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Effects of site preparation on runoff, erosion, and nutrient losses from *Pinus* plantations established on the coastal lowlands of south-east Queensland, Australia

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Abstract

Site preparation practices used during establishment of second rotation *Pinus* plantations on the coastal lowlands of south-east Queensland became more conservative during the 1990s. Traditionally, site preparation included stick raking of residue into windrows, followed by burning. Areas subject to periodic saturation were then cultivated to form continuous high mounds, while better drained sites were contour strip cultivated. These practices were replaced by retention of residue biomass on hillslopes. Similarly, intensive site disturbance was increasingly replaced by tillage of the immediate planting zone only and, as far as possible, avoidance of continuous furrows, major drainage structures, and high mounding works.

In the study reported here, simulated rainfall and overland flows were used to assess the impacts of the earlier, less-conservative site preparation practices on hillslope soil loss, nutrient loss, and the potential for off-site nutrient movement.

Where residue from clearfell harvesting of the first rotation was not removed, runoff, erosion, and nutrient loss were negligible. Harvesting tended to distribute residue widely across hillslopes, and, together with naturally occurring understorey biomass, it formed a largely continuous groundcover.

Highest concentrations of sediment in overland flow were recorded for hillslopes in the newly stick-raked condition. Sediment concentrations in overland flows applied to properly designed and constructed high mounds were low, even for large flows simulating relatively long furrow lengths. However, sediment in rainfall-induced runoff from mounded areas was observed to be nutrient enriched, indicating potential for an off-site nutrient pollution risk, at least prior to establishment of grass cover along furrows. Nutrient enrichment was correlated with enrichment of finer size classes of sediment in runoff.

The work reported in this paper vindicated the move away from traditional residue removal and site preparation practices to an approach based on residue retention, minimum site disturbance, and, wherever possible, 'spot' rather than continuous mounding/cultivation.

Introduction

The Queensland Department of Primary Industries Forestry (QDPIF) has established some 110 000 ha of *Pinus* plantations in the coastal lowlands of the State's south-east, mostly on acidic, coarse-textured soils of low fertility. Described in detail by Coaldrake (1961), the coastal lowlands drain into 2 highly sensitive, environmentally valuable marine resources: Great Sandy Straits between the mainland and Fraser Island, and Pumicestone Passage between the mainland and Bribie Island. As a result, QDPIF policy is to maintain (or improve) productivity of its plantations within a framework of sound environmental stewardship (Costantini and Gilmour 1993). For plantation hillslopes, this means maintenance and improvement of productivity while protecting against erosion, off-site nutrient pollution, and damage to soil ecological processes (Costantini and Gilmour 1993; Costantini *et al.* 1997).

For much of a plantation rotation, the groundcover of litter and understorey vegetation is continuous and undisturbed, and accelerated hillslope erosion together with off-site

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nutrient removal is not considered a problem (see also Bormann and Likens 1981). The period of greatest risk for many tropical and subtropical plantations is the inter-rotation period between clearfall of one rotation and development of continuous cover in the next, when mineral soil may be exposed and/or disturbed (see also Costantini *et al.* 1997).

Traditional residue management and site preparation techniques used during the inter-rotation period in the coastal lowlands were adapted from that described by Foster and Costantini (199l*a*, 1991*b*, 1991*c*) for first-rotation *Pinus* establishment. Clearfall residue and any associated understorey vegetation were stick-raked and burnt prior to the site being cultivated and/or mounded (drained). Stick raking removed up to 95% of residue in a manner that exposed mineral soil, and often disturbed the surface 0–50 mm of the soil profile.

Following stick raking and burning, well-drained sites were contour strip cultivated, while sites subject to periodic saturation were drained with continuous high mounds (Foster and Costantini 1991*b*, 1991*c*). On average, some 2500 ha of land was site-prepared annually during the early 1990s, with 50–80% comprising poorly drained sites. Mounds formed during site preparation were typically 2 m in width, spaced at 4.5 m (Foster and Costantini 1991*b*, 1991*c*). Mound profiles were bordered by furrows, and the outside furrows of adjacent mounds defined an inter-mound zone, resulting in 3 distinct zones: (*i*) mound profile; (*ii*) mound furrows; and (*iii*) inter-mound area.

The mound profile was characterised by tilled and exposed soil, steep mound walls, and some incorporation of residue remaining after stick raking (see also Costantini *et al.* 1995*a*). Mineral soil (A2 horizon) was exposed in the furrows, and while some loose soil moved into furrows from the mound walls, these areas tended to be compacted as a result of vehicle passage during plantation establishment (Costantini 1995). Inter-mound zones tended not to be further disturbed beyond stick raking. Because mound furrows were designed to transfer hillslope runoff efficiently off hillslopes, the potential existed for any entrained sediments or nutrients to be transported rapidly off-site. The experimental work reported in this paper was designed to investigate, for both stick-raked and mounded soils in the coastal lowlands of south-east Queensland: (*i*) runoff and erosion under rainfall; (*ii*) erosion by overland flows (simulating longer slope lengths); and (*iii*) quantities of nutrients carried in runoff.

Methods

A field rainfall simulator and overland flows were used to study runoff, erosion, and nutrient loss under a range of site conditions.

Site selection and description

To represent the range of site conditions observed in stick-raked and mounded areas, the following sites were selected:

(1) freshly mounded upslope site with 2% furrow grades;
(2) freshly mounded upslope site with 1% furrow grades;
(3) freshly mounded downslope site with 1% furrow grades;
(4) ‘consolidated’ (8-month-old) mounded upslope site with 1% furrow grades;
(5) clearfall logged site on 5% gradient, with the residue stick-raked;
(6) clearfall logged site on 5% gradient with the residue left undisturbed.

Mounds constructed during site preparation are designed with an optimal furrow grade of 1.5% (range 1–2%, Foster and Costantini 1991*b*). Whilst much of the coastal lowlands is flat to gently undulating (Coaldrake 1961), impeded drainage is typically more pronounced in downslope positions of the landscape.

Typical residue loads following clearfall in the coastal lowlands comprise 30 t/ha of branches, tops and twigs; 8 t/ha of foliage; and 10 t/ha of surface litter (dry weights) (A. Costantini, unpublished data). Site 6

Table 1. Soil types at each rainfall simulation study site together with a description of key soil characteristics

Site	Classification			A1 Horizon			A2 Horizon		
	Isbell (1996)	Northcote (1979)	Stace *et al.* (1968)	Depth (mm)	Texture^A	Structure	Depth (mm)	Texture	Structure
1 & 2	Yellow Kandosol	Uc2.23	Yellow earth	150	LS	Massive	700	LS	Massive
3	Yellow Kandosol	Uc2.23	Yellow earth	250	LS	Massive	650	LS	Massive
4	Yellow Kandosol	Uc2.23	Yellow earth	150	LS	Massive	1000	LS	Massive
5 & 6	Red Kandosol	Gn2.14	Red earth	150	LS	Massive	300	SL	Massive

^{A}See McDonald *et al.* (1990); LS, loamy sand; SL, sandy loam.

Table 2. Management history at each rainfall simulation study site

Site	Clearfall date	Stick raking	Mound formation	Mound age at time of study
1 & 2	May 1994	November 1994	June 1995	1 week
3	May 1994	November 1994	June 1995	1 week
4	January 1993	February 1994	November 1994	8 months
5	November 1994	April 1995	n.a.	n.a.
6	November 1994	n.a.	n.a.	n.a.

n.a., not available.

was selected as being representative of newly clearfallen areas with residue left intact. Site 5 was selected as being typical of newly stick-raked areas. Mounds studied at Sites 1–4 were designed and constructed using guidelines of Foster and Costantini (1991*a*, 1991*b*, 1991*c*). At Sites 1–3, no rainfall was received during the period between mound construction and rainfall simulation.

Soils at each site are described in Table 1. For soils with sandy loam texture in the surface, erodibility for the universal soil loss equation (USLE) (Wischmeier and Smith 1978) is typically about 0.02 (SI units) (Rosewell 1993), which would be considered as low–moderate erodibility. Such soils typically have low cohesion (especially if saturated), will have low cohesion, and will be particularly susceptible to detachment by concentrated flows. Given the low site gradients, and the (usually) high surface roughness due to surface litter cover, the risk of overland flow erosion is generally low, but can be significantly increased by management practices that concentrate overland flows.

Management histories and key surface soil properties are summarised in Tables 2 and 3, respectively. At all sites, levels of nitrogen (N), phosphorus (P), and potassium (K) in the 0–10 cm layer (Table 3) were <0.05%, <50 mg/kg, and <1000 mg/kg, respectively, and on the basis of the classification proposed by Bruce and Rayment (1982) could be considered ‘very low’. As a result, *Pinus* seedlings are routinely fertilised with 60 kg/ha of P and 23 kg/ha of N at planting (Simpson and Grant 1991). The only exception to the low nutrient levels observed throughout the study area was for total P in the ‘consolidated’ Site 4. This site was planted with *Pinus* cuttings in June 1994 and fertilised in July of that year. Samples analysed to compile Table 3 were collected from the mound profile, and hence were representative of the fertilised area adjacent to pine seedlings.

Experimental design

Three plots were studied at each of Sites 1–4, and two at each of Sites 5 and 6. For each plot, the sequence of operations and measurements was as follows:

(I) simulate rainfall (with a 1-in-10 year, 30-min duration event), with measurement of runoff rates through time, and samples taken of runoff for measurement of sediment and nutrient contents;

(II) after rainfall, simulate increasing overland flows in order to investigate erosion on longer furrow/slope lengths, with measurement of runoff rates through time and samples taken of sediment in runoff.

Two of the plots in each of the mound treatments were fertilised with metered doses of mono-ammonium-phosphate applied to the tops of mounds 2 days prior to simulation.

Table 3. Contents of total nitrogen, phosphorous, and potassium, and particle size distributions in the sites studied

Site	Sampling depth (mm)[A]	Total N (%)	Total P (mg/kg)	Total K (mg/kg)	Clay (%)	Silt (%)	Fine sand (%)	Coarse sand (%)
1 & 2	0–100	0.0605	39.85	109.71	6	6	34.7	53.3
3	0–100	0.0612	34.94	104.33	4	10	34.6	51.4
4	0–50	0.0315	589.54	83.24	6	7	37.4	49.6
4	50–100	0.0253	181.84	67.58	4	8	36	52
5	0–50	0.0353	51.87	123.94	4	4	27.3	64.7
5	50–100	0.0198	52.51	96.68	4	5	27.8	63.2
6	0–50	0.0416	39.85	93.60	4	4	30.7	61.3

[A] Sampling depths of 0–100 mm were used for freshly-disturbed sites (where the surface layer had been mixed), with sites that were undisturbed or not recently disturbed being sampled in 0–50 and 50–100 mm increments. Site 6, which was undisturbed and experienced virtually no erosion, was only sampled to 50 mm.

Rainfall simulation and addition of overland flows

Simulated rain

The rainfall simulator used during the study is described by Loch *et al.* (2001). It uses nozzles spraying downwards to apply simulated rain with kinetic energy similar to that of natural rain at intensities >40 mm/h to a plot area of 12 by 1.5 m. A simulated rainfall design intensity of 110 mm/h, applied for at least 30 min, was selected, consistent with a 1-in-10-year storm of that duration. Typically, rainfall was applied until a steady runoff rate was reached. Rain gauges on the plot were used to record actual intensities applied.

Plot installation

All plots were bounded on 3 sides by metal plates hammered into the soil to confine runoff and, on the fourth (downslope) end, with metal fittings to concentrate runoff and enable sampling. Bentonite was used to seal the fittings into the soil and prevent any undercutting. On the mounded areas, plots were located over a mound/furrow/inter-mound area so that one of the long boundaries of each plot was located on the centre of a mound. On non-mounded areas, plots were located with their long axes aligned downslope.

Overland flows

Following rainfall simulation, water was pumped onto the plots with flow rates monitored using a rotameter and controlled using a gate valve, to generate successive overland flows of 1, 3, and 5 L/s, which were applied to the upslope ends of plots over a plastic sheet in order to minimise scour at the point of application. Flows were applied into the furrows of mounded plots, and across the top end of remaining plots, and maintained to produce a steady runoff rate over 6 min.

Flow rates were used to simulate slope lengths greater than the 12-m length of simulator plots. For example, in the freshly mounded treatment plots, where simulated rainfall produced steady runoff rates of approximately 0.25 L/s, the selected overland flow rates simulated furrow lengths of 50, 150, and 250 m. Comparable lengths for the consolidated mounds, where the plots produced runoff rates of 0.5 L/s, were 25, 75, and 125 m.

Measurements

Runoff rates were determined during simulated rain by direct sampling over fixed time periods, and during overland flows by recording flow heights in a flume installed at the downslope end of plots. During rainfall simulation, runoff samples from each plot were collected as follows:

- 8 samples for sediment analysis;
- 2 samples, one collected soon after initiation of runoff and the other towards the end of the simulation period, for measurement of sediment size distributions;
- 3 samples, collected at approximately the beginning, middle, and end of runoff under simulated rain, for measurement of total N, P, and K using techniques outlined in the following section.

A sample of the water supplied to the simulator was also collected for nutrient analysis. All samples collected for nutrient analysis were refrigerated immediately.

During the overland flow study, 4 samples of runoff were taken at each flow rate for sediment analysis, the first being taken 30–60 s after runoff rate stabilised, and subsequent samples at 2-min intervals.

Gravimetric soil water contents were assessed for 0–50 mm and 50–100 mm surface soil layers before, and for the 0–50 mm layer after, simulated rainfall. Samples of the 'rain-wet' surface to a depth of 3 mm were taken from the mound sideslopes and mound furrow beds at the top and bottom of plots immediately following rainfall for measurement of settling velocity distributions using techniques described by Loch (2001).

Measurement of total N, P, and K in runoff

Runoff (including sediment) was analysed as follows:

- nitrogen—treated with sulfosalicylic acid to complex nitrate and then digested using the Kjeldahl method to convert all nitrogen to ammonium, which was determined colorimetrically using the salicylate–hypochlorite method (Rayment and Higginson 1992);
- potassium—digested with sulfuric and nitric acids, with potassium determined by atomic absorption spectrophotometry (Knudsen *et al.* 1982);
- phosphorus—digested with sulfuric and nitric acids to convert all forms of phosphorus to orthophosphate, which was analysed colorimetrically using the reduced molybdenum blue method (Rayment and Higginson 1992).

No distinction was made between runoff and sediment it carried. As the soils studied are low in clay (Table 3) and in a highly leached, low nutrient environment (Coaldrake 1961), it was assumed that virtually all of the nutrient in runoff was associated with sediment, rather than being in soluble form.

Data analysis

Because durations of applied rainfall varied from 30–45 min across all plots, runoff results were standardised to 48 mm of rain to facilitate comparison.

A linear model was fitted to the data with a term for sites, using the pooled within-site variability as an estimate of error. Data from one of the study plots at Site 4 were not included in the study, as that plot had considerably more grass cover than the 2 other plots at Site 4, and was considered atypical. Data of sediment concentrations in overland flows were log transformed prior to analyses to stabilise within-site variance. Least significant differences were calculated where differences were significant.

Results

Runoff, erosion, and nutrient movement under simulated rain

Runoff and infiltration

To compare infiltration capacities of the various surface treatments, infiltration parameters would normally be derived from runoff data—see for example the procedures proposed by Silburn and Connolly (1995) for estimating parameters for the Green Ampt infiltration equation (Green and Ampt 1911). However, for many of the coarse-textured and 'hydrophobic when dry' soils of the coastal lowlands, changes in infiltration rates through time are not consistent with such equations (see also Costantini *et al.* 1995*b*). This is highlighted in Fig. 1 where runoff began quite early from some water repellent parts of the plot, and infiltration rates declined rapidly to a 'stable' level. In contrast, based on measured water deficit in the soil, and even with the energy for surface seal development set extremely low, the Green Ampt equation predicted much slower development of runoff, and a more gradual decrease in infiltration rate with time. As a result, infiltration parameters were not derived for comparison of treatments, and total runoff after 48 mm rain was used to compare infiltration into the various plots.

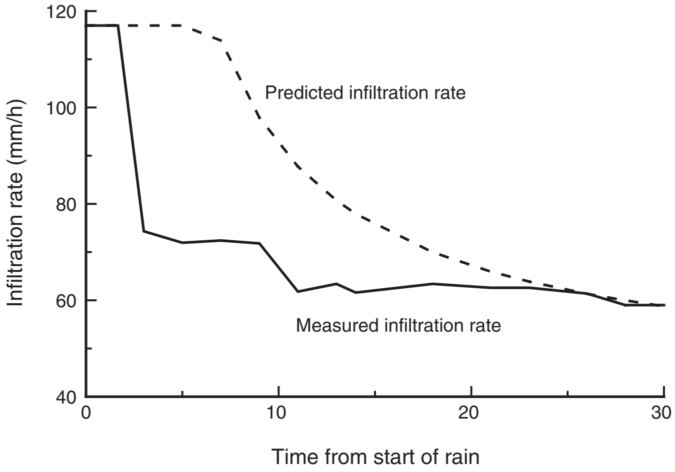

Fig. 1. Comparison of measured and predicted infiltration rates for Plot 1 at Site 1. (Green Ampt equation parameterised to match final infiltration rate.)

Table 4. Rainfall intensities and total runoff from 48 mm rain for 12-m-long plots under simulated rain

Between sites, means followed by the same letter are not significantly different at $P = 0.05$

Site	Plot	Rain intensity (mm/h)	Total runoff (mm)	
1	1	117	17.2	b
	2	96	20.4	
	3	109	21.1	
2	4	119	12.9	c
	5	110.3	15.4	
	6	121.7	6.8	
3	7	106.3	5.8	c
	8	130.8	11.0	
	9	125.4	10.1	
4	10	113.4	32.6	a
	11	118.8	(20.1)[A]	
	12	119.6	30.6	
5	13	127.5	1.4	d
	14	130.8	1.4	
6	15	124.5	0	e
	16	125	0	

[A] Omitted from statistical analysis because plot contained significantly higher grass cover.

Runoff from mounded plots was significantly ($P < 0.05$) higher than runoff from the stick-raked site, which in turn was significantly higher than runoff from the undisturbed site (Table 4). There were also significant differences between mounded plots, with highest runoff from consolidated plots (Site 4), and lowest from plots with furrows on 1% slope (Sites 2 and 3).

Erosion and sediment properties

Observations of mounded plots during simulated rainfall led to the conclusion that erosion followed a consistent pattern of:

Table 5. Total erosion and losses of sediment <0.05 mm after 48 mm of simulated rain

No erosion was observed from the Site 6 undisturbed plots

Site	Plot	Total erosion (t/ha)	Eroded sediment <0.05 mm (t/ha)
1	1	0.97	0.64
	2	1.74	0.40
	3	3.16	1.28
2	4	0.59	0.22
	5	0.54	0.28
	6	1.89	0.21
3	7	0.81	0.2
	8	0.88	0.31
	9	0.52	0.15
4	10	1.97	0.92
	11	0.27	0.13
	12	9.10	1.20
5	13	0.43	0.08
	14	0.17	0.03

1. high rates of sediment detachment from mound sideslopes;
2. subsequent deposition of most of the detached sediment in the furrows;
3. transport of (mostly) fine material and organic matter along furrows and off plots.

Particularly for freshly mounded plots, initial runoff was visibly enriched in dark organic matter. In the mound sites, coarse-textured sand, which contrasted markedly with soils exposed on furrow sideslopes, was deposited in the furrows, consistent with separation of organic matter from the sand grains. Compared with soil on mound sideslopes, deposited soil in furrows contained a higher proportion of particles in the size range 0.1–0.5 mm, whereas eroded sediments contained a higher proportion of particles <0.05 mm.

There were no significant differences in either total erosion or eroded sediment <0.05 mm standardised to 48 mm of rain between Sites 1 and 5 (Table 5). Neither runoff nor erosion was observed under simulated rainfall at Site 6. Considerable scouring of the furrow in Plot 12 (Site 4), associated with a local irregularity (stump) and bed gradient up to 7% over a distance of 4 m, resulted in a much higher soil loss than observed in other plots (Table 5). Data from this plot were not used in statistical comparisons, but they do illustrate the importance of furrow slope in controlling erosion.

Nutrients in runoff

Flow weighted means of total sediment concentration and total N, P, and K concentrations in runoff are shown in Table 6. Water used in the study was taken from nearby watercourses, and had mean concentrations of total N, P, and K of 0.86, 0.041, and 0.33 mg/L, respectively. There was no significant ($P > 0.05$) effect of fertiliser addition on concentrations and losses of either total N or P, nor did the relatively high soil P observed in consolidated sites (Table 3) have any effect on P removal or concentration from these plots. (Note that fertiliser was placed on top of mounds—not the sideslopes—and was therefore not within the area of high sediment entrainment.) The only significant differences noted in nutrient removals were for total K, which, in the case of the stick-raked plots, was associated with large amounts of organic material carried in runoff. Organic

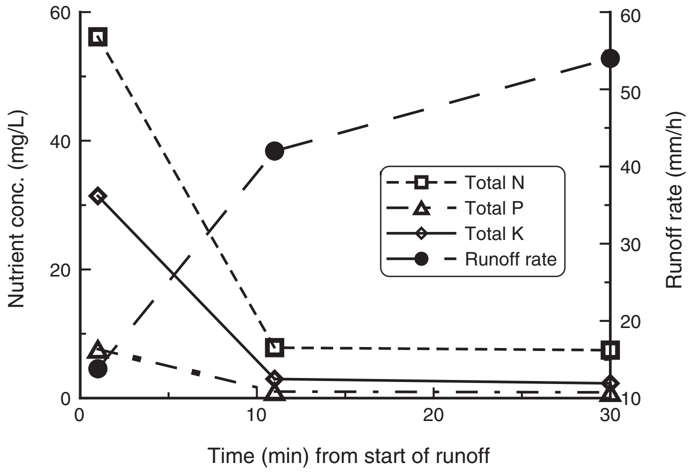

Fig. 2. Changes in runoff rate and concentrations of N, P, and K during rainfall simulation on Site 2, Plot 5.

Table 6. Flow weighted mean concentrations of total sediment and total N, P, and K in runoff

Within columns, values followed by the same letters are not significantly different at $P = 0.05$

Site	Plot	Fertiliser[A]	Sediment conc. (g/L)	Mean conc. (mg/L)				Loss (kg/ha)			
				N	P	K		N	P	K	
1	1	N	5.40	14.01	3.70	4.50	b	2.41	0.64	0.77	a
	2	Y	9.58	11.46	1.87	4.71		2.81	0.46	1.15	
	3	Y	13.83	27.28	1.21	4.06		5.75	0.25	0.85	
2	4	Y	6.28	10.59	3.95	3.82	b	1.37	0.51	0.49	abc
	5	Y	3.57	11.42	1.49	4.98		1.76	0.23	0.77	
	6	N	32.04	18.47	1.16	4.47		1.25	0.08	0.3	
3	7	N	14.17	7.38	1.03	6.45	b	0.43	0.06	0.37	bc
	8	Y	7.50	14.20	1.648	5.31		1.56	0.18	0.58	
	9	Y	4.99	7.18	0.54	2.73		0.73	0.05	0.28	
4	10	Y	6.63	8.47	1.02	3.58	b	2.76	0.33	1.17	ab
	11	Y	1.68	2.89	0.78	2.89		0.59	0.16	0.59	
	12	N	38.46	11.17	2.10	3.74		3.42	0.64	1.15	
5	13	N	12.35	19.79	1.20	12.38	a	0.29	0.02	0.18	c
	14	N	3.04	11.27	0.99	10.26		0.16	0.01	0.15	

[A] Plots which were (Y) and were not (N) fertilised prior to simulation.

material was concentrated at the surface of stick-raked areas, whereas in the mounded areas, inversion of soil by tillage had reduced the surface litter of organic material.

Concentrations of all nutrients were very high during the initial period of runoff, and then declined (Fig. 2). Given these runoff characteristics, flow weighted mean concentrations of nutrients in runoff (as per Table 6) can be expected to decline as the rainfall and runoff duration increases.

Considerable enrichment of N, P, and K was observed in sediment relative to concentrations found in the soil, consistent with large amounts of coarse sand deposition in furrows and highly selective transport of fines and organic matter (Table 7). The lower enrichment ratios observed for P on consolidated mounds at Site 4 reflect high levels of background P (Table 3), and mask the actual enrichment that occurred from mound sides, which were not fertilised.

Table 7. Enrichment ratios of N, P, and K in sediment in runoff from five sites, calculated as the ratio of concentrations in sediment to concentrations in the original surface soil (shown in Table 3)

Site	Mean enrichment ratio for each site N	P	K
1	3.4	9.0	5.6
2	3.4	11.1	7.3
3	2.0	3.7	5.3
4[A]	5.7	0.7	17.1
5	5.6	2.9	12.5

[A] Plot 12 was omitted from the calculations.

Relationships between sediment and nutrient losses

For all data, except those from Plot 12 where the furrow bed was subject to considerable scour, loss of total N was linearly correlated with total erosion ($R^2 = 0.77$) and slightly more strongly correlated with total loss of sediment <0.05 mm ($R^2 = 0.87$). In addition to being concentrated in the finer fraction of sediment, the dark, organic enrichment of initial runoff which contained high levels of N (Fig. 2) suggested that most of the total N in runoff was organic in origin.

Loss of total P was poorly correlated with total erosion, but was correlated with sediment <0.05 mm ($R^2 = 0.57$). Investigation of organic P distribution in the various equivalent sand size classes (separated using the settling column described earlier) showed concentrations (mg/kg) of 14.4, 35.4, and 11.4 for size ranges of <0.05 mm, 0.05–0.1 mm, and >0.1 mm, respectively. For the sample prior to separation of the various size classes, organic P concentration was 22.9 mg/kg, indicating that up to two-thirds of total P was in organic form (based on comparison with data in Table 3). Consistent with the high organic P concentrations found in the 0.05–0.1 mm size class, loss of total P was more strongly correlated with loss of sediment <0.1 mm ($R^2 = 0.7$).

Losses of total K showed greater correlation with sediment <0.05 mm than with total sediment loss. The log relationship fitted was of the form $Y = 0.315(\log X) + 1.015$, where Y = total K, and X = sediment <0.05 mm. This indicates that the sediment size fraction carrying most total K was finer than 0.05 mm, that the concentration of K decreased as the amounts of sediment <0.05 mm increased, and that losses of total K tended to a maximum.

Erosion of furrows and rills by a range of flow rates

In mounded treatments, the typical (all plots except 1 and 12) response observed for each flow rate was high initial sediment concentrations in runoff, which then decreased as supplies of readily available sediment in the furrows were exhausted (Fig. 3, Plot 5). In Plot 1, a tree stump disrupted the continuity of flow along the furrow, resulting in runoff scouring the mound profile. As was the case with the furrow bed scouring observed in Plot 12, this provided a continuing source of sediment for entrainment.

There were no significant differences between treatments for mean sediment concentrations at the lowest flow rate of 1 L/s (Table 8). Significant treatment differences at the higher flows are indicated by letters in Table 8. Outflow rates were highest for the mounded treatments (furrowed plots). Indeed, at 1 L/s inflow, runoff could not be generated from non-furrowed plots in a practical time period.

Table 8. Effects of in-flow rate on sediment concentrations carried by overland flows applied after simulated rainfall ceased

Within columns, means followed by the same letter are not significantly different at $P = 0.05$

Site	Plot	Mean sediment concentrations (g/L) for in-flows (L/s) of:					Measured out-flow rates (L/s) for in-flows (L/s) of:		
		1	3		5		1	3	5
1	1	4.4	4.6	b	7.3	b	0.8	2.9	4.7
	2	2.5	3.2		2.8		0.8	2.5	4.5
	3	6.2	6.4		9.1		0.8	2.7	4.5
2	4	1.9	2.8	bc	5.2	bc	0.5	2.3	4.2
	5	3.0	6.1		4.6		0.5	2.2	4.3
	6	1.1	1.8		1.0		0.6	2.6	4.7
3	7	9.4	4.2	bc	4.5	bcd	0.9	2.9	4.7
	8	1.0	1.7		1.9		0.5	2.3	4.4
	9	1.9	1.9		1.1		0.7	2.3	4.5
4	10	1.0	2.1	cd	0.9	cd	0.7	2.5	5.0
	11	0.4	0.6		0.7		0.5	2.3	4.4
	12	18.3	14.4		8.4		0.6	2.4	4.7
5	13	nil	23.0	a	47.1	a	Nil	1.5	4.6
	14	nil	8.1		17.2		Nil	1.9	2.7
6	15	nil	0.3	d	0.1	a	Nil	1.4	3.4
	16	nil	0.1		0.1		Nil	1.9	2.7

Although sediment concentration in overland flow was unaffected by inflow rate in the mounded treatments, there was a strong relationship between inflow rate and sediment loss in the stick-raked treatment (plots 13 and 14) (Table 8). Erosion from the stick-raked plots was also associated with considerable movement of loose, fine residue (barks, twigs, and needles). Even at the highest inflow rates, erosion was negligible from the newly clearfallen, undisturbed treatment (Site 6). If Plot 12 is excluded from consideration due to the observed bed scour, there is some suggestion that the consolidated furrows in plots 10 and 11 are less susceptible to erosion than the freshly formed mounds of plots 1–9.

Discussion

Infiltration

The undisturbed plots that had clearfall residue left intact did not generate runoff during simulated rain. Half-hour final infiltration rates for these plots exceeded 100 mm/h, suggesting that sites in this condition would not generate Hortonian overland flow in most storm events. Water erosion, other than gully erosion, could only occur if the upper soil profile became saturated, so that overland flow occurred. This finding is of major importance to plantation managers. Clearfallen sites with a good distribution of logging and understorey residue are not prone to accelerated erosion (Tables 5 and 8). However, residue management by stick raking followed by site preparation (cultivation or high mounding) reduces infiltration capacity and increases erosion potential.

The qualitative ranking of infiltration rates of simulated rainfall for the various stick-raked and mounded treatments (Table 4) was as follows: stick-raked > freshly mounded 1% > freshly mounded 2% > consolidated mounds 1%.

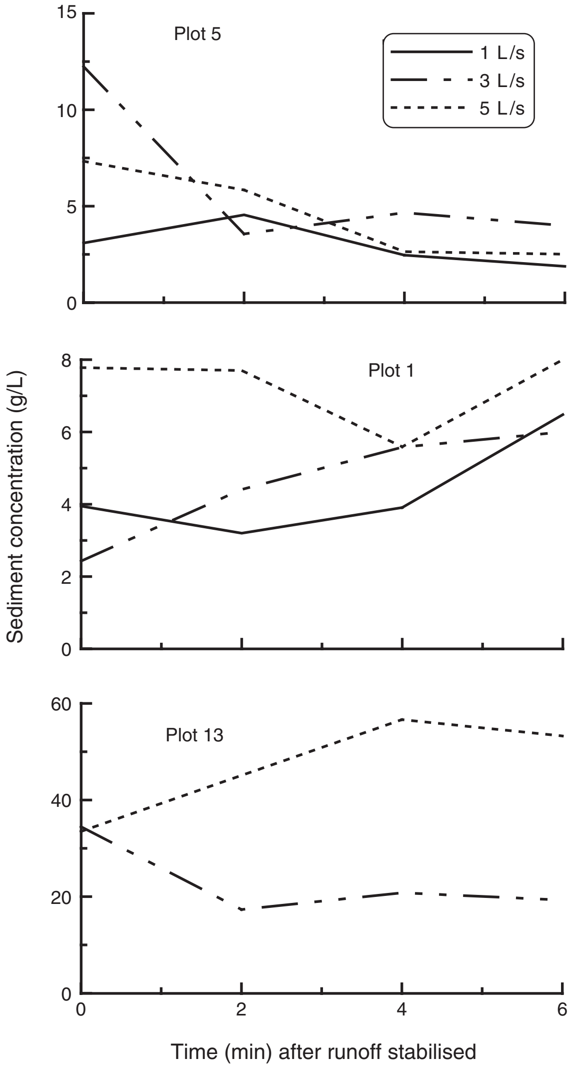

Fig. 3. Effects of flow rate on changes through time in sediment concentrations carried by overland flows on Plots 5, 1, and 13.

Infiltration rates of the stick-raked areas were high, comparable to highly permeable agricultural soils (see Coughlan *et al.* 1991).

Infiltration rates observed in mounded areas are a synthesis of differing infiltration rates in the various mound components, i.e. mound profiles, furrows, and inter-mound areas. Costantini (1995) reported very low infiltration rates for bare, compacted mound furrows in the coastal lowlands. He also observed that mound profiles were typically rounded or peaked, and that, rather than pond, rainfall tended to run off rapidly from mound to furrow. Similar observations were made during the present study. The effect of mound consolidation (ageing) was to further decrease infiltration in the mound profile and furrow (Table 4), as a result of: (*i*) sealing of the mound profile surface, and (*ii*) increased hydrophobicity. Hydrophobicity is widely observed in coarse-textured, coastal lowlands soils (Bridge and Ross 1983; Costantini *et al.* 1995*b*). Notwithstanding the high infiltration rates reported in Table 4, Hortonian overland flow both from the mound profile into furrows and along furrows is observed even under low-intensity rainfall. However, as Plot 11 demonstrated, infiltration increases markedly when grass regenerates.

Susceptibility to erosion

Major factors influencing erosion by overland flows were, in order of importance:

- resistance to overland flow provided by cover;
- slope gradient;
- furrow discontinuities, such as stumps from the previous crop.

The least resistance to erosion by overland flows was observed in stick-raked plots (Table 8), which had loosened surface soil, sparse cover of fine, easily washed residue, and relatively high (5%) slopes compared with the gradients of the cross-slope furrows. In contrast, the undisturbed area, although on the same relatively high slope, had cover that could not be removed by overland flow, and showed negligible erosion. The little erosion by overland flow measured on the undisturbed plots was mostly derived from the bentonite used to seal collection gutters at the ends of plots.

Clearfallen sites with a continuous groundcover of understorey vegetation and residue

The data confirm for the coastal lowlands that freshly clearfallen sites are stable, provided there is a continuous and undisturbed groundcover of understorey vegetation and residue. Results from the overland flow study suggest that sites in this condition are suitable discharge points for some channelised flows such as those associated with road tabledrains.

Stick-raked sites and well-drained sites that are stick-raked plus strip-cultivated

Total erosion observed during rainfall simulation on the stick-raked sites was very small (Table 5), primarily because of high infiltration rates (Table 4). On the basis of data from the 18-m^2 rainfall simulation plots, these sites could be considered stable. However, the overland flow data indicate that site stability declines markedly when runoff channelises and rills develop, as would be expected due to the low cohesion of such sandy soils. Mean sediment concentrations in overland flow from stick-raked plots were generally much higher than those observed in the mounded treatments (Table 8). Moreover, sediment concentrations did not decline as flow duration increased (Fig. 3, Plot 13).

Stick-raked sites can therefore be expected to be unstable in 3 important situations:

(1) on long and/or steeper hillslopes where runoff has increased potential to form substantial rills;
(2) on areas of steep country such as the top-bank side of roadcuts, where runoff water accelerates into tabledrains;
(3) where channelised water is released.

In the plantation forests, the most important sources of released channelised water onto hillslopes are mound turnouts and road tabledrain turnouts. Mound turnouts are located away from stick-raked and cultivated areas during plantation design. Results from this study suggest, and field observations confirm, that stick-raked sites are inappropriate discharge points for road tabledrain turnouts, particularly in undulating to steeper country.

While it was not determined in this study, stick-raked areas are likely to remain susceptible to accelerated erosion until substantial groundcover redevelops—a period that may extend to 6 months in the coastal lowlands.

Continuous high mounded sites

On the 18-m^2 plots, erosion under simulated rainfall was greater in the mounded areas than the stick-raked areas (Table 5). This was a consequence of increased runoff (Table 4), particularly from the mound walls and furrow base, and hence an increased capacity to entrain and transport sediment. By contrast, on a broad-acre basis (simulated by overland flows), mounded areas yielded considerably less erosion than stick-raked areas. For example, although runoff rates for plots 1–3 with 5 L/s flow-on were similar to the runoff rate for Plot 13, the concentration of sediment in runoff from Plot 13 was some 7 times greater (Table 8). A similar comparison with Plots 4–6 reveals 15-fold higher levels of sediment concentration from Plot 13. This is consistent with the much lower (1–2%) gradient of the mound furrows compared with the gradient of rills formed in stick-raked areas (approximately 5%). The instability of stick-raked areas relative to mounded areas could be expected to increase on steeper land.

Both runoff and erosion from plots were greater when furrows were of 2% rather than 1% gradient (compare Plots 1–3 with 4–6 in Tables 4 and 5). The data indicate that sediment transport from consolidated mounded plots is less than that observed from freshly mounded plots (Table 5, excluding Plot 12), despite considerably higher runoff from the consolidated plots (Table 4). This suggests that consolidation reduces amounts of finer sediment available to be entrained in runoff. Plot 5 (Fig. 3) provides a useful insight into erosion processes in mounded sites not colonised with grass. The 1 L/s flow-on produced reasonably constant sediment loss, suggesting that sediment availability for entrainment and movement off-site did not become limiting during the 6 min period. At 3 L/s, sediment concentrations declined rapidly through time, suggesting that available sediment sources were rapidly depleted, and that erosion rates were limited by sediment availability. Sediment concentrations remained low during the 5 L/s flow, providing further evidence that flow detachment from the furrow beds of 1–2% slope was minimal, and that sediment carried by flow was mainly fine sediment detached by earlier simulated rainfall.

Specifications for continuous high mounds used in the coastal lowlands were developed by Foster and Costantini (1991*b*) using the technique of Queensland Department of Primary Industries (undated). The mound system was designed to stabilise furrow flow velocities, so that mound profile and furrow bed erosion were avoided for a 1-in-10 year recurrence interval storm when the furrows were colonised with a 150–250-mm-high grass sward. The flow-on studies reported here demonstrated the stability of both freshly constructed and consolidated mounds even when flow included upslope runoff equivalent to 250 m and 125 m of furrow length, respectively, and even before the development of a continuous sward. While these furrow lengths are less than the (rarely used) maximum permissible lengths of 550 m for non-highly erodible soils (Foster and Costantini 1991*b*), the data suggest that flow along properly constructed mound furrows is unlikely to result in unacceptable soil loss. Furrow irregularities such as localised steep slopes (Plot 12) and presence of tree stumps (Plot 1) can increase scour, whereas grass development along the furrow (Plot 11) will further reduce sediment loss.

Nutrients in runoff

On-site impacts

Nutrient loss was highly correlated with weights of the finer components of eroded sediment, including organic matter. Nutrient losses measured during rainfall simulation on mounded sites (Table 6) equate to some 0.1–1.0% of the surface 100 mm store of total nitrogen, potassium, and phosphorus (Table 3). Stick-raked plots experienced little nutrient loss under simulated rain (Table 6). However, high sediment loads carried by applied overland flows suggest that freshly stick-raked sites may be unstable on a broadacre basis (Table 8), resulting in high levels of fine sediment and organic matter removal. By comparison to the stick-raked and mounded plots, the undisturbed Site 6 plots showed negligible nutrient loss.

Potential off-site impacts

Preferential transport of smaller sized particles and organic matter of low bulk density was particularly marked in mounded sites, where high nutrient concentrations in runoff result from high rates of detachment on the steep mound profiles. The detached coarser fractions are low in nutrients and typically deposit in the mound furrows, while the nutrient-rich fine sediments and organic matter are preferentially transported off-site. Interestingly, enrichment of N and K is greater in the runoff from consolidated plots (Plot 12 excluded, Table 7) than from the freshly mounded plots, with freshly mounded plots on 1% slope showing the greatest enrichment in P.

Nutrient concentrations of the local stream water used for simulation were 0.86, 0.041, and 0.33 mg/L for N, P, and K, respectively. For N and P, these values are slightly above and slightly below (respectively) the trigger values of 0.5 and 0.05 mg/L for total N and total P defined by ANZECC and ARMCANZ (2001) to separate ‘low risk’ from ‘potential risk’ situations for lowland rivers in south-east Australia. The enrichment of nutrients that occurred (Table 7) produced nutrient concentrations (Table 6) approximately 10–70 times higher than those trigger concentrations.

When time-weighted concentrations are considered, the risk of off-site pollution from freshly stick-raked and mounded sites becomes more serious. Over the 30-min rainfall simulation period, concentrations of all 3 nutrients fell dramatically (Fig. 2), with initial concentrations of nutrient in runoff being much higher than average values. These are the nutrient concentrations that can be expected in runoff from shorter duration storms of the same intensity. It should be noted that ANZECC and ARMCANZ trigger values are intended to be compared with low flow data and do not refer to stormflow concentrations, and that even in natural undisturbed forests, intense rainfall events can result in nutrient flushes. However, the data from this study show that short duration, intense storms may result in flushes of high nutrient concentrations, which, depending on contributing catchment area, background nutrient levels, and in-stream attenuation processes, may have adverse downstream impacts.

Conclusions

Newly clearfallen *Pinus* plantation areas, with a relatively uniform distribution of residue and remnant understorey vegetation, were observed to be stable, presenting no significant risk of off-site nutrient pollution.

When similar areas were stick-raked—the traditional management practice for well-drained sites—they became vulnerable to erosion, nutrient loss, and off-site nutrient movement by concentrated overland flows.

Construction of continuous high mounds (on stick-raked areas) greatly reduced soil loss risks, suggesting that (if mounds are to be constructed) the duration between stick raking and mounding should be minimised. Properly designed and constructed mounds were stable to water erosion, even for long furrow lengths, and restricted sediment availability for entrainment and transport in runoff. However, because fine sediments and organic material were preferentially transported off-site via mound furrows, the risk of off-site nutrient pollution was indicated, at least prior to establishment of grass cover.

The data therefore support the move away from traditional residue removal and site preparation practices in QDPIF plantations in this area to an approach based on residue retention, minimum site disturbance, and, wherever possible, 'spot' rather than continuous mounding/cultivation.

Use of a settling column to separate soil into a range of settling velocity classes provided a useful tool for identifying size classes enriched in nutrients, and explained the enrichment of nutrients observed in runoff. This approach offers a method for assessing and (depending on the erosion model used) predicting enrichment ratios of nutrient in eroded sediment for a range of soils. (Clearly, some soils will show either less enrichment in specific settling velocity classes, or enrichment of nutrients in settling velocity classes other than those found in this study.)

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