. Variation in copper concentrations in Reharvest wood chip should be investigated to reduce concentrations to below Grade A biosolids. Crushed shells are potentially valuable amendments to enhance bioretention performance. Landscape architects may benefit from a decision tree to help them match the optimum mulch to site characteristics and treatment priorities.

Raingarden mulches can achieve a variety of functions that enhance the performance and aesthetics of raingardens, and are vital to minimise the risk of surface sealing (inadequate infiltration rates) and maintenance costs associated with weeding. Inorganic and organic mulches are available that will achieve these functions with nil or minimal floating, and will also control the associated risk of overflow blockage or surface water contamination.

6.0 Acknowledgements

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Auckland Council (undated) Raingarden construction guide. Stormwater Device information Series.
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