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Vegetative filter strips to control sediment movement in forest plantations: validation of a simple model using field data

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Abstract

A field study of sediment movement through vegetative barriers was carried out to assess the sediment-trapping effectiveness of vegetative barrier types typically used in forest forest plantation management in south-east Queensland, Australia, and to develop a simple methodology for predicting sediment movement through these barriers.

For sites at the centre of Queensland's 110 000 ha *Pinus* plantation and 45 000 ha *Araucaria* plantation program, small field flumes (plots) were established on a range of vegetation types and slope gradients, and sediment-laden flows passed through them. Sediment trapping in the plots was assessed by comparing paired samples taken from the inlet and outlet of the plots at pre-determined sampling times. Measurements included total sediment and equivalent size distributions of sediment particles (the latter measurements being based on settling velocities).

For plots that did not erode, the degree of sediment trapping, if based on total sediment only, was quite variable. However, if rates of transport were considered in terms of the various size fractions, results were very consistent. A simple conceptual approach equating the vegetated area to a sedimentation pond allowed deposition to be calculated on the basis of settling velocity, flow depth, and residence time within the vegetated area. Estimated transport rates of sediment through the vegetated areas were in close agreement with measured transport rates, confirming the efficiency of this approach.

The results highlight a number of issues for management of sediment movement from forest estates.

Introduction

Control of sediment generation on forest roads

In a review of impacts of timber harvesting on streams, Campbell and Doeg (1989) noted that roads in forested country, particularly those constructed during harvesting, were one of the major sources of suspended sediment. Reasons for this include their lack of vegetation cover and surface of loose, fine material overlying an impermeable, compact layer. Because road networks in managed plantations remain in place throughout the cropping cycle, they can act as sources of sediment throughout a forest rotation.

The preferred method for controlling sediment movements from forest roads is to spread runoff water and avoid channelisation (Costantini *et al.* 1999). However, where concentration of runoff cannot be avoided, standard design techniques include channelling runoff water into table drains which run along roads, together with construction of turn-out drains at prescribed intervals to

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restrict flows to non-erosive quantities. In forest plantations, turn-out drains typically discharge runoff onto areas of vegetation or surface litter where entrained sediment will be deposited rather than being transported off-site. The vegetated discharge areas are effectively vegetative filter strips (VFS), and are used in association with both hillslope and roading system management practices to provide additional protection against movement of sediments to surface waters (Clinnick 1985; Heede 1990; Gilliam *et al*. 1992; Costantini *et al*. 1993). In the vicinity of watercourses, forest managers use VFS widths varying from 2 to 30 m, depending upon watercourse classification (Costantini *et al*. 1993) to protect against stream bed and bank erosion, and in the case of wider VFS, to provide a final barrier between sediment pollution sources and watercourses. (Note that throughout this paper, VFS *width* is used to describe the distance from upslope to downslope boundaries of a VFS.) If VFS are to be used for the purpose of filtering runoff-borne sediments from road turn-out drains, it is essential that vegetated areas and buffer zones used for sediment control are effective.

Use of vegetative filter strips

VFS have been widely recommended for control of sediment and sediment-bound contaminants in runoff. Experiments have shown reductions in sediment when runoff passes through VFS (Wilson 1967; Tollner *et al*. 1977; Young *et al*. 1980; Dillaha *et al*. 1989; Magette *et al*. 1989; Meyer *et al*. 1995; Raffaelle *et al*. 1997) as a result of *(i)* acting as areas of high infiltration, thus reducing amounts, depths, and sediment transport capacity of overland flows; and/or *(ii)* slowing the velocity of flow, allowing time for sediment to deposit.

Relatively high infiltration capacity is not uncommon in vegetated areas, due to increases in stable macropores, improvements in soil organic matter and structure, and increased evapotranspiration (thus increasing soil water deficits). However, for some riparian zones, the periodic presence of watertables at or close to the soil surface may, on occasions, reduce infiltration capacities of vegetated areas to almost zero. This latter situation occurs in some soil types on the coastal lowlands of subtropical, south-east Queensland (Coaldrake 1961), an area which supports some 110 000 ha of *Pinus* plantations. When this occurs, the main role of VFS close to watercourses will be to enhance sediment deposition.

Modelling sediment deposition in VFS

In considering the possible structure of a simple model of sediment deposition, it was recognised that the 2 basic issues for deposition are: *(i)* whether the strip causes a sufficient reduction in flow velocity for sediment transport capacity to be reduced and deposition to occur; and *(ii)* the rate (speed) with which deposition occurs, as that will determine whether the VFS is wide enough to achieve maximum possible sediment deposition before the flow exits the strip.

Theoretically, any increase in surface roughness or decrease in slope has the potential to cause deposition, and for this reason, the following analysis assumes that deposition will occur, and that the critical feature is speed of deposition. There are issues with respect to the stability of surface roughness that are highlighted by the results of this study and that warrant further research, but they are not considered in detail in this paper.

Within VFS where no erosion occurs, deposition of sediment will be due to normal settling processes. (The component of sediment directly trapped and intercepted by vegetation is considered small, and is ignored for our present purposes.) Therefore, it seems reasonable to treat a VFS as a sedimentation pond, with deposition being a function of residence time and settling depth. Some bedload transport may occur within a VFS, though for most slopes it can be assumed that particles reaching the bed and staying close to it have a high probability of being deposited relatively quickly.

The model tested was based on WEPP (Water Erosion Prediction Program) model algorithms to predict sediment deposition in impoundments (Lindley *et al.* 1995):

$$D = t_{\mathrm{R}}/t_{100} \tag{1}$$

where D is the proportion of sediment in a particular size class that is deposited, t_{R} is the residence time for flow in the VFS, and t_{100} is the time required for all sediment of that equivalent size class to settle out of the flow. Calculation of t_{100} was based on:

$$t_{100} = d_{\mathrm{f}}/V_{\mathrm{s_i}} \tag{2}$$

where d_{f} is the flow depth and $V_{\mathrm{s_i}}$ is the settling velocity of the lower bound of the equivalent sediment size class i.

Potential errors implicit in this approach include an assumption that sediment is evenly spread throughout the depth of flow, which is unlikely for coarser (bedload) size classes. As well, the residence time of sediment within a VFS may be somewhat longer than that of flow, as bedload sediment velocity will be less than that of flow. The use of a lower bound of a sediment size class could introduce large errors unless the sediment size range considered is relatively small, though the use of a single figure to describe a size range will always have potential for error.

A spreadsheet using Eqns 1 and 2 was prepared to consider transport/deposition of a range of settling velocity classes, together with equations to estimate residence times and flow depths. No attempt was made to consider infiltration losses of overland flow, nor any spreading of flow within the VFS. This approach has a degree of similarity to other models of sediment deposition in VFS.

In a series of papers, Barfield *et al.* (1979) and Hayes *et al.* (1979, 1984) presented a model that estimated sediment deposition within non-submerged filter strips. The model separated a VFS into 4 functional zones, which included an area of sediment deposition upslope of the VFS, a wedge of sediment extending into the VFS, a zone where deposition enabled bedload transport to occur, and a zone where all sediment reaching the bed is trapped. The model considered particle size distributions of sediment entering and exiting the VFS.

Flanagan *et al.* (1989) presented simplified equations from the CREAMS model (Knisel 1980) for predicting sediment movement through VFS. They treated the VFS as a single zone, but used 5 classes of sediment size and density, based on the predictive equations of Foster *et al.* (1985). Testing of the model indicated that it gave most accurate predictions of sediment trapping for situations where rates of deposition where high. This may have resulted from the sediment size/density classes adopted being restricted to relatively fixed (and broad) size ranges.

In seeking a simple model of sediment deposition/transport within filter strips, it was decided that (unlike some aspects of the previously published models) it was desirable to: *(i)* be able to treat a VFS as a single zone; and *(ii)* have some degree of flexibility in the dimensions and number of sediment size/density classes that are considered. This latter requirement ensures that measured size distributions can be input. It also ensures that emphasis can be given to size fractions that are affected by the particular VFS widths considered. There would be little value in a model that focused on size fractions that were either all deposited or all transported.

Aims of the present study

The studies reported in this paper were designed to evaluate the effectiveness and importance of sediment deposition in VFS commonly used in plantation management in south-east Queensland, Australia, during the inter-rotation period. This is the period between clearfall of one rotation and control of the site by the next rotation crop when the hydrologic stresses on the forest are greatest (Costantini *et al.* 1997*a*, 1997*b*). During this period, forest managers make use of understorey vegetation and clearfall residue to supplement VFS, especially those located away from the watercourse system and its network of filter strips. A major consideration for the study was to develop methods by which the effectiveness of vegetation strips could be predicted on the basis of relatively simple input data.

Methods

Description of sites and vegetation treatments

Twelve plots were used in the experiment, covering 6 different vegetation types, selected to represent a range in vegetation cover and quantity of surface litter likely to be found in current field practice in areas where road drains are discharged. Three of the vegetation types were located in the coarse-textured soils of Queensland's coastal lowlands used for *Pinus* plantations (Toolara; Costantini *et al.* 1997*a*). The other 3 types were on steeper, finer textured soils used for *Araucaria* plantations (Imbil; Costantini *et al.* 1997*b*) in subtropical, south-east Queensland. Average slopes along experimental plots were 6·3% and 29·1% at Toolara and Imbil, respectively. Generally, the gradients shown are of land slope. However, for plots 3–5, gradients were taken of the water surface as one of the plots developed a significant backwater upstream of the vegetation, so that the flow gradient was greater than land slope. Further descriptions and locations of sites are given in Table 1.

At each site, both vegetation cover and surface litter were sampled and oven-dried to obtain precise measurements of biomass. For each vegetation type, several samples of vegetation and surface litter were collected from quadrats of 300 by 500 mm located in the surroundings of the plots, dried at 80°C for 72 h, and weighed. Surface litter and vegetation biomass data are given in Table 2, together with other plot properties.

Equipment used for studying overland flows and sediment movement

Each plot was effectively a temporary field flume 0·3 m wide and of varying length. The flume sidewalls were constructed by anchoring overlapping metal sheets to the soil and sealing the sheets into the soil with bentonite. Care was taken to prevent any preferred flow paths or areas of lower than average vegetation in the areas closest to the walls of the flume. Areas where the sheets overlapped were sealed with plastic tape to minimise losses of overland flow from the test area.

At the downslope end of each plot, a metal frame was driven into the soil to create a flume outlet. The outlet was level with the soil surface and included a short chute to concentrate overland flow to facilitate sampling. Runoff from the plot discharged into pits dug into the soil to give sufficient space for sampling of the flow, and to enable drainage by a pump.

Flow rates pumped onto the plots were controlled by a tap, and monitored using a rotameter. The flow inlet area consisted of a metal chute 0·3 m wide and 0·6 m long, which received water from the rotameter and channelled it into the plot. At Toolara, the gradient of the inlet chute was adjusted to be higher than that of the plot, so that deposition within the chute was minimised. Additional fall within the chute was approximately 1 in 10. At Imbil, where land gradients were higher, no additional fall was applied to the chute, as there was little potential for deposition in it.

Table 1. Locations and descriptions of the sites studied

Site	Location	Site description
1	Toolara	<50% cover of swamp grass (*Schoenus brevifolius*), and a medium quantity of surface litter left after clear-felling of *Pinus* sp.
2	Toolara	Almost 100% cover of swamp grass, and a very small quantity of surface litter
3	Toolara	Recently clear-felled, very high quantity of *Pinus* residue on the soil surface. Vegetation cover <10%
4	Imbil	Clear-felled area recently re-planted to *Araucaria cunninghamii*, <10% vegetation cover and high quantity of surface litter
5	Imbil	Clear-felled area recently re-planted to *A. cunninghamii*, similar vegetation cover to Site 4, but a smaller quantity of surface litter
6	Imbil	Area of re-planted *A. cunninghamii* (trees of approx. 2 m height). Vegetation cover almost 100% (dominantly *Paspalum wettsteinii*, a relatively prostrate grass), and a small quantity of surface litter

Table 2. Length and gradient of plots, and average values of vegetation and surface litter biomass of the sites where the plots were located

Site	Plot	Plot length (m)	Slope (%)	Vegetation biomass (kg/m^2)	Surface litter biomass (kg/m^2)
1	1	1·5	5·9	0·50	1·24
	2	3·0	4·2	0·55	1·69
2	3	1·0	10·2	3·19	0·12
	4	2·0	6·9		
	5	0·5	9·2		
3	6	3·0	0·9	0·07	3·84
	7	1·5	6·6		
4	8	3·0	29·0	0·07	1·23
	9	1·5	35·0		
5	10	1·5	19·9	0·07	0·79
	11	3·0	25·6		
6	12	1·5	36·0	0·62	0·32

Sediment in runoff was produced by mixing water and soil in a spherical fibreglass tank of approximately 1200 L volume. A pump was used to circulate and mix sediment within the tank, with a second pump being used to convey sediment-laden water from the tank to the rotameter and then to the flume. This system produced generally consistent sediment concentrations and size distributions, but with some occasional variations depending on the level of mixing that was achieved. To enable interpretation of data despite the temporal variations in sediment loads, paired samples of sediment were taken to enable comparison of inlet/outlet sediment loads and settling velocity distributions.

The sediment concentrations and size fractions in flow applied to the study plots were selected to reflect sediment loads in runoff that might be found at Toolara and Imbil, and were prepared by using local soils. Silt concentrations (0·02–0·002 mm) were generally less at Toolara than Imbil. At Toolara, the silt and clay fractions typically accounted for between half and two-thirds of the sediment <0·05 mm. However, at Imbil, the silt fraction typically accounted for up to 80–100% of the <0·05 mm fraction.

Experimental procedures

For each treatment (vegetation and slope length combination), 2 flow rates of 2 and 4 L/s were tested. Each flow rate was applied for 7 min, with sampling of inlet/outlet sediment being carried out at 1, 3·5, and 7 min from the start of the test. The highest flow rate is consistent with the flow rates/unit width estimated for turnout drains on a road/table drain system subjected to a 1 : 10 year storm. In referring to the plots, the plot number is given, plus flow 1 or 2, depending on whether the flow applied was 2 or 4 L/s. For example, plot 2/2 indicates data for plot 2 with the 4 L/s flow applied.

Bulk samples of flow were taken at various times during the run, with duration of sampling and sample weight being used to estimate flow rates exiting the plot. This was done to overcome uncertainties in some flow readings, where very muddy flows made reading of the rotameter difficult, and some jamming of the rotameter occurred at higher sediment loads (see Table 6 for data on variations in flow rates). At the flow rates studied, infiltration was unlikely to represent a significant proportion of the flows. For example, infiltration of 100 mm/h on a plot 1 m long and 0·3 m wide equates to 0·008 L/s.

Flow depths were measured at 3 locations, at least, within the test flumes on 2 occasions during each run, and an average flow depth was calculated. Gradients of the test areas were recorded. Where plots were at least 1·5 m long, land slope was taken as indicating the flow gradient, but for shorter slopes, the gradient of the flow surface was recorded. For one plot, 0·5 m long and containing a high density of swamp grass, the water surface showed a much higher gradient than the land slope. This resulted from a backwater developing at the entry of flow to the strip.

Analyses of sediment properties

At each sampling time, 3 separate samples were taken at the outlet of the plot. At the inlet, 3 separate samples were taken at 1 and 7 min with 2 samples being taken at 3·5 min. The 3 samples were used for measurements of total sediment concentration, silt, and clay contents (particles 0·20–0·002 mm and <0·002 mm), and settling velocity distributions (reported as equivalent sand sizes).

Silt and clay contents were measured by transferring samples to sedimentation cylinders, gently stirring the sample, and then using pipette sampling at depth/time combinations to measure silt and clay concentrations.

The settling column is an automated version of a design by Hairsine and McTainsh (1986), incorporating an injection barrel design by Kinnell and McLachlan (1988). Sampling times for the settling tube were selected to consider equivalent sand sizes of 1, 0·5, 0·25, 0·125, 0·085, and 0·05 mm. Equivalent sand size is based on settling velocity, so that, for example, particles with an equivalent sand size of 2 mm have the same settling velocity as a sand particle of 2 mm diameter (even though the actual particle diameter may be quite different). Settling velocity is a function not only of particle size, but also of density, shape, and roughness.

As little sediment was present in the larger size fractions (especially in flows exiting the plots), those size fractions were bulked to give equivalent sand size classes of >0·25 mm and 0·25–0·125 mm. In this paper, the sizes >0·125 mm were grouped for convenience, although in some data analysis the 2 size fractions were considered separately. Greater detail was gathered on sizes <0·125 mm as Meyer *et al.* (1995) showed that variations in transport of sediment occurred mainly in the range 0·1–0·032 mm.

Only 2 samples were taken at 3·5 min at the inlet, and those samples were used for laboratory measurements of total sediment and silt and clay. Settling velocity distribution for the inlet sample at 3·5 min was estimated using a series of decisions based on data available:

(i) If sediment concentrations at all 3 times were similar and settling velocity distributions for the samples at 1 and 7 min were similar, then the settling velocity distribution assigned was the mean of those measured at 1 and 7 min. This procedure accounted for most of the samples taken at 3·5 min.

(ii) If sediment concentrations varied between the 3 sampling times, with the sampling at 3·5 min being similar to one of the other 2 samples, the settling velocity distribution assigned was similar to that of the sample having a similar total sediment concentration.

(iii) If the sample taken at 3·5 min had a different total concentration to either of the other samples, it was assigned a settling velocity distribution similar to a sample of similar concentration for the same soil.

Limitations in the number of settling velocity samples that could be processed made this procedure necessary.

Results

Observations during flow experiments

Although Meyer *et al.* (1995) observed a backwater upstream of the grass hedges they tested, a pronounced backwater was only observed on plot 3, which carried heavy swamp grass cover. At Toolara, with the exception of the plot where a backwater was observed to cause sedimentation up-stream of the plot, sediment deposition occurred within the vegetation/roughness type being tested, with the area of deposition gradually extending downslope as the runs progressed.

At Imbil, the litter cover studied was not totally resistant to movement by the overland flows applied, and, in general, erosion occurred rather than deposition. On plots 8 and 9 (heavy litter cover), small areas of scour were observed to develop during overland flows. Where the litter cover was less (plots 10 and 11), areas of removal of the litter were visible, with virtually all litter being removed from plot 11 when it was initially exposed to flow. Any remaining litter was immediately removed from this plot when the higher flow rate commenced.

For the plots at Imbil carrying litter cover, the presence of weed stems, etc., appeared to be a major factor in anchoring the litter to the soil, even though the weeds had been earlier killed by herbicides. The plots with light litter cover had not had any vegetation growth on them, and this appeared to leave surface litter more vulnerable to removal by overland flows.

Total sediment concentrations

Table 3 shows the total sediment concentrations of inlet and outlet flows of each plot averaged over the 3 sampling times.

Deposition was much higher for plots at Toolara than for those at Imbil because *(i)* the gradients studied at Toolara were lower; *(ii)* some of the plots at Imbil were eroded by the flows applied, so that erosion occurred rather than deposition; and *(iii)* in one instance at Imbil, the applied sediment was extremely fine, so that measurements of total sediment showed minimal deposition.

Longer plots had greater deposition than smaller ones within the same sites. Stability of the vegetation cover to overland flows was also important. For example, when comparing plots 9 and 12 at Imbil, both with the same length and very similar sediment concentration of the inlet flow, there was no detachment on plot 12, which had heavy grass cover, whereas plot 9 showed considerable erosion.

Table 3. Total sediment concentrations (g/L) in inlet and outlet flows for each plot and flow rate, averaged across all three sampling times

Plot	Low flow (2 L/s)		High flow (4 L/s)	
	Inlet	Outlet	Inlet	Outlet
1	14·44	4·64	14·10	7·42
2	7·30	4·55	38·79	7·55
3	13·93	6·29	41·1	9·05
4	26·82	4·26	21·82	6·83
5	14·46	13·19	62·86	45·05
6	12·57	3·65	34·33	6·34
7	13·91	4·17	18·90	5·88
8	54·88	21·79	60·51	30·02
9	6·96	7·39	12·22	16·59
10	16·17	15·83	13·17	11·97
11	19·53	14·46	4·72	9·97
12	n.t.	n.t.	5·03	5·03

n.t., not tested.

Efficiency of transport—values for total sediment

Transport efficiencies for each plot at each sampling time were defined as the proportion of sediment that passed through the plot without being deposited, and were calculated by dividing the sediment concentration at the outlet by the sediment concentration at the inlet. These values were calculated for both the total sediment load and for the different particle size fractions. Table 4 shows transport efficiencies of total sediment for the different plots, averaged across the 3 sampling times.

Table 4. Efficiency of transport of total sediment—means for each flow rate on each plot

Site	Plot number/ flow rate		Transport efficiency (%) for flow rates:	
			(1)	(2)
Toolara, light swamp grass				
1·5 m long	1/1	1/2	32·12	52·61
3·0 m long	2/1	2/2	62·29	19·47
Toolara, heavy swamp grass				
0·05 m long	5/1	5/2	91·26	71·66
1·0 m long	3/2	3/2	45·16	22·03
2·0 m long	4/1	4/2	15·90	31·32
Toolara, pine litter				
1·5 m long	7/1	7/2	29·95	31·08
3·0 m long	6/1	6/2	29·06	18·46
Imbil, heavy litter				
1·5 m long	9/1	9/2	106·18	135·82
3·0 m long	8/1	8/2	39·7	49·61
Imbil, light litter				
1·5 m long	10/1	10/2	97·85	90·86
3·0 m long	11/1	11/2	74·03	211·14
Imbil, heavy grass				
1·5 m long		12/2		100·0[A]

[A] Based on separate samples taken for total sediment. Sediment for this plot was dominantly <0·05 mm, and deposition of larger size fractions had only slight effects on transport efficiency of total sediment.

Although there is, in general, a reduction in transport efficiency as plot length increased, the results superficially suggest inconsistencies between the various plots and flow rates. (The explanation lies in the differential transport efficiencies of different sediment size fractions, and variations in equivalent size distributions of sediment applied during experimentation, see next Section.) Results in Table 4 also highlight the development of erosion on plots 9–11 on the steeper slopes at Imbil.

Transport of sediment <0·05 mm equivalent size

In general, there were no appreciable differences in the concentrations of fractions <0·05 mm between inlet and outlet flows. Apart from 2 exceptions, >95% of particles <0·05 mm entering a VFS were measured to exit from it, and differences in deposition rates were due to differences in transport of equivalent size fractions >0·05 mm.

This result contrasts slightly with data of Meyer *et al.* (1995), who generally found about 20% of sediment <0·032 mm was trapped by VFS. This could be explained by the sediment used by Meyer *et al.* (1995) having a high proportion of particles with diameters close to the upper bound of the <0·032 mm size class. In contrast, sediment <0·05 mm in this study may have tended to have diameters closer to the lower bound of the silt size class, i.e. with diameters close to 0·002 mm. It is also possible that the wedges of deposited sediment in the backwater upstream of the VFS reported by Meyer *et al.* may have involved some trapping of clay and silt in the interstices of coarser particles.

Transport of sediment with equivalent sizes >0·05 mm

Table 5 shows average transport efficiencies of the coarser sediment size classes for each plot. Overall, results from this study are very similar to those reported by Meyer *et al.* (1995), who found 90–100% of all particles >0·125 mm were trapped by vegetative hedges.

For most of the plots at Toolara, transport of particles with equivalent sizes >0·125 mm was <5%. For plots 8–11 at Imbil, transmission of the >0·125 mm fraction was greater, largely due to the presence of erosion on these plots. The high gradients of those plots meant that flows reached high shear stresses, and partially or totally removed surface litter. Given the high gradients and the relatively high flows applied, the erosion measured on plots 8–11 is relatively low, indicating that the soil is strongly cohesive. In other studies, sediment concentrations as high as 300 g/L have been recorded for disturbed soils on similar slopes (R. J. Loch, unpubl. data.)

In contrast to plots 8–11 which had only litter cover, plot 12 had a good vegetation cover, and trapping of the coarser fraction was quite high, despite the steep slope.

Across all plots, transport efficiency of the 0·125–0·05 mm fraction showed great variation, between 15·14% and 212·98%. Again, erosion is responsible for some of the higher transport efficiencies shown.

For the higher flow rate on plot 5, a transport efficiency >100% was recorded for sediment 0·125–0·05 mm, even though the plot did not erode. This result may have been due to some re-entrainment of sediment <0·125 mm deposited within this very short (0·5 m long) plot during application of the first flow rate.

Table 5. Average transport efficiencies (%) for sediment with equivalent size >0·05 mm

Site	Plot number/ flow rate	Transport efficiency (%) for size classes: >0·125 mm	0·125–0·05 mm
Toolara, light swamp grass			
1·5 m long	1/1	0·12	25·86
	1/2	2·78	50·83
3·0 m long	2/1	2·66	15·14
	2/2	0·74	43·9
Toolara, heavy swamp grass			
0·5 m long	5/1	n.d.	n.d.
	5/2	67·03	116·48
1·0 m long	3/1	4·25	63·61
	3/2	7·7	51·09
2·0 m long	4/1	1·41	25·62
	4/2	4·33	53·57
Toollara, pine litter			
1·5 m long	7/1	1·52	42·54
	7/2	9·14	70·74
3·0 m long	6/1	0·28	29·78
	6/2	2·23	47·01
Imbil, heavy litter			
1·5 m long	9/1	116·6	92·83
	9/2	143·5	145·21
3·0 m long	8/1	15·57	76·58
	8/2	48·67	82·44
Imbil, light litter			
1·5 m long	10/1	132·44	139·77
	10/2	75·03	212·98
3·0 m long	11/1	45·91	91·25
	11/2	226·5	168·22
Imbil, heavy grass			
1·5 m long	12/2	5·41	73·47

n.d., not determined.

Roughness coefficients—Manning's n values

The Manning equation is commonly used to relate flow velocities and depths to surface roughness:

$$V = (R^{0\cdot 66} S^{0\cdot 5})/n \tag{3}$$

where V is flow velocity, R is hydraulic radius, S is slope, and n is the Manning roughness coefficient. In shallow overland flows, R is typically taken as flow depth. However, for situations where flows pass through non-submerged vegetation, Tollner *et al.* (1976) calculated a modified hydraulic radius, based on the analogy of flow in a rectangular channel with a width equal to the average spacing between grass stems. As the average spacing of grass stems was difficult to estimate under field conditions, initial calculations of n values equated flow depths with hydraulic radius.

The values obtained (Table 6) are high relative to typical values used for open channel flow. This is consistent with experience in similar studies (G. W. Titmarsh, pers. comm.) involving flows that are shallower than the vegetation roughness elements. Similarly, Huggins and Burney (1982) cited n values of 0·40 for grass swards and up to 0·80 for timberland with deep forest litter.

The n values calculated are highest for the heavy grass cover at Imbil, and high for the plots with heavy swamp grass cover at Toolara (Table 6). Low values of n were calculated for plot 11 at Imbil, for which most of the surface litter was removed by flow to expose mineral soil, although some litter remained to cause retardance of flow. Low values were recorded for pine litter at Toolara (plot 6), and may reflect a loss of retardance due to deposition of sediment along the length of the plot during flow studies.

Other data derived from these calculations include flow velocity and residence time (the time taken for the flow to pass through the test area).

Table 6. Overland flow data—depths, gradients, velocities, and Manning's n

Plot	Manning's n	Gradient	Depth[A] (m)	Flow velocity (m/s)	Residence time (s)	Mean flow rate (m^3/s)
1/1			n.r.			0·0016
1/2			n.r.			0·0042
2/1	0·158	0·043	0·038	0·15	20·25	0·0016
2/2	0·176	0·043	0·07	0·20	15·01	0·0041
3/1	0·198	0·059	0·045	0·15	6·45	0·0020
3/2	0·181	0·104	0·055	0·26	3·88	0·0042
4/1	0·270	0·0685	0·045	0·12	16·30	0·0016
4/2	0·212	0·071	0·06	0·19	10·37	0·0034
5/1	0·172	0·089	0·035	0·19	2·69	0·0019
5/2	0·130	0·0965	0·045	0·30	1·66	0·0040
6/1	0·089	0·01	0·045	0·14	21·28	0·0019
6/2	0·089	0·01	0·07	0·19	15·71	0·0040
7/1	0·147	0·066	0·025	0·15	10·07	0·0011
7/2	0·149	0·066	0·05	0·23	6·43	0·0035
8/1	0·153	0·29	0·018	0·24	12·38	0·0013
8/2	0·102	0·29	0·027	0·47	6·33	0·0038
9/1	0·154	0·35	0·023	0·31	4·84	0·0021
9/2	0·157	0·35	0·035	0·40	3·73	0·0042
10/1	0·107	0·199	0·02	0·31	4·90	0·0018
10/2	0·087	0·199	0·03	0·49	3·04	0·0044
11/1	0·087	0·27	0·018	0·41	7·34	0·0022
11/2	0·105	0·27	0·03	0·48	6·27	0·0043
12/2	0·289	0·36	0·05	0·28	5·33	0·0042

n.r., data not reported. [A] Mean values.

Model testing and evaluation

Prediction of measured sediment transport through VFS

Data for the plots that were not subject to erosion and for which there were consistent data on flow depths (plots 2–7, and plot 12) were analysed to predict efficiencies of sediment transport through the VFS. Means across the 3 sampling times for each of the flow rates were used. As sediment size data were available for only one flow rate on plots 5 and 12, this gave 12 data points for each sediment size class. The results obtained showed good agreement with the general pattern of sediment transport measured in this study.

Firstly, sediment $<0{\cdot}05$ mm was considered, using an assumption that the lower bound of the sediment was $0{\cdot}002$ mm, as measurements had shown that a significant proportion of this size class was in the silt range ($0{\cdot}02$–$0{\cdot}002$ mm). Eqn 1 predicted that, generally, $>99\%$ of sediment with $0{\cdot}05$–$0{\cdot}002$ mm equivalent size would be transported through the strips, a result in close agreement with data from this study.

Secondly, sediment $>0{\cdot}25$ mm was considered, with the assumption that the lower bound of this equivalent size class was $0{\cdot}25$ mm. No transport of this size class was predicted for any non-eroding strip—again in close agreement with the data.

For sediment $0{\cdot}25$–$0{\cdot}125$ mm, transport of $>5\%$ of sediment was predicted to occur for only 2 plot–flow rate combinations (with transport of 8–10% of this size fraction being predicted for short strips). In fact, transport of 6–10% of this size class was measured for 4 plot–flow rate combinations, but 2 of the 4 plots where transport of $>5\%$ occurred were correctly predicted.

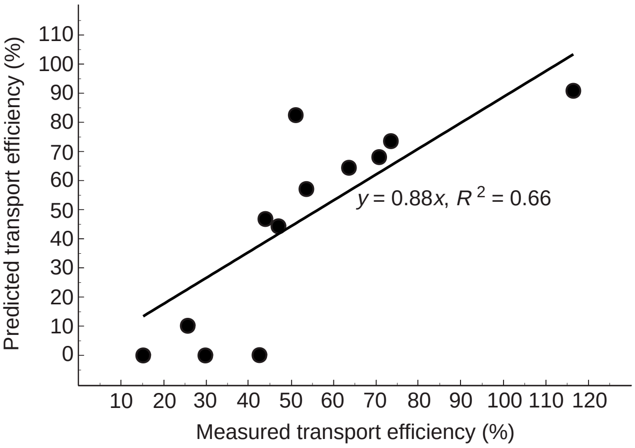

Fig. 1. Comparison of predicted and observed transport efficiencies for sediment of equivalent size $0{\cdot}125$–$0{\cdot}05$ mm.

Prediction of transport of the $0{\cdot}125$–$0{\cdot}05$ mm equivalent size class is shown in Fig. 1. It shows encouraging prediction of the measured transport efficiency of this size class, with the linear correlation being highly significant ($P < 0{\cdot}001$), and the gradient of the line fitted through the origin being close to $1{\cdot}0$. Of the points that were less well predicted, 2 points show considerable transport where none was predicted. Both points were recorded for pine litter at Toolara; interestingly, both were for low flows on different plots. These results may have been due to some effects of preferential flow paths at the lower flows, with the deeper flows at the higher flow rate being less influenced by preferential flow paths. One point shows considerably lower transport than predicted, and is the result for the higher flow rate on the plot where a backwater was observed. For that point, an increase in the strip width, to account for the magnitude of the backwater, reduced, but did not eliminate, the over-prediction of transport.

Overall, however, Eqns 1 and 2 gave reasonable prediction of sediment movement through VFS. The concept applied correctly identified size fractions for which transport was either total or zero, and gave highly significant predictions of rates of transport for the size fraction that was only partially deposited within the VFS widths tested. The availability of directly measured data on settling velocities undoubtedly contributed to the ease of model validation.

Flow turbulence considerations

A crucial assumption in algorithms such as Eqns 1 and 2 developed for sedimentation ponds is that particle settling will occur under tranquil flow conditions. However, if impacts of vegetation on the wetted perimeter are ignored, estimated Reynolds numbers (R_e) for flow in the VFS studied are typically in the range 3500–7000 for the lower flows applied, and in the range 11 000–15 000 for the higher flows applied. This would indicate that most of the flows were transitional to turbulent, suggesting that the assumptions underlying the approach used to describe sediment deposition in the strips are unreasonable. (For laminar flow R_e is <500, for transitional flow R_e is 500–12 500, and for turbulent flow R_e is >12 500.)

Nonetheless, there are a number of reasons why the approach can be expected to provide reasonable predictions of deposition. Firstly, consideration of vegetation elements projecting through the flow has a dramatic impact on the Reynolds number, which is calculated as:

$$R_e = VR/\nu \tag{4}$$

where R is the hydraulic radius (the cross-section area of flow divided by the wetted perimeter), V is the mean flow velocity, and ν is the kinematic viscosity. When vegetation elements were taken into account (using estimates of stem-spacing from photographs), typical reductions from 8- to 10-fold occurred in estimates of R and R_e for the vegetated plots. The resulting Reynolds numbers (in the approximate range 350–1500) indicate that flow ranged from laminar to transitional, with none of the flows approaching Reynolds numbers consistent with fully turbulent flow.

As well, flows within VFS were not spatially uniform, with some areas of flow separated from the main flow lines, within which the flow would have been relatively tranquil. On some occasions, hydraulic jumps developed within a strip as a result of spatial variation in vegetation density.

There is also the possibility that the use of the lower bound of a sediment size class, rather than an average size for that size class, may have produced some underestimation of potential particle deposition that balanced any slight overestimation of deposition resulting from neglect of flow turbulence. Data presented by Storm *et al.* (1994) suggest that impacts of turbulence on deposition may alter the fraction of a size class that is deposited by a maximum of 25%, and considerably less for some size classes.

Therefore, it seems that the assumptions underlying the approach used are not unreasonable, and that potential errors are not large and may be balanced to some extent by the computation used.

Applications of the simple model of deposition in VFS

Provided the roughness coefficient of a vegetation strip is known, it is possible to use Eqns 1 and 2 to assess impacts of strip width on sediment transport for a range of flow rates, slope gradients, and sediment sizes.

Table 7. Effects of sediment size distribution on sediment concentrations (g/L) entering and leaving a vegetative filter strip 5 m wide

Manning's n, 0·2; flow, 6 L/s.m width

Sediment size class	Inlet conc. in each size class (Sediment A)	(Sediment B)	Exit conc. in each size class (Sediment A)	(Sediment B)
>0·25	5	5	0·00	0·00
0·125–0·25	5	12·5	0·00	0·00
0·05–0·125	5	15	0·00	0·00
0·02–0·05	12·5	7·5	8·13	4·88
0·002–0·02	17·5	7·5	17·45	7·48
<0·002	5	2·5	5·00	2·50
Total conc. (g/L)	50	50	30·57	14·85
Transport efficiency (%)			61%	29·7%

For a 5-m-wide strip, with Manning's n of 0·2, on a 5% gradient, it is possible to compare transport efficiencies for 50 g/L sediment carried by flow of 6 L/s.m width passing through the strip. Table 7 shows equivalent sand-size distributions of sediment reaching the strip, and predicted concentrations of the various equivalent size classes exiting the strip. It demonstrates the large differences in sediment trapping that can be expected for different distributions of equivalent sand size. For sediment A, 61% of the total sediment load was predicted to pass through the strip, whereas, for the coarser sediment B, only 29·7% of the total sediment load was predicted to exit the strip.

Backwaters

Within the conceptual model used, backwaters could be considered as an extension of the effective length of slope over which sedimentation occurs. For example, a narrow hedge aligned perpendicular to flow may represent a sedimentation area no more than 0·2 m wide, but may create a backwater for (say) 2 m upslope. In that instance, a 0·2-m-wide hedge may have an effective width (in terms of deposition) of 2·2 m, illustrating the importance of backwaters for narrow hedges to be effective in trapping sediment. However, to deal with backwater effects more accurately, issues of flow depth and velocity within the backwater—as affected by sediment deposition and changes in flow depth and velocity—may need to be considered.

Limitations of the approach used to predict deposition in VFS

Issues not addressed by Eqns 1 and 2 include:

(i) Possible re-entrainment of the sediment deposited within the strip.

(ii) Effects of raindrop impacts, which may induce turbulence in overland flows and reduce strip effectiveness where a VFS was primarily some form of litter. It would be of less significance where the VFS consisted of taller vegetation or where flows were deeper than about 10 mm.

(iii) Sediment transport capacity. It is assumed that flow energy is not sufficient to sustain continued transport of the particles. If, for example, strips of high gradient and/or low roughness were considered, it may be possible to find situations where flows had sufficient capacity to transport at least some sediment size classes. Eqn 1 would not apply in such cases. Equally, in applying Eqn 1, it is assumed that the strip is non-eroding.

(iv) Reductions in flow depth due to infiltration or to spreading of the flow. Eqn 1 shows clearly that any reductions in depth will increase deposition rates and effectiveness.

Issues for forest management

The data raise several management issues, including the need for vegetative areas to be able to resist detachment by overland flows, and the potential difficulties of removing fine sediment from runoff.

Resistance of surface litter to detachment by flow

Observations indicate that concentrated flows on steep slopes can easily remove surface litter if it is not anchored to the soil in some way. This suggests a need both to retain heavier residue loads (see Costantini 1997*b*) and to delay weed control operations in the period between harvesting and planting until regrowth anchors the fine litter.

As well, there is a need to prevent concentrated flows from being directly discharged onto areas of surface litter *on steep slopes*. This may be achieved by ensuring that the initial point of discharge is into a windrow of larger vegetative material (branches, etc.) that will spread the flow, reduce flow depths, and reduce the capacity of the flow to remove surface litter.

The ability of different residue covers to resist removal by concentrated flows has been studied in agricultural situations (e.g. Foster *et al.* 1982), with residue removal by flow being referred to as 'mulch failure'. Overland flow studies are probably the most straightforward way in which mulch failure could be studied, and could be used to identify critical shear levels for residue removal, analogous to the critical shear values established for initiation of rilling on bare soils in the WEPP model (Flanagan and Livingston 1995). It would be useful to have information for a range of residue quantities (mass/area), types (probably mainly dependent on the length and diameter of the litter), and degree of anchoring (by grasses, weeds, etc.). All of these attributes can be expected to affect the resistance of mulch to removal by overland flows. However, at this stage, soil erosion models such as WEPP do not consider mulch failure, and it would be difficult to incorporate such considerations within the existing model structure.

Roughness of vegetative barriers

The equations developed in this work do not indicate major impacts of the hydraulic roughness of vegetative barriers on transport efficiency, provided the barrier is sufficiently rough to cause deposition. Although increases in roughness are predicted to reduce flow velocity, the resulting increase in residence time is predicted to be balanced by an increased flow depth and, therefore, in t_{100} (Eqn 2). This result is consistent with normal experience with sedimentation ponds (Tebbutt 1971, p. 86), where deposition is a function of flow quantity and tank surface area, but not of flow depth.

However, in field practice there are likely to be benefits from increased VFS roughness. Firstly, there is potential for increases in residence time to increase infiltration. As well, because discharge points for turn-out drains represent point discharges, high vegetation roughness may have benefits in achieving the greatest possible spreading of flow across hillslopes, thus reducing flow depths and increasing both deposition and infiltration. There may also be potential for VFS of greater roughness to develop backwaters, thus increasing their effective width.

Depositing fine sediment

Because of its slow settling velocities, fine sediment will be very difficult to remove from runoff. For example, particles of 0·02 mm equivalent diameter in a 20-mm-deep flow would be completely deposited in approximately 48 s. From the residence times shown in Table 6, it appears that on areas of low gradient, this may be achieved with strip widths in the order of 10 m.

However, sediment particles with an equivalent diameter of 0·002 mm would require a time of approximately 90 min for all such particles to settle from a flow 20 mm deep. Such times indicate a requirement for impossibly wide areas of vegetation.

Nonetheless, there are approaches that could achieve at least some deposition of these finer size fractions (see Costantini *et. al.* 1999):

(i) By minimising flow depths, by spreading flows as widely as possible. By halving flow depth, the effectiveness of any vegetative area would double.
(ii) By, as much as possible, using hillslopes as VFS. Sediment in runoff discharged from cross-drains high in the landscape will have considerable travel time before reaching a watercourse and may achieve considerable deposition and infiltration. Concentration of overland flows on hillslopes should be avoided.
(iii) By reducing concentrations of fine sediment in runoff from roads, with special emphasis on the areas of road discharging runoff closest to watercourses.

Information on the size distributions of sediment likely to be eroded from a range of forest road surfaces would be useful in assessing management practices for control of water quality. Equally important are data on practices to control sediment movements from road surfaces.

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