Part IV

Impact of Harvesting and Burning

Chapter 15

The Oleolega Catchment Experiment

15.1 Background Information

15.1.1 Introduction

The third phase in plantation forestry involves the harvesting of the timber and the site preparation for the next rotation. During this phase landings, landing access roads and skid tracks are constructed, the forest is felled and merchantable timber is extracted, often with the help of heavy machinery. This is usually followed by burning of slash, undergrowth vegetation and litter to prepare the site for replanting. All these practices change the water and nutrient cycles, and in places leave the soil vulnerable to physical and chemical deterioration by compaction, erosion and enhanced leaching of nutrients (Bruijnzeel, 1990; Anderson and Spencer, 1991).

No information was available in this respect for the plantation forests in Fiji, and only very little for pine vegetation on grasslands elsewhere in the tropics (Hudson *et al.*, 1983a,b). Hence the Oleolega catchment experiment was conducted with the following objectives:

- to quantify changes in the water cycle as a result of forest felling and burning of slash
- to quantify the impacts of timber harvesting and subsequent burning of the slash on the nutrient content of the vegetation – litter layer complex
- to study the impact mechanized timber harvesting on soil physical and chemical properties
- to provide information on changes in soil and stream water quality, and to quantify losses of nutrients in streamflow associated with harvesting and burning

This information of course is vital for forest managers as it enables the identification of critical management practices and associated nutrient losses, and helps to evaluate the sustainability of the plantation forests from the nutrient point of view.

Studies on the impacts of harvesting and burning of first rotation forest planted on fire-climax tropical grassland on the availability of nutrients for a second rotation are as yet non-existent. However, a number of studies have been published describing changes in soil properties following the conversion of natural rainforest to plantation forest (*e.g.* Cornforth, 1970; Lundgren, 1978; Chijioke, 1980; Hase and Fölster, 1983; Russell, 1983; Bruijnzeel, 1992b). Furthermore, comprehensive reviews of the literature on effects of disturbance of tropical rain forest ecosystems on carbon, nutrient and water cycles have been published by Bruijnzeel (1990) and Anderson and Spencer (1991). Although these studies pertain to natural forests, of which the biomass and nutrient content are much higher than those of pine plantation forests, some clues are provided as to what changes in soil chemistry, as well as water and nutrient cycles are likely to occur as a result of timber removal and burning of slash of the first rotation.

Forest clearance and subsequent burning usually results in an increase in soil bulk density, and a decrease in topsoil porosity and infiltration capacity. This is the result of soil disturbance and compaction, either by vehicles (Van der Weert and Lenselink, 1972; Lundgren, 1978; Kamaruzaman Jusoff, 1991; Malmer, 1993; Van der Plas and Bruijnzeel, 1993; Jetten, 1994) or by raindrop impact and increased losses of soil organic matter (as a consequence of higher soil temperatures and exposure to solar radiation) leading to structural degradation and erosion (Nye and Greenland, 1960; Lundgren, 1978; Lal, 1987; Anderson and Spencer, 1991). The extent to which physical soil properties are altered depends mainly on the type of equipment used for timber extraction and the volume of timber that is extracted. Manual extraction generally leads to low disturbance, whereas damage increases greatly when heavy machinery is used (Lal, 1987; Malmer and Grip, 1990; Bruijnzeel, 1992a), particularly if the soil is wet (Dias and Northcliff, 1985a,b; Kamaruzaman Jusoff, 1991)

Removal of the forest cover generally reduces the amounts of water lost by rainfall interception and transpiration, thereby increasing the annual water yield (Bosch and Hewlett, 1982), mostly through increased baseflow levels (Bruijnzeel, 1990; Malmer, 1993). However, in some instances shifts in the streamflow regime after deforestation, were such that reductions in the dry season flow were observed (Bruijnzeel, 1989b). Whether such a shift occurs seems to depend mainly on the intensity of the soil disturbance. Infiltration capacities of undisturbed forest soils are usually high, limiting the occurrence of overland flow and associated erosion, and allowing the replenishment of groundwater reservoirs during periods with high rainfall. Removal of the forest and the associated construction of impervious roads and landings leads to a reduction in catchment infiltration capacity, with the largest reductions on tracks, roads and landings (Bruijnzeel, 1992a). If basin infiltration capacity is reduced beyond a certain treshold value, overland flow may become widespread, thereby affecting the shape of the hydrograph (*e.g.* time to peak, magnitude of peak discharge) and thus increasing stormflow volume and limiting the percolation of water to groundwater reservoirs. Erosion as a result of overland flow may cause further degradation of the soil. The combined effect of changes in the hydrograph and high erosion rates may lead to flooding and sedimentation problems in downstream areas during periods of high rainfall, whereas the reduction in groundwater replenishment may lead to reduced flows during the dry season (Bruijnzeel, 1990). It follows that it is of utmost importance to minimize disturbance to the soil during harvesting, particularly in areas with steep topography, high rainfall intensities and a seasonal rainfall regime (Pearce and Hamilton, 1986).

Upon wood extraction substantial amounts of nutrients may be removed in harvested timber and even larger amounts are transferred from the nutrient-rich canopy to the forest floor in slash (Bruijnzeel, 1992a; Nykvist, 1992). For plantations established on grasslands, the amounts of nutrients stored in slash and litter after completion of a logging operation will be much higher than that stored in the initial grassland vegetation – litter complex, and burning results in the sudden release of a large proportion of these nutrients, which may easily be lost by volatilization during the burn (*e.g.* N, S; Little and Clock, 1985), or in water leaving the site as runoff or drainage to deep groundwater (*e.g.* K, Mg, Ca; Tiedemann *et al.*, 1979; Hudson *et al.*, 1983b). Therefore soil nutrients reserves may be reduced considerably after harvesting and burning compared to those present in the original grassland soils.

Cornforth (1970) observed reductions of 18–70% for total N, 0–67% for 'available' P and 13–81% for exchangeable K in acid sandy soils under 4–12 year old *Pinus caribaea* plantations in Trinidad compared to reserves in soils under nearby natural forest. Results for exchangeable Ca and Mg were less clear as reductions of up to 83% and 92%, as well as increases of up to 138% and 21% were observed, respectively. These nutrient losses were ascribed to erosion, but the possibility of leaching may not be excluded in this area of high rainfall (about 3000 mm $year^{-1}$; Cornforth, 1970).

Lundgren (1978) compared soils under natural forest with those underlying an age series of *Pinus patula* and *Cupressus lusitanica* plantations in upland Tanzania and observed that the soil organic matter and nitrogen contents increased during the first 4–8 years after establishment. This was followed by a decrease during periods of high nutrient uptake (age 15–20 years) and by an increase in older plantations (age above 30 years). Stocks of P and K, both in available and reserve forms, declined with plantation age whereas no clear trends were observed for Ca and Mg. Lundgren (1978) concluded that logging during the period of maximum productivity would have resulted in a deterioration of the soil fertility.

Chijioke (1980) studied the effects of the establishment of plantations in Nigeria and Brazil on soil physical and chemical properties and concluded that K deficiency could become a problem in future rotations of *Gmelina arborea* in Brazil, and to a lesser extent in Nigeria. No evidence was found that the removal of nutrients in harvested *Pinus caribaea* would create problems for future rotations, provided that soil disturbance during harvesting would be minimized and slash not be burned.

Russell (1983) compared the nutrient contents of ultisols under rain forest with those in recently logged and burned areas and with those under an 8.5 year old *Gmelina arborea* stand and a 9.5 year old *Pinus caribaea* forest in Jari Florestal, Brazil. The fertility of the soil was reported to have increased initially as a result of the harvesting and burning of the rain forest but it decreased in the course of the first rotation. The decrease in total nutrient stock was such that nutrient deficiencies (*e.g.* Mg, P, Ca) were predicted for the second or third pine rotations. It should be noted, however, that all of the above studies used the 'false time series' referred to earlier and the results should therefore be treated with caution.

Soil disturbance associated with the harvesting process was high in all these studies and considerable quantities of nutrients were eventually lost after the conversion of natural forest to plantation forest. Therefore some kind of nutrient deficiency was predicted to occur in future rotations, suggesting that sustained yields may not be possible with the current methods of logging and intensities of wood extraction and site preparation. The information given above also suggests that any soil physical or chemical improvement obtained during the active growth phase of the forest (*i.e.* phase two) may be offset by the disturbance of the soil and associated losses of nutrients during phase three.

The situation is slightly different in Fiji where the *Pinus caribaea* plantation forests have been planted on old grasslands without much disturbance to the soil during the first rotation. Furthermore, the soils are not too depleted, and roots were observed to penetrate into the zone of active weathering and even in cracks in the bedrock. As

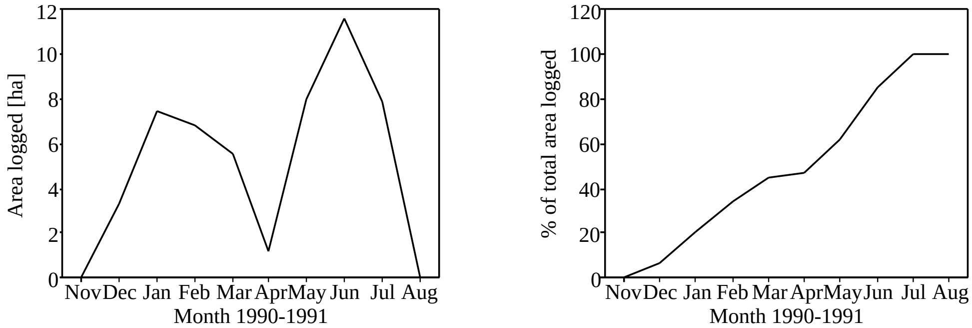

Figure 15.1: *Monthly totals of the area cleared from pines and the progress of harvesting expressed as a percentage of the total forested area in the Oleolega catchment.*

such the forests in Fiji may obtain some of their nutrient requirements directly from weathering of primary minerals. However, even under these relatively favourable conditions depletion of the soil nutrient reserves may eventually occur if the atmospheric nutrient input, the nutrient supply from weathering, the retention of nutrients that would otherwise have been removed during periodic grassland wildfires and the gain of nutrients from reductions in water yields during phase two are less than amounts removed by leaching, erosion, volatilization and in harvesting of merchantable timber during phase three.

The first 11 months of research in the Oleolega catchment were conducted when the catchment was completely under forest. Data on soil characteristics (Sections 4.3 and 4.4), water yield (Section 8.3) and water quality (Section 13.7.2) collected during this period were used as a baseline against which the impact of harvesting and subsequent burning of slash could be assessed. The impacts of cyclone Sina, harvesting and burning on, respectively, the vegetation, litter layer, soil, and water quantity and quality will be examined in the following sections, whereas a nutrient budget for a full rotation and an evaluation of the sustainability of the pine plantations in Fiji will be presented in Chapter 16.

15.1.2 Logging Procedures, Infrastructure and Site Preparation

Harvesting started in December 1990 at age 15.9 as a salvage operation after the forest had been severely damaged by cyclone Sina in November 1990 and continued until August, 1991. Absolute and cumulative monthly totals of logged areas, and the harvesting progress expressed as a percentage of the forested area (51.6 ha) are shown in Figure 15.1. Logging proceeded slowly during the wet season, partly due to adverse weather conditions (wet soils preventing wood extraction), and partly due to conflicts between the land owners and Fiji Pine Ltd. About 50% of the area had been logged in May 1991 whereas the remainder was removed much more quickly during the subsequent drier months.

Before harvesting the area taken up by frequently used and regularly maintained roads (for fire prevention) totalled 1.4 ha (2.2% of total area) with a total road length of 2.0 km. These were located on the ridges forming the southern and eastern catchment boundaries (Figure 3.4). The area of roads constructed for planting purposes in 1975, and infrequently used thereafter, amounted to 1.0 ha (1.6%) with a total length of 1.2 km. These roads were located on the ridges forming the western catchment boundary. At the time of the study some sections of this road (area 0.5 ha) were completely overgrown with grasses and young pine and *Casuarina* trees. The total area covered by roads prior to harvesting amounted to 2.4 ha, or 3.8% of the catchment area, with a total road length of 3.2 km. Before and shortly after harvesting started (December 1990, January 1991) existing roads were upgraded and landings and landing access roads constructed. To facilitate extraction additional road cuts were later constructed in poorly accessible areas (*e.g.* on steep slopes) using heavy earth moving machinery. An uphill logging technique was used in which skidders operated from tracks fanning out from the landings to retrieve trees felled downslope. The effect on the infrastructure of the catchment is visualized in Figure 15.2. By the end of July, 1991, road length had increased nearly threefold to 9.9 km, and the area covered by roads and landings had increased to 4.9 ha, whereas skidder tracks occupied another 1.2 ha. As such the topsoil in an area covering some 10% of the total catchment area was disturbed severely after completion of harvesting.

The slash, undergrowth vegetation and litter layer were burned in the evening of August 15, after harvesting had been completed by the end of July. The fire was ignited on the ridges and burning proceeded downwards until the fire reached the wet riparian zone where it stopped due to lack of dry fuel. The burn was done at night when low wind speeds minimized the risk of spreading of the fire to adjacent forested areas. The litter layer moisture content was measured on August 2 and amounted to 28($\pm$13)% of dry weight. No rainfall was recorded until August 15 and the low moisture content of the slash resulted in a high intensity burn.

The undergrowth vegetation returned within several months after the burn. In April 1992 a map of the vegetation density was compiled by Mr. T.T. Rawaqa from Fiji Pine Ltd. from visual observations. This showed that the vegetation had densities of 60–100% , 30–60% and 0–30% on 49%, 30% and 21% of the logged catchment area, respectively. The vegetation had not returned at all on the severely compacted surfaces of landings, roads, and tracks (T.T. Rawaqa, pers. comm.). Replanting of the catchment to pines commenced in January 1992. Second rotation pines were also planted on landings, roads and tracks and it will be interesting to see how the compaction of these surfaces will affect the growth of the crop.

15.1.3 Methods and Instrumentation

To study the effect of timber harvesting and subsequent burning on soil chemical properties, samples were collected in December 1990 when the catchment was under forest, and in September 1991 shortly after timber harvesting and burning of slash. A rectangular grid (100∗100 m) was placed over a map of the catchment and on both occasions samples were collected at the 25 randomly chosen grid points shown in Figure 15.3. Sampling was done with an auger in a similar fashion as described for the forest plots (Section 4.2). Pre-harvesting samples were collected at depths of 0–10 cm, 10–20 cm and at one 10 cm depth interval between 30–60 cm, depending on the depth of the bedrock. Post-burning samples were collected at depths of 0–10 cm, 10–20 cm, 30–40 cm and, if possible, at 50–60 cm. Landings and tracks had been constructed during harvesting on nine sample points, and at these locations samples were collected at the initial sample point, as well as at a point in the vicinity where

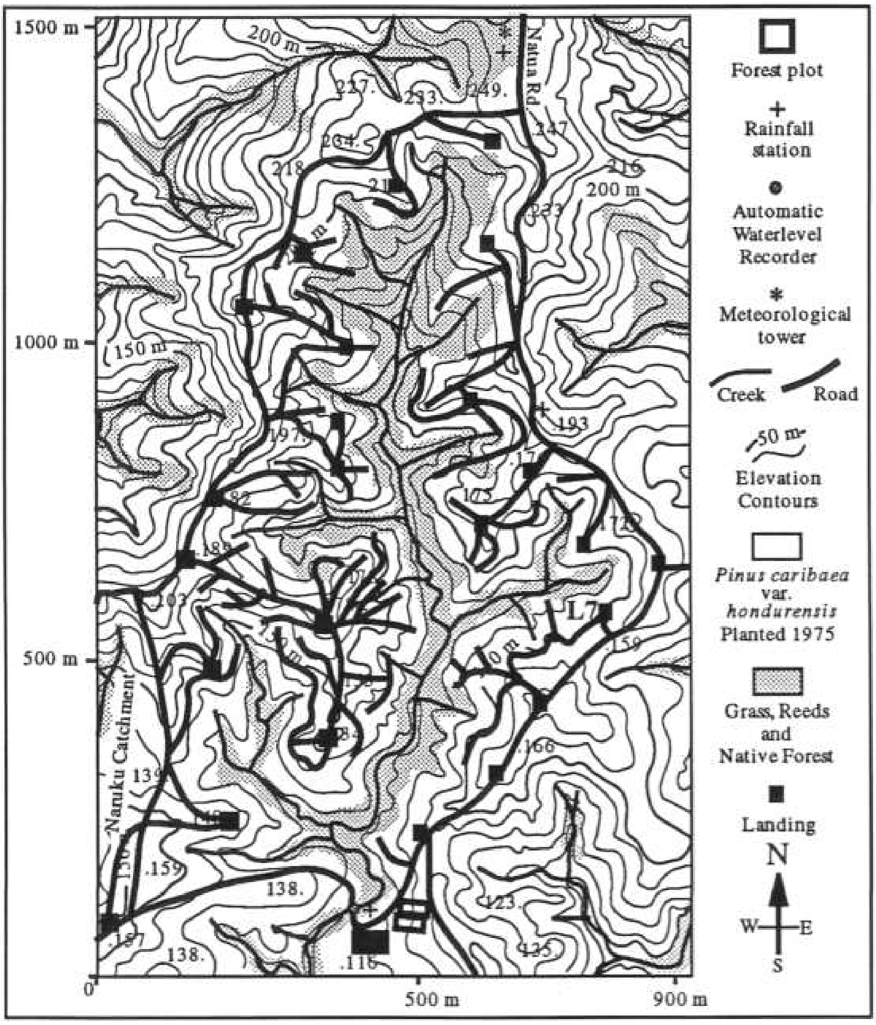

Figure 15.2: *Network of roads, landings and skidder tracks after the completion of harvesting in the Oleolega catchment.*

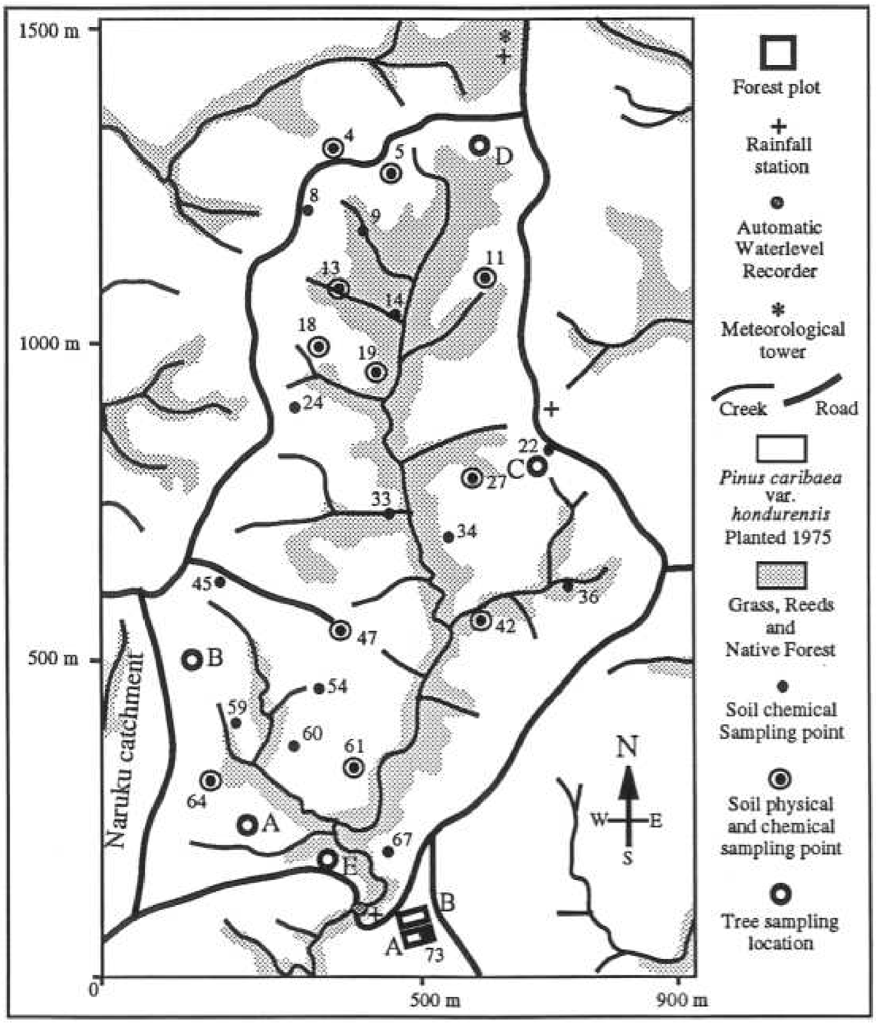

Figure 15.3: *Map of the Oleolega catchment showing the locations of soil, litter and tree sample points.*

the soil was similar but had not been disturbed by heavy machinery.

Undisturbed soil cores were collected on both occasion for determination of saturated hydraulic conductivity, soil moisture retention characteristics and bulk density (*cf.* Section 4.2) at 11 of the 25 selected grid points (see Appendix 25). Samples were collected at the surface (1–6 cm) before harvesting as well as after burning. Samples were also collected at a depth between 20 and 30 cm before harvesting, and near the bedrock (30–55 cm) after burning. When a road, track or landing been constructed on a sample point during harvesting, samples were collected at the sample point as well as from an adjacent undisturbed soil.

To obtain information on the impact of harvesting on the chemical composition of soil moisture and on variations in dry season soil moisture contents, a forested and a harvested plot (both 25*50 m) were established on the same slope near the catchment outlet at the beginning of October, 1990 (see Figure 15.3). Three pairs of vacuum tube lysimeters were installed along the slope in each plot to extract moisture from the topsoil (at -30 cm) and from the subsoil (at -60 cm). Sampling procedures were similar to those used in the forest plots as described in Section 13.2. Soil moisture extraction was possible until April, 1991, after which soil moisture levels prevented further extraction. One access tube for the capacitance soil moisture probe was installed at midslope position in each plot and the tubes were some 40 m apart. The access tube in the forested plot was installed on March 28, 1991, down to a depth of 110 cm, whereas that in the logged plot was installed on May 2, 1991, down to a depth of 54 cm. Profiles of θ were measured twice a week.

Changes in the mass and nutrient content of the litter layer following harvesting and burning were examined by comparison of samples collected before logging (December 13–17, 1990), shortly after completion of logging (August 2, 1991) and after burning of the slash (August 20, 1991) at 16 of the 25 sampling points of Figure 15.3. Sampling procedures were as in Section 11.2. Additional samples were collected on skidder tracks and landings close to several of the sample points. Stemwood and large branches could not be included in the sampling. On each occasion field and dry weights (70 °C) of the samples were determined. The samples collected at sample points 4,5,11,13; 27,34,36,42; 45,47,54,64 and 60,61,67,73 were bulked to obtain a set of four samples representing the whole catchment area. These were analysed at the Forest Research Institute in Rotorua, New Zealand, for macronutrients and micronutrients (with the exception of the first batch) as described previously.

Monitoring of streamflow amounts and composition (see also Sections 8.2 and 13.2) continued after the start of harvesting for the quantification of increased nutrient removal after the cyclone event, timber harvesting and burning of slash. The chemical composition of streamflow was studied from water samples collected during baseflow and stormflow events after harvesting started. Rising and falling stage collectors were installed in December 1990 (Schellekens, 1992) to facilitate the collection of such samples. The large sediment load of the streamflow during stormflow events prevented the filtering of water sampled for cation analysis. Hence no acidified samples could be collected in the field under these conditions, and instead samples were collected in 200 ml bottles and filtered and acidified in the laboratory at the FES-VUA before analysis. The effect of this procedure on the chemical composition of the sample was determined by comparing analysis of acidified and non-acidified samples collected simultaneously during periods with elevated sediment loads (but not such that samples could not be filtered in the field), which are shown in Table 15.1. No significant differences were observed between batches for Na, K, Mg, Ca and Mn. However, concentrations of PO_4, Si, Al, and Fe were significantly higher in the non-acidified samples, whereas NH_4

Table 15.1: *Comparison of means of samples filtered during sample collection, and samples filtered in the laboratory in the Netherlands. The comparison is based on 18 duplicate samples, concentrations are in mg* l^{-1}.

	Na	**K**	**Mg**	**Ca**	**NH4**	**PO4**	**Si**	**Al**	**Fe**	**Mn**
Filtered during collection (A)										
Average	8.79	1.91	2.64	1.40	0.14	0.03	8.1	0.34	0.23	0.01
SD	*1.44*	*0.66*	*0.73*	*0.65*	*0.05*	*0.06*	*2.7*	*0.62*	*0.17*	*0.05*
Filtered in the laboratory (B)										
Average	8.82	2.17	2.88	1.34	0.03	0.12	13.5	3.44	2.02	0.01
SD	*1.65*	*0.73*	*0.72*	*0.73*	*0.03*	*0.13*	*2.1*	*2.35*	*1.27*	*0.04*
A<>B	ns	ns	ns	ns	>***	<***	<***	<***	<***	ns

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance

was significantly lower in these samples, suggesting that sediment and organic matter present in the unfiltered sample absorbed NH_4, and released considerable amounts of the other ions. Several stormflow samples showing such unrealistic concentrations of NH_4, PO_4 and Si were discarded since the presence of sediment obviously influenced the analytical result.

15.2 Changes in the Vegetation – Litter Layer Complex

The impact of cyclone Sina, the removal of merchantable timber, and the burning of slash on the vegetation – litter layer complex will be discussed in this section, with the objective of quantifying the export of nutrients in timber from the catchment, as well as the changes in litter layer nutrient content after the various treatments.

15.2.1 Timber and Nutrient Exports

The biomass of merchantable timber (stemwood and bark) removed from the Oleolega catchment during harvesting between December 1990 and August 1991 was determined by TROPIK Wood Industries Ltd. The fresh weight of logs recovered from PU 10-3 (which includes both the Oleolega and Naruku catchments), amounted to 10411 tonnes and consisted for 20.5% of saw logs and 79.5% of pulp logs (pers. comm. Mr. J. Bale, Fiji Pine Ltd.). The dry weight was calculated using a conversion factor of 0.52 (Section 11.3.2). The amount of wood extracted from the Oleolega catchment could be calculated using the ratio of the forested area in Oleolega catchment (51.6 ha) to the total forested area in PU 10-3 (81.3 ha). Hence 3436 tonnes (dry weight) of wood were recovered from the catchment, or 54.6 t ha^{-1}. This included an estimated 6.6 t ha^{-1} of bark, which was used as fuel for power generation at the TROPIK Wood Industries Ltd. sawmill.

As the dimensions of the trees in the Oleolega catchment were not significantly different from those in Koromani forest (α= 0.01) an estimate of the total pine biomass in the Oleolega catchment could be obtained by multiplying the pine biomass in

Table 15.2: *Average nutrient concentrations and standard deviations (SD) in harvestable timber sampled at various locations in the Oleolega catchment. The average dimensions of the sample trees are shown for comparison. Concentrations of macronutrients and micronutrients in % and in ppm, respectively, n represents the sample size.*

Site	N	P	K	Ca	Mg	Zn	Mn	B	n	Dbhob	h
Northern part (on dacite)											
Average	0.081	0.008	0.051	0.041	0.020	10	60	1.1	9	0.265	18.8
St. deviation	*0.011*	*0.002*	*0.011*	*0.012*	*0.003*	*4*	*30*	*0.2*		*0.029*	*1.0*
Southern part (on andesite/diabase)											
Average	0.084	0.013	0.056	0.046	0.021	13	47	1.4	5	0.276	19.4
St. deviation	*0.015*	*0.003*	*0.009*	*0.009*	*0.002*	*11*	*10*	*0.5*		*0.038*	*0.7*
Whole catchment											
Average	0.082	0.010	0.053	0.043	0.021	11	57	1.2	14	0.269	19.0
St. deviation	*0.012*	*0.004*	*0.010*	*0.011*	*0.002*	*7*	*27*	*0.3*		*0.033*	*0.9*

Koromani forest (Table 11.7) with the ratio of the stocking of Oleolega forest (459 trees ha^{-1}) to that of Koromani forest (621 trees ha^{-1}). This resulted in an estimate of 106 t ha^{-1} for the total pine biomass and of 86 t ha^{-1} for the stem biomass (including bark). The latter value is 1.6 times higher than that actually obtained earlier for harvested merchantable timber (54.6 t ha^{-1}), which may be explained by the fact that a large number of cyclone damaged trees with little or no economic value were left to rot in the field.

No data were obtained for undergrowth biomass, nor for biomass of the natural forest in the riparian zone. However, visual observation indicated that the density and composition of the undergrowth vegetation in the afforested areas of the Oleolega catchment were roughly comparable to those in the Koromani forest plot, and the undergrowth biomass was therefore assumed equal to 3300 kg ha^{-1}. However, this may well be an underestimate in view of the lower stocking of the forest at Oleolega.

Average nutrient concentrations in tree stems (wood and bark) sampled in the Oleolega catchment are given in Table 15.2. Averages for the northern part of the catchment, where soils were derived from dacitic rock (Chapter 4), were obtained from tree samples collected at locations B, C and D (Figure 15.3), whereas those for the southern part, where soils were derived from andesitic to diabase rock, were sampled at locations A and E. Phosphorus levels in tree stems growing in the southern part of the catchment were significantly higher ($\alpha = 0.01$) than in the northern part, possibly reflecting differences in soil or rock. Differences for the other nutrients were not significant.

Amounts of macro- and micronutrients exported from the catchment in merchantable timber between December 1990 and August 1991 are given in Table 15.3 together with estimates for the macronutrient export in bark only. The latter were obtained from the estimated total nutrient export using the average ratios of bark nutrient content to the total of stemwood and bark as observed in the Tulasewa, Korokula and Koromani forest plots (Table 11.17). The average ratios for Ca (0.18) and K (0.19) were lower than for N (0.25), P (0.25) and Mg (0.22). Differences between

Table 15.3: *Nutrient exports (kg ha^{-1}) from the Oleolega catchment in merchantable timber (stemwood & bark) and in bark only.*

Component	N	P	K	Ca	Mg	Zn	Mn	B
Stemwood & Bark	44.8	5.3	28.7	23.4	11.2	0.6	3.1	0.1
Bark	11.0	1.3	5.4	4.2	2.5			

the plots were small, with the exception of the ratio for P which ranged from 0.16 in Koromani forest to 0.40 in Korokula forest. No data were available in this respect for B, Mn and Zn.

Although the amounts of nutrients in timber exported from the catchment were small compared to the total nutrient content of the forest biomass (Section 11.6), they were much larger than the annual export of nutrients in streamflow from the catchment in the forested state (Table 13.14).

15.2.2 Litter Layer Mass and Nutrient Content

Cyclone Sina inflicted severe damage to the forest in the Oleolega catchment and the amount of litter on the forest floor at the end of November was therefore much higher than usual even before logging commenced in December 1990. Litter standing crop in December averaged 29,130 kg ha^{-1} (range 10,820–56,540 kg ha^{-1}, n= 16; Table 15.5) which was not significantly different (α= 0.05) from that measured in Koromani forest in January 1991 (22,688($\pm$4882) kg ha^{-1}, n= 12). As the damage afflicted to the Oleolega forest was comparable to that to Koromani forest (visual observation), the pre-cyclone litter layer mass observed in the latter (13,500 kg ha^{-1}; Table 12.7) may be used as an approximation for the pre-cyclone litter layer mass in the former.

The timber extraction procedure was such that the spatial heterogeneity of the litter layer was increased compared to the pre-logging heterogeneity. Several intensities of disturbance were distinguished which were associated with distinct phases in the timber extraction process. In the first extraction stage branches and foliage had not yet been stripped from the stem after logging by chainsaw, and the litter layer in an area several metres wide was pushed aside and accumulated in patches along the paths made by the trees when hauled (with a winch) to the skidder. This disturbance was considered to be of low intensity, and the mass of the litter layer sampled in these areas ranged from 2,960 kg ha^{-1} to 69,160 kg ha^{-1} (n= 16), with an average of 30,762($\pm$20137) kg ha^{-1}, which is somewhat larger than the post-cyclone range (10,820–56,540 kg ha^{-1}) and average. In the second stage trees (including the crown) were towed behind the skidder to a landing access road or landing. The disturbance of the litter layer on these skid tracks was more severe, especially after several passes had been made over the same track (*cf.* Kamaruzaman Jusoff, 1991). Litter under the tires of the skidder was pushed to the sides as well as into the soil, leaving the wheel tracks largely bare and causing an accumulation of litter along the edges of the track (*cf.* Gillman *et al.*, 1985). Where earth moving machinery had been used to construct access roads to the landings, a mixture of soil and litter accumulated along the roadside leaving the road surface free of litter. When litter samples collected in these areas were included, observed amounts of litter mass ranged from 1,380–153,380

Table 15.4: *Averages and standard deviations (SD) of nutrient concentrations (in % and ppm for macro- and micronutrients, respectively, n= 4) in the litter layer in the Oleolega catchment before harvesting, after harvesting, and after burning, as well as levels of significance for the differences between the means of the different treatments. Post-cyclone concentrations in the litter layers in Tulasewa, Korokula and Koromani forests are shown for comparison.*

	N	P	K	Ca	Mg	Zn	Mn	B
TULASEWA FOREST	0.725	0.049	0.138	0.558	0.189			
KOROKULA FOREST	0.608	0.029	0.084	0.501	0.221			
KOROMANI FOREST	0.685	0.040	0.091	0.559	0.181			
OLEOLEGA CATCHMENT								
Before logging (1)	0.745	0.038	0.246	0.379	0.142			
SD	*0.168*	*0.007*	*0.066*	*0.061*	*0.024*			
After logging (2)	0.779	0.054	0.240	0.344	0.166	30	654	9.3
SD	*0.109*	*0.014*	*0.069*	*0.062*	*0.025*	*2*	*171*	*0.9*
After burning (3)	0.747	0.175	0.283	0.497	0.364	44	821	11.9
SD	*0.136*	*0.023*	*0.102*	*0.116*	*0.128*	*8*	*401*	*2.5*
Difference in means of litter after treatments								
1 <> 2	ns	<*	ns	ns	ns			
2 <> 3	ns	<***	ns	<**	<**	<***	ns	<*

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

kg ha^{-1}, with an average of 37,185 kg ha^{-1} (Table 15.5), which is a factor 1.3 higher than the litter layer mass before harvesting started. However, as soil and litter were often well mixed, sampling of litter on the tracks was very difficult, and the actual range may have been much larger. The disturbance of the litter layer was considered to be of medium intensity on infrequently used skidder tracks (one or two passes), and of high intensity on frequently used tracks and access roads (more than two passes). In the third extraction stage trees were prepared for transport to the saw mill after arrival on the landings. This involved the stripping of the branches and foliage from the trees. To keep the landing area clear the slash was regularly pushed to the edges where it formed large piles consisting of a mixture of soil and slash. The spatial heterogeneity reached a maximum on these landings, and due to the size and composition of the piles no estimates could be obtained in these areas.

As a result of this increased spatial heterogeneity of the litter layer, it was difficult to determine whether the average value obtained from the limited number of sampling points was representative for the amount of litter present after the completion of harvesting. However, as the dimensions of the trees at Oleolega were similar to those in Koromani forest an independent estimate of the potential slash production could be obtained by using the pre-cyclone biomass data of Koromani forest (Table 11.7) corrected for differences in stocking. This resulted in a potential slash production of 22,600 kg ha^{-1} and with an estimated pre-cyclone litter layer mass of 13,500 kg ha^{-1}, the total mass of the litter layer after harvesting would be 36,100 kg ha^{-1}. This is close to the measured post-logging value, and the error in the areal estimate given earlier was therefore considered small.

The prescribed burn in August consumed the slash as well as the undergrowth

Table 15.5: *Averages and standard deviations (SD) for the litter layer mass and nutrient contents (kg ha^{-1}) in the Oleolega catchment before harvesting, after harvesting, and after burning, as well as levels of significance for the differences between the means of the different treatments.*

	Mass	N	P	K	Ca	Mg	Zn	Mn	B	n
Pre-cyclone+	13511	71.2	2.9	11.6	85.1	26.5	0.13	5.3	0.09	60
Before logging (1)	29130	206.9	10.8	71.7	108.2	40.7				16
SD	*12491*	*79.6*	*4.8*	*38.1*	*44.8*	*17.5*				
After logging (2)	37185	292.3	20.2	91.2	121.8	61.9	1.09	25.2	0.34	22
SD	*33632*	*278.4*	*20.3*	*92.6*	*100.0*	*56.8*	*0.96*	*26.6*	*0.30*	
After burning (3)	5787	46.7	9.7	18.9	27.1	25.4	0.28	6.1	0.07	19
SD	*7992*	*73.4*	*12.4*	*29.8*	*36.7*	*43.8*	*0.43*	*10.5*	*0.10*	
1 <> 2	ns	ns	<**	ns	ns	<*				
2 <> 3	>***	>***	>**	>***	>***	>**	>***	>***	>***	

+:Data from Koromani forest
ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

vegetation in the previously forested areas but did not have a large effect on the vegetation in the riparian zone. Post-burn measurements of the ash layer in the previously forested areas showed a significant decrease of the litter layer and undergrowth vegetation mass, from a pre-burn total of about 40,000 kg ha^{-1} to a post-burn total of 5,800 kg ha^{-1} (range 320–33,560 kg ha^{-1}, Table 15.5). As a result, after the burn the soil surface was exposed in most parts of the catchment.

The average nutrient concentrations in the litter layer on the three sampling occasions are shown in Table 15.4 together with the levels of significance for the differences between means (*Student's t* test). No significant differences were found for the concentrations of N, K, Ca and Mg in the litter layer before and after logging, but the concentration of P was significantly higher after logging. However, it must be remembered that the large input of fresh litter by cyclone Sina had already changed the concentrations of N, P, K, and Ca in the litter layer significantly as compared to the pre-cyclone composition (see Section 12.5.2). No data were available for the concentrations of Zn, Mn and B in the samples collected in December 1990. Burning of the litter layer had no significant effects on the concentrations of N, K and Mn but caused significant increases in the concentrations of P, Ca, Mg, Zn and B, suggesting that these elements were retained in the ash.

Litter layer nutrient contents for each treatment were calculated from litter layer mass and corresponding concentrations of nutrients. The results are presented in Table 15.5. The contents of all nutrients increased after harvesting, but the increases were only significant for P and Mg which increased by factors of 1.9 and 1.5, respectively. Again it must be stressed that cyclone Sina had increased the nutrient content of the litter layer considerably compared to the pre-cyclone situation (Table 12.7), and the effect of harvesting was therefore for a large part drowned by that of the cyclone. Litter nutrient content was reduced significantly by the burning, with post-burn amounts being 16% (N) to 48% (P) of the pre-burn contents. Therefore large amounts of nutrients were released from the slash during the fire, which greatly increased the

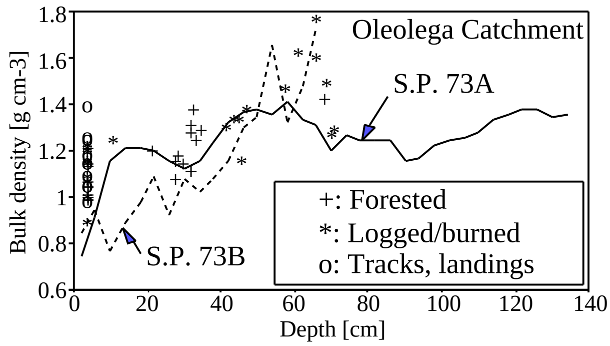

Figure 15.4: *Bulk density data for the soil at various locations in the Oleolega catchment.*

possibility of subsequent losses by leaching, or in overland flow during large storms (O'Loughlin *et al*, 1980; Hudson *et al.*, 1983b; Uhl and Jordan, 1984).

15.3 Impact of Harvesting on the Soil Physical Properties

Baseline data on soil physical properties have been provided in Chapter 4 and the effects of harvesting and burning on these properties are examined in this section.

15.3.1 Bulk Density

Figure 15.4 shows bulk density data for the Oleolega catchment collected before logging and after logging and burning of the slash. Two access tubes for the capacitance probe were installed close to sample point 73 (see Figure 15.3). Access tube S.P. 73A was installed in a small forest plot on relatively deep soil (rock at ±1.5 m) whereas access tube S.P. 73B was installed on the same slope at a distance of about 40 m from S.P. 73A in a shallow soil (rock at ± 70 cm) in a deforested area (see also Appendix 24). The two profiles compared well with bulk densities obtained from core samples (Appendix 25) collected at other sample points in the catchment (Figure 15.4).

To assess the impact of harvesting on soil bulk density, data collected for the upper 10 cm of soil in the forested state in December 1990 were compared with those collected in areas that had been logged and subsequently burned, but not disturbed otherwise, and with data collected on new roads, tracks and landings between August and October 1991. Due to the massive structure of the subsoil it was unlikely that harvesting and burning would have had a major effect below a depth of 30 cm (Van der Plas and Bruijnzeel, 1993) and the results obtained for the samples collected below this depth after logging and burning were therefore used to derive estimates for the bulk densities at intermediate depths for the pre-logging situation as well as for the soil under tracks, roads and landings. Estimates for depths up to 60 cm in the forested and in the logged and burned catchment are presented in Table 15.6, together with those for soils under roads, tracks and landings. Harvesting and burning greatly increased the spatial variation in bulk density as indicated by the increase in standard

Table 15.6: *Average bulk densities (g cm^{-3}), standard deviations, number of sample points and significance levels for the differences between means for soil samples collected in the Oleolega catchment in December 1990 (forested) and September 1991 (logged and burned; tracks & landings).*

Location	**Depth [cm]:**	0-10	10-20	20-30	30-55
Forested		1.07	0.535	1.21	1.41+
Standard deviation		*0.07*		*0.09*	
Number of samples		12		12	
Logged & burned		1.13	1.17	1.21+	1.41
Standard deviation		*0.11*			*0.17*
Number of samples		13			12
Tracks & landings		1.17	1.25	1.33	1.41+
Standard deviation		*0.11*			
Number of samples		10			
Differences in means between treatments					
Forested <> Logged & Burned		<*			
Forested <> Tracks & Landings		<**			
Logged & burned <> Tracks & landings		ns			

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.001; +: Assumed value; Underlined values have been obtained by linear interpolation

deviations. Although the sample sizes were small, the data suggested that the bulk density of the top 10 cm of soil increased significantly (α= 0.10) after harvesting and burning in the absence of further disturbance of the topsoil. This may have been due to degradation of soil aggregates (Lal, 1987). However, the increase was not large enough for the average value to fall outside the range observed for the soils in the forest plots (0.97–1.16 g cm^{-3}) and this increase should therefore not have a major impact on the productivity of a second rotation forest. Naturally, higher bulk densities were observed on tracks and landings where the topsoil had been disturbed severely and these were significantly different (α= 0.05) from those of the soil under forest but not from those of undisturbed soil after logging and burning. On the landings the growth of the newly planted second rotation forest may be poor due to the complete removal of the topsoil, which exposed the saprolite, or due to the severe compaction of soil and subsequent erosion (Assenberg, 1993). The high bulk densities observed in these areas may also impede root development (Van der Weert, 1974) which is likely to lead to lower productivity rates in the next rotation. It seems unlikely that the planting of pines on the roads and landings will improve the soil structure to a large extent.

15.3.2 Saturated Hydraulic Conductivities

Estimates of the hydraulic conductivity (K_{sat}) obtained from undisturbed core samples collected before and after logging and burning, as well as on roads, tracks and landings,

Table 15.7: *Averages, standard deviations (SD), medians, modes and ranges of K_{sat} for top- and subsoils before and after harvesting and burning in the Oleolega catchment and for the top 10 cm after construction of tracks and landings.*

Treatment	**Depth** [cm]	**Average** [m day-1]	**SD**	**Median** [m day-1]	**Mode** [m day-1]	**Minimum** [m day-1]	**Maximum** [m day-1]	**n**
Forested	1-6	73	73	52	27	0.1	225	12
Logged & burned	1-6	15	41	1.5	1.06	0.01	153	14
Tracks & landings	1-6	0.17	0.23	0.049	0.043	0.0001	0.69	11
Forested	25-35	3.1	5.3	1.22	0.58	0.06	19	12
Logged & burned	40-70	0.05	0.08	0.0088	0.0082	0.0004	0.24	13

are shown in Table 15.7. Data for the individual samples are given in Appendix 25. Although the sample sizes were small significant differences were observed between the various intensities of disturbance. The K_{sat} of the topsoil decreased significantly (α= 0.01) as a result of the forest clearance and subsequent burning of the slash, possibly due to a collapse of the soil structure as a result of raindrop impact and exposure to solar radiation (Lal, 1987).

The K_{sat} of compacted topsoil of tracks, roads and landings was significantly lower (α= 0.01) than measured in adjacent relatively undisturbed soils. Widespread overland flow and erosion was indeed observed on these compacted surfaces during larger storms but not in the adjacent less disturbed areas (Assenberg, 1993). The impact of these changes on the streamflow hydrograph and water quality will be discussed in Section 15.6.

15.3.3 Porosity and Moisture Retention

The modelled (Van Genuchten, 1980; see Appendix 25) average pre-harvesting porosity of core samples collected in the top 6 cm of soil (60±6%; Table 25.10) at nine points in the catchment on which roads, tracks or landings were later constructed during harvesting was not significantly different from that derived after the burn on these tracks, roads and landings (57±4%, n= 9; Table 25.14), nor from that derived for the adjacent relatively undisturbed locations (62±5%, n= 9; Table 25.12).

However, the porosity of the soil of tracks and landings (Table 25.14) was significantly lower (α= 0.05) than of the soil in adjacent areas subjected to logging and burning but without disturbance by heavy equipment (Table 25.12). This was supported by the fact that macropores, which were abundant in the undisturbed soils, were not observed in the compacted soils on roads and landings (*cf.* Jetten, 1994). However, as the difference was rather small the decrease in pore size may in some way have been balanced by an increase in the number of smaller-sized pores. Since soil moisture retention characteristics are likely to change as a result of changes in pore size (increasingly higher suctions are needed to remove moisture from pores of decreasing size), a study of the corresponding moisture retention characteristics should indicate whether such a change occurred. Figure 15.5 shows the average moisture retention curves for the pre- and post-harvesting/burning periods as well as for soils on tracks, roads and landings. Moisture retention data for individual core samples are given in

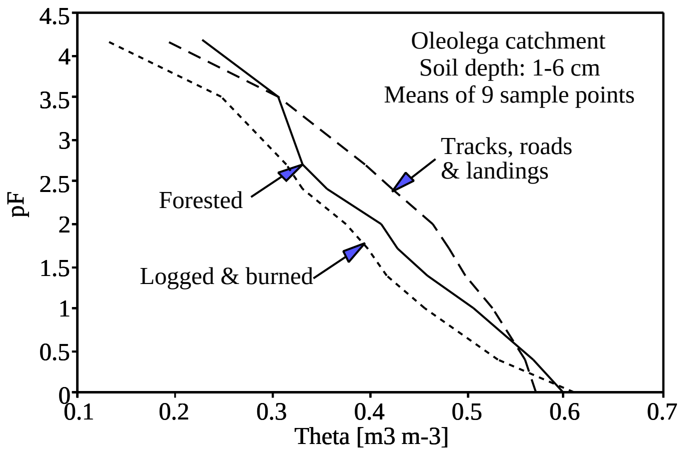

Figure 15.5: *Average moisture retention curves for the topsoil in Oleolega catchment before and after logging and burning and on tracks, roads and landings.*

Appendix 25. Although the average post-harvesting/burning porosity of topsoil in areas not disturbed by heavy machinery was higher than that of topsoil on adjacent roads, tracks and landings, the average below field capacity (pF= 2) moisture content was significantly lower (α= 0.05 for 0.4<pF<1.4 and 0.10 for pF= 1.7–2.0). This indicated that a reduction in (macro)pore size had indeed occurred as higher suctions were now needed to remove water from topsoil on roads, tracks and landings. Differences between the moisture retention of soil under forest and on tracks, roads and landings were not significant below a pF of 1.0 but above this value significantly higher moisture contents (α= 0.10 for pF= 1.4 and 0.05 for pF>1.4) were again observed for the latter (Figure 15.5). The moisture content above pF= 2.0 of the samples collected under forest was modelled (Van Genuchten, 1980) due to lack of laboratory facilities in Fiji, whereas those for the samples collected after logging and burning were actually measured. Therefore, it was not possible to determine if the observed changes in the soil moisture retention characteristics affected soil water holding capacity. However, the present data do not suggest any major change in the water holding capacity. However, as the removal of soil (*e.g.* on roads and landings) reduced the soil depth (already low on the ridges), the amount of water available for plants will have been reduced accordingly. Hence second rotation forest planted on landings and roads may experience periodic water stress during the dry season and this, in combination with the poor structure of the compact soil will almost certainly lead to lower productivity. Due to the small textural differences between topsoil and subsoil the impact of logging and burning on soil texture could safely be neglected and therefore no granulometric analyses were done on samples collected after logging and burning.

The observed changes in porosity and moisture retention were similar to those observed by Kamaruzaman Jusoff (1991), who studied changes in porosity and available water holding capacity after up to 50 passes were made with a crawler tractor and a rubber tyred loader on undisturbed clay loam soil during wet and dry months in Central Pahang, Malaysia. Kamaruzaman Jusoff (1991) observed that the porosity decreased from 46–47% to 37–41%. Shifts in the soil moisture retention curves were also observed and this resulted in a decrease of the available water holding capacity from 100–110 mm m^{-1} to 83–94 mm m^{-1} after 50 passes. The largest changes were observed during the first 2–4 passes of the vehicles and changes caused by the rubber tyred loader were larger than those by the crawler tractor which was attributed to differences in contact pressure. Dias and Northcliff (1985a,b) also observed decreases in the number of macropores (from 20% in undisturbed topsoil to about 7% after several tractor passes) and the topsoil water holding capacity of a clayey Oxisol after clearing of rainforest in Amazonia, with the largest changes after mechanical clearing by bulldozers.

15.4 Impact of Harvesting Soil Chemical Properties

The effect of logging and subsequent burning of the slash on soil chemical characteristics in the Oleolega catchment was studied by comparing samples collected before logging started with those collected after the burn. The samples representing the forested situation, were collected in December 1990, shortly after cyclone Sina had deposited salts (sea spray, Table 13.4) and large amounts of fresh litter (Table 12.7) on the soil surface. However, the amounts of nutrients deposited as sea spray were small compared to the corresponding nutrient reserves in the soil (Table 4.10) and because rainfall in the period between the passage of the cyclone and the collection of samples had been low (17 mm) the transfer of nutrients from the freshly deposited litter to the soil by leaching (*e.g.* K) was neglected. As such the influence of the cyclone on the soil chemistry at the time of sampling was considered small.

The post-burn samples were collected between 5 September and 1 October 1991. On the other hand, some 66 mm (September 5) to 224 mm (October 1) of rainfall was recorded after the burn, which was considered sufficient to transfer readily soluble nutrients present in the ash to the soil. The loss of nutrients from the litter layer and slash following the burn was discussed in Section 15.2.2 (Table 15.5). Average values for various chemical properties of the soil before and after logging and burning are presented in Table 15.8, whereas the raw data are listed in Appendix 26. The effects of logging and burning were most evident in topsoil and the largest differences were observed between soil under forest and that of tracks and landings. Exchangeable NH_4 decreased significantly whereas the pH_{H2O} and the pH_{KCl} showed significant increases throughout the soil profile after logging and burning. The increase in pH_{H2O} was sufficient to bring the soil from the cation exchange buffer range to the silicate buffer range (Ulrich and Khanna, 1984). Ca-lactate extractable PO_4 did not show significant changes in topsoil after burning but increased in subsoil. No significant changes for other soil chemical characteristics were observed in the subsoil. Exchangeable K increased whereas exchangeable NO_3 decreased in the topsoils of relatively undisturbed areas and tracks and landings after logging and burning. Exchangeable Na showed a significant decrease and exchangeable Ca a significant increase in the 0–10 cm layer of the soil in relatively undisturbed areas but neither was the case for the soils of tracks and landings.

The N content did not change significantly after harvesting and burning in areas where the topsoil was not disturbed by heavy equipment, but it was significantly lower in the surface layer on tracks and landings due to the removal of N-rich topsoil. However, no significant changes were observed in for the carbon content. As a result,

Table 15.8: *Chemical properties of the soil at several depths before logging started in the Oleolega catchment, and after harvesting had been completed and the slash had been burned. The sample size is represented by n, the depth is in cm, the LOI is in % whereas exchangeable cations, available PO_4 and soluble NO_3 are in meq 100 g^{-1} soil.*

Location	Depth	n	pH	pH*	%N	%C	C/N	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
Oleolega	0-10	25	4.60	3.97	0.136	2.22	18.0	8.3	0.170	0.114	1.28	1.93	0.170	0.129	0.013
Forested	10-20	25	4.56	3.87	0.084	1.25	15.7	7.1	0.118	0.081	0.75	1.67	0.133	0.068	0.004
	30-60	25	4.72	3.83	0.033	0.37	11.4	6.2	0.127	0.062	0.29	2.06	0.070	0.025	0.001
Oleolega	0-10	25	5.25	4.26	0.130	2.17	20.9	8.7	0.111	0.179	1.73	2.43	0.103	0.042	0.012
Logged &	10-20	25	5.16	4.12	0.077	1.25	21.9	7.6	0.101	0.120	1.16	2.20	0.065	0.025	0.003
Burned	30-60	25	5.01	4.01	0.034	0.43	15.0	6.5	0.105	0.052	0.32	2.46	0.011	0.024	0.002
Oleolega	0-10	14	5.14	4.19	0.079	2.16	27.8	9.6	0.147	0.158	1.32	2.65	0.097	0.039	0.008
Tracks &	10-20	14	5.17	4.10	0.065	1.57	25.3	9.1	0.111	0.119	0.86	1.99	0.067	0.030	0.007
Landings	30-60	14	5.36	4.03	0.023	0.29	13.2	7.3							
Significance levels of differences between means by Student's t-test															
Depth interval 0-10 cm															
Forested <> Logged			<***	<***	ns	ns	ns	ns	>***	<***	<*	ns	>***	>**	ns
Forested <> Tracks			<***	<**	>**	ns	<***	<*	ns	<***	ns	ns	>**	>**	ns
Logged <> Tracks			>*	ns	>**	ns	ns	ns	<**	ns	ns	ns	ns	ns	ns
Depth interval 10-20 cm															
Forested <> Logged			<***	<***	ns	ns	ns	ns	ns	<***	<**	ns	>***	>***	ns
Forested <> Tracks			<***	<**	ns	ns	<***	<**	ns	<*	ns	ns	>***	ns	ns
Logged <> Tracks			ns	ns	ns	ns	ns	<**	ns	ns	>*	ns	ns	<*	<*
Depth interval 30-60 cm															
Forested <> Logged			<***	<***	ns	ns	ns	ns	ns	ns	ns	ns	>***	ns	<*
Forested <> Tracks			<***	<*	ns	ns	ns	ns							
Logged <> Tracks			<***	<*	>*	>*	ns	ns							

pH*: pH of soil in KCl solution
ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

the C/N ratio of the topsoil on tracks and landings increased significantly after logging and burning but the observed increase in relatively undisturbed areas was not significant due to the large standard deviation calculated for the post-logging samples (16.9–21.7). The standard deviation of the C/N ratio in the soil before logging ranged from 4.0 in the topsoil to 5.5 in the subsoil and the increase observed after logging and burning suggested a much higher spatial variation throughout the soil profile. The standard deviation on tracks and landings ranged from 5.8 to 6.6 and was therefore comparable to that of the subsoil before logging. Surprisingly, the %LOI of the topsoil on tracks and landings was significantly higher than that of the soil under forest.

Total amounts of available nutrients in the soil before and after logging and burning are given in Table 15.9 together with the estimated enrichment of the soil. The overall totals for the post-logging and burning period were calculated from the respective values observed for relatively undisturbed soils and soils on tracks and landings weighted by the area covered by each soil type.

Total amounts of available K, Ca, Mg and total C increased as a result of harvesting

Table 15.9: *Total amounts of available nutrients, N and C (kg ha^{-1}) in the 0–60 cm soil layer of the Oleolega catchment before and after harvesting and burning and the enrichment due to logging and burning.*

	Na	K	Ca	Mg	P+	P*	NH4-N	NO3-N	N-Tot	C-Tot
Oleolega Forest	230	220	816	1837	2.7		105	53	4513	63563
Logged & burned areas	211	280	1084	2006	2.4		80	30	4798	73090
Tracks & landings	231	280	923	2063	2.9		82	32	3313	69183
Oleolega Logged & Burned	213	280	1069	2011	2.4		80	30	4654	72711
Nutrient enrichment	*-17*	*59*	*252*	*174*	*-0.3*		*-25*	*-23*	*141*	*9148*

P+: Ca-Lactate extraction method; P*: Bray II extraction method, estimates for soil pits

and burning, partly because of increases in the concentrations (K, Ca) and partly because of increases in bulk density (Mg, C). The total Ca-Lactate extractable P content did not change. No data was available for amounts of 'available' P according to the P-Bray II method. The total N content increased but corresponding available totals of NH_4–N and NO_3–N decreased suggesting that the increase of N was mainly in the form of organic compounds or ash. Non-decomposed ash particles were indeed observed in the topsoil samples collected after logging and burning. The errors in the given totals may be considerable due to the limited number of samples used in the calculations but the values seem realistic in view of the totals released from the litter layer after the burn as given in Table 15.5.

No information was available on the effects of harvesting and subsequent burning of slash of pine plantations growing on former grassland soils in the tropics. Russell (1983) observed an increase in soil pH (from 3.9 to 4.8 in the top 5 cm) and available P, K, Ca and Mg, but not in total N, in a sandy Ultisol after clearing of rainforest and burning of slash. Soil nutrient contents declined below those observed under adjacent rainforest during the growth of *Pinus caribaea* and *Gmelina arborea* (except total N and Ca) forests planted on these soils. Available K, Mg and total N increased again after harvesting of an 8.5-year-old *Gmelina arborea* plantation, whereas available P and Ca decreased.

Uhl and Jordan (1984) observed increases in pH (from 3.2 to 3.5) and exchangeable Ca, Mg and K, but not in total P and total N, in topsoil (0–10 cm) five years after cutting and burning of rainforest on a sandy Oxisol.

In a prescribed burning experiment (low intensity burn) of *Pinus oocarpa* planted on sandy soils in Honduras, Hudson *et al.* (1983b) observed increases in available K and Na, but not in available Mg and P, whereas a decrease in available Ca was observed.

In the coastal lowlands of Florida, Fisher (1981) observed a decrease in total N in the upper 25 cm of a wet sandy Ultisol one year after harvesting of *Pinus elliottii* forest, site preparation (chopping and bedding, no burn) and replanting, although fertilizer (N and P) was applied during planting. In contrast to total N, extractable P and Ca were higher one year after the treatment. Relatively small changes were observed for K and Mg.

Stromgaard (1984) observed changes in the soil stores of N, P, K, Ca, Mg and Na in a *chitimene* shifting cultivation experiment on a sandy soil (pH$\approx$ 4.7) in NE Zambia, where biomass of surrounding areas was collected in piles and burned to improve soil fertility. Increases in available K, and to a much lesser extent in N and P stores, were observed within 24 hours after the burn. The increase of P was delayed and a major increase in the store of this element was only observed 40 days after the burn. A decrease in available Ca was observed immediately after the burn but higher levels were observed after 40 days. Available Mg and Na decreased after the burn.

In Malaysia, Ghulam and Norhayati (1989) observed relatively small changes in soil chemical properties six months after felling of rainforest on a sandy clay loam to clay loam soil. Much larger changes were observed in the soil nine months after the site was prepared (slash burned) for rubber cultivation. Burning resulted in a 25% decrease in the organic carbon content and a slight decrease in total N, whereas exchangeable K, Ca and Mg and available P increased by 88%, 219%, 68% and 83%, respectively, of their values under forest. Fifty months after the planting of rubber trees and cover crops, exchangeable K and Mg were down to their levels measured under rainforest, whereas exchangeable Ca had declined as well but was still 71% higher than its level under rainforest. Soil pH increased from 4.1 under rainforest to 4.5 after burning and decreased again to 3.9 50 months after planting of rubber trees and crops. In contrast, Amir (1989) observed a significant decline in soil pH and contents of N, P, C, Mg and Na and CEC after logging of rain forest on sandy clay to clay loam soils in Malaysia. The content of K, however, increased immediately after logging, but returned to its initial value one year after logging.

All these experiments were on acid, nutrient-poor, mostly sandy soils with much lower CEC values than those observed for the present study sites. As such the capacity of these soils to retain nutrients released after the conversion must be considered low and this resulted in enhanced leaching of soil nutrients in runoff following the conversion (Fisher, 1981; Hudson *et al*, 1983b; Stromgaard, 1984), especially in areas with high rainfall (Russell, 1983; Uhl and Jordan, 1984). Furthermore, the amounts of nutrients released during the burn in these studies were higher than those released by the burn in the Oleolega catchment. As such the soils in the Oleolega catchment are more likely to retain these nutrients, thereby limiting leaching losses after the burn (*cf.* Section 15.6.3).

15.5 Effect of Harvesting on Soil Moisture

15.5.1 Soil Moisture Content

The effect of harvesting on soil moisture profiles with depth was evaluated by comparing the dry season variation of soil moisture in a forested plot (plot A) with that in an adjacent area that had been logged (plot B) in December 1990 (Figure 15.3). The measured dry season variations at various depths at the two locations are shown in Figure 15.6. The reduction in moisture extraction for transpiration at the deforested site resulted in a much slower decrease of θ compared to that observed under forest. As there was little vegetation left around the access tube in the deforested area, the decreased variation in topsoil θ may be attributed largely to evaporation from the soil.

A gradual decrease in θ was observed in the subsoil under forest during the dry season until mid September when the soil moisture was replenished by large storms. Drainage to groundwater from the root zone during this period could be neglected. In contrast, the subsoil in the harvested area did not show any signs of soil moisture depletion and remained moist throughout the dry season (Figure 15.6). These trends

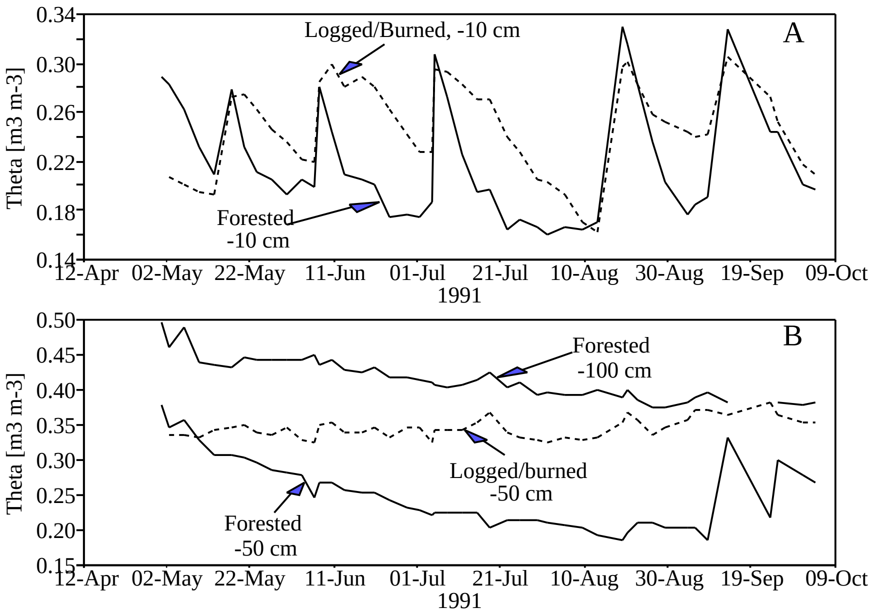

Figure 15.6: *Dry season variations of θ in topsoil (A) and subsoil (B) before and after deforestation.*

are in agreement with the results obtained for the respective forest plots (Section 6.5) and the Nabou grassland (Section 5.3).

15.5.2 Soil Moisture Chemistry

An attempt was made to determine the impact of harvesting on the chemical composition of soil moisture by comparing samples collected in the forested and harvested plots at Oleolega, referred to in the previous section. Collection of soil moisture started in October, 1990, when both plots were under forest and the period served as a calibration period until the occurrence of cyclone Sina on 27–28 November (*cf.* Hewlett and Fortson, 1983). The cyclone severely defoliated the forest and also deposited sea spray on the ecosystem. One of the plots (Plot B) was subsequently logged on January 17, 1991. No soil moisture could be extracted anymore by the end of April, 1991, due to drying out of the soils. As such the data pertains to the wet season of 1990–1991. Weighted averages of the ion concentrations in soil moisture for the pre-cyclone, post-cyclone and post-harvesting periods are shown in Table 15.10. The spatial variation in pre-cyclone chemical composition of soil moisture was high, as indicated by the differences between sites. A high NO_3 concentration was measured by the lysimeter pair in the mid slope position in the forested plot (plot A), but not by the other pairs in the same plot. The deposition of sea spray, and large amounts of fresh litter on the forest floor by the cyclone caused large changes in soil moisture chemical composition, similar to the ones discussed for the other sites in Section 13.6. The highest concentrations were observed shortly after the cyclone passed, whereas concentrations had decreased somewhat before one of the plots was logged, *i.e.* six weeks after the event.

Table 15.10: *Mean weighted concentrations (mg l^{-1}) of top- and subsoil moisture of two forested plots (A and B) before and after cyclone damage (November 28, 1990) and clearfelling (Plot B only on January 17, 1991, not burned) for the period October, 1990 – April, 1991*

Location	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
								TOPSOIL (-30 cm)										
Pre-cyclone																		
Forested A	105	6.21	6.4	1.56	6.9	1.73	0.30	13.2	8.5	2.9	24.8	0.06	6.3	0.02	0.02	0.03	0.53	0.02
Forested B	86	6.27	7.2	0.52	5.3	0.91	0.24	13.9	15.7	4.2	5.5	0.01	5.6	0.02	0.02	0.02	0.76	0.02
Post-cyclone																		
Forested A	162	6.40	13.3	2.13	8.5	2.40	0.18	41.6	6.1	5.6	18.8	0.01	6.0	0.10	0.02	0.06	0.49	0.02
Forested B	138	6.58	10.1	0.72	9.7	0.99	0.23	33.6	10.2	3.3	6.0	0.02	5.3	0.08	0.02	0.02	0.41	0.02
Post-harvesting																		
Forested A	155	6.06	12.0	1.67	9.1	1.79	0.17	30.6	6.7	4.3	19.9	0.03	6.1	0.05	0.02	0.02	0.56	0.03
Logged B	110	6.47	8.5	0.48	7.4	0.74	0.16	23.2	11.7	3.7	1.2	0.02	5.1	0.05	0.02	0.02	0.42	0.03
								SUBSOIL (-60 cm)										
Pre-cyclone																		
Forested A	89	6.34	9.6	0.84	5.3	0.52	0.21	9.1	22.5	4.6	8.4	0.01	7.8	0.02	0.02	0.02	0.29	0.02
Forested B	120	6.70	9.5	0.23	10.4	0.78	0.06	14.7	44.5	4.8	2.3	0.01	7.7	0.03	0.02	0.02	0.31	0.02
Post-cyclone																		
Forested A	119	6.39	11.9	0.31	8.5	0.56	0.20	19.5	16.5	4.8	10.4	0.02	7.7	0.08	0.06	0.02	0.35	0.02
Forested B	155	7.02	11.0	0.22	12.4	0.61	0.28	26.5	38.0	4.3	5.8	0.02	7.7	0.10	0.02	0.02	0.34	0.02
Post-harvesting																		
Forested A	112	6.40	11.6	0.48	6.6	0.29	0.22	19.5	12.3	2.8	11.4	0.02	6.6	0.05	0.02	0.02	0.43	0.03
Logged B	145	6.75	10.2	0.24	13.0	0.53	0.25	21.9	37.6	3.5	3.3	0.02	7.4	0.05	0.02	0.02	0.32	0.03

The impact of the cyclone was such that any changes in the soil moisture chemistry as a result of logging were drowned in the changes already caused by the cyclone. It proved impossible, therefore, to evaluate the impact of harvesting separately. No samples could be collected after the burn in August, 1991, because soil moisture levels remained low due to lack of rainfall in the post-burn period.

15.6 Impact of Harvesting and Burning on Water Use and Quality

15.6.1 Water Use

Water yield from the Oleolega catchment was expected to rise following harvesting due to the associated decrease in evapotranspiration, as has been observed after clearing catchments planted to pines in the warm temperate zone (Douglas and Swank, 1975; Pearce and Griffiths, 1980; Swindel *et al.*, 1983a,b,c; Hewlett *et al.*, 1984; Hsia, 1987; Rijsdijk and Bruijnzeel, 1991; Smith and Scott, 1992). Furthermore, the increase in area with a compacted surface (*e.g.* landings, roads) from 2.4 to 6 ha, in combination with the higher soil moisture levels after harvesting, might affect the rainfall–runoff response of the catchment as well. This section discusses the results.

Independent ET rates were determined from soil moisture depletion data collected in the forested and clearfelled plots within the catchment already referred to earlier (Figure 15.3) using the method described in Section 6.5. Only a single access tubes had been installed in each plot and spatial variations in ET_{sm} could therefore not be evaluated. Spatial variation was presumably high, with large differences between the soil moisture status and thus ET in the riparian zone and on the ridges. Hence the values presented here serve only to illustrate the difference in ET_{sm} between the two plots, rather than providing accurate estimates for the whole catchment. The average daily ET_{sm} calculated for the forested plot during the period May 20 until October 4, 1991, averaged 2.11($\pm$1.17) mm day^{-1} (n= 94), whereas that of the deforested area was 28% lower at 1.52($\pm$0.79) mm day^{-1} (n= 94). The forest was capable of extracting moisture from depths below that of the access tube and the ET_{sm} will therefore have been underestimated (*cf.* Section 6.5). Because ET_{sm} for the deforested area may be considered accurate, the actual reduction after clearance could be somewhat higher than 28%.

The simplest method to determine the impact of timber harvesting and subsequent burning on the catchment water use would be a direct comparison of pre- and post-logging ET values obtained from water balance calculations over the respective periods. However, the results of this approach would only be reliable if the amounts and distribution of rainfall in the two periods would be comparable and when changes in soil moisture and groundwater storages can be evaluated properly. Whilst it is recognized that a paired catchment study might yield more reliable results (Bosch and Hewlett, 1982; Hewlett and Fortson, 1983), such an approach was not possible in the present context. Therefore in the following a judicious comparison of water balances for the respective periods is offered. This will be followed by an application of the single-catchment approach of Ibrahim and Chang (1989). The effect of cyclone Sina and partial logging of the catchment (up to 50% clearfelled until May, 1991) on basin water use was studied by Assenberg (1993). However, because he used a preliminary stage – discharge relation which overestimated peak flows (*cf.* Section 8.2), his estimate of 3.5 mm day^{-1} for the initial post-logging period December 1990 – May 1991

Table 15.11: *Regression constants and coefficients of determination (CD) for the best fits of wet and dry season master recession curves for the Oleolega catchment after harvesting and burning.*

Recession Curve	Q1	Q2	K1	K2	CD
Wet Season 1992	0.044	0.124	0.958	0.420	0.99
Dry Season 1991	0.030	0.130	0.970	0.180	0.96

will have been too low. A new estimate was calculated with the water balance method for the 151 days period between January 1 and May 31, 1991. To determine ΔG, a new master baseflow recession curve was constructed graphically, and non-linear regression analysis (Marquardt, 1963) yielded values for Q_1 (0.027 mm h^{-1}), Q_2 (0.172 mm h^{-1}), K_1 (0.920) and K_2 (0.480) in Equation 8.4. Applying the latter coefficients to the period under consideration resulted in a ΔG of less than 0.1 mm, which could be neglected safely. Rainfall totals in the months prior to the start (P= 84 mm) and end of the period (P= 35 mm) differed by 49 mm, and ΔS could therefore not be neglected and was, somewhat arbitrarily, set at -34 mm ($0.7 \cdot \Delta P$).

Total rainfall between January 1 and May 31, 1991, amounted to 855 mm, whereas the corresponding streamflow output amounted to 200 mm, resulting in an ET of 689 mm, or 4.6 mm day^{-1}. The corresponding E_0 amounted to $5.2(\pm 1.4)$ mm day^{-1}, implying an ET/E_0 ratio of 0.88 which is considerably lower than that obtained for the wet season a year earlier (1.06, Section 8.3). Because the amounts of rainfall during both periods were comparable and evapotranspiration could be at its potential rate as soil moisture was not limiting, the lower ET/E_0 ratio for 1991 would suggest that water use had indeed decreased after harvesting commenced, although some of the effect must undoubtedly be attributed to a decrease in the evaporative surface (LAI) following cyclone Sina (*cf.* Section 11.3.6).

The difference in water use was likely to increase with the size of the area cleared from pines (Bosch and Hewlett, 1982; Bruijnzeel, 1990). Therefore catchment water use was also determined for the 284-day period between June 24, 1991 (86% logged) and April 2, 1992 (undergrowth regeneration following logging and burning). Master depletion curves for the dry and wet season during this period were constructed by Van Well (1993b) using non-linear regression analysis (Marquardt, 1963; *cf.* Equation 8.4). The resulting regression constants are given in Table 15.11.

The period was chosen in such a way that the discharge at the beginning of the period (0.54 mm day^{-1}) was similar to that at the end (0.51 mm day^{-1}) so that changes in groundwater storage could again be neglected. Rainfall totals for the months preceding the beginning and end of the period were 36 and 5 mm, respectively, and ΔS was therefore neglected as well. A rainfall total of 887 mm was recorded whereas a total of 181 mm was discharged during the post-harvesting period. The water balance approach thus yielded an estimated ET of 706 mm, or 2.5 mm day^{-1}, suggesting a reduction in water use of 39% as a result of harvesting and burning (pre-harvesting ET was 4.1 mm day^{-1}; *cf.* Section 8.3). Because the above-ground dead and live biomass was low for most of the post-harvesting period, rainfall interception by the vegetation – litter layer complex during this time was assumed to be less than 5% of total rainfall (*cf.* Section 5.5). Therefore the amount of water reaching the soil was in the range of 840–890 mm, or 3.0–3.1 mm day^{-1}. This was 14–17% less than the average daily amount of water reaching the soil in the period for which the water use of the forested catchment was determined ($\bar{P}$= 3.6 mm day^{-1}, Section 8.3). Despite the lower rainfall inputs as compared to those in the the pre-harvesting period, the runoff coefficient increased from 0.16 to 0.21. However, the influence of the difference in rainfall amounts between the periods on the magnitude of ET may perhaps not be neglected entirely, and a simple runoff simulation model developed for the forested catchment (Schellekens, 1992) was used to explore this further.

The model used a shape parameter derived from a master unit hydrograph (Nash, 1957, 1959), and a set of regression equations to compute stormflow volume (SV) and duration from the hourly mean areal precipitation (P) and a 7-day antecedent precipitation index (API_7). The API was calculated from the following formula (Viessman *et al.*, 1977):

$$API_7 = \sum_{t=1}^{t=7} P_t K^t \tag{15.1}$$

where t is the number of days before the day for which the API is calculated, P_t the rainfall total on day t, and K a constant taken as 0.82 (Schellekens, 1992, following Ward and Robinson, 1990). The equation for the prediction of the stormflow volume was of the form:

$$SV = \exp^{(a \ln P + b \ln(API_7 + 1) + c)} \tag{15.2}$$

where a, b and c are regression coefficients. Their values were obtained using regression analysis on a pre-harvesting dataset containing 40 storms, and amounted to 1.814(±0.149), 0.457(±0.108) and −8.213(±0.560), respectively, with a coefficient of determination of 0.81 (Van Well, 1993b). To account for variations in baseflow rise due to precipitation, a treshold value of 10 mm was introduced. No baseflow rise was assumed to occur during storms below this value (Schellekens, 1992).

During periods of baseflow recession the master depletion curves obtained for the forested catchment in Section 8.3 were used to simulate streamflow. Total flow was determined by adding stormflow volumes to the baseflow volumes. More details on the model are provided in Schellekens (1992).

To test the predictive capacity, it was run for the rainfall data collected during the pre-harvesting calibration period. Model prediction for the period January 4 – November 13, 1990 (192 mm) was poor, being some 22% lower than the measured streamflow total (247 mm). However, if the extreme rainfall associated with cyclone Rae in March 1990 was excluded, model prediction improved to a 6% underestimation of the measured streamflow total, which is within the combined measurement errors of rainfall and streamflow. As such the model seemed to perform well under normal rainfall conditions, but not during extreme rainfall events when quickflow is seriously underestimated by the model. Because such extreme rainfall events were not encountered during the post-harvesting period, a comparison of the streamflow predicted for the forested catchment with measured streamflow after harvesting may provide a good indication of changes in water use and yield following harvesting.

Van Well (1993b) compared the observed streamflow total from the logged and burned catchment (163 mm), measured in the period between August 1, 1991, and March, 31, 1992 (243 days) with the predicted total for the catchment in the forested state (115 mm) using the corresponding rainfall data (822 mm), and obtained an ET of 2.7 mm day^{-1} as opposed to a modelled ET of 2.9 mm day^{-1}. However, the period was not chosen in such a way as to minimize errors in ΔS and ΔQ, and the calculated

ET may therefore not be accurate. To minimize these errors, the model was rerun for the period June 24, 1991 – April 2, 1992 (283 days). Changes in groundwater storage during this period could be neglected since discharges at the beginning and end of the period were equal. As rainfall totals for the months preceding the beginning and end of the period differed little (36 *versus* 25 mm) ΔS could be neglected as well. Total rainfall during this period amounted to 886 mm, whereas the observed streamflow output amounted to 181 mm, implying an ET of 705 mm, or 2.5 mm day^{-1}. The model predicted a streamflow output of 120 mm, corresponding with an ET of 766 mm, or 2.7 mm day^{-1}, which was only 10% lower than the value obtained for the similarly aged Koromani forest during the dry season of 1991 (2.96 mm day^{-1}; Section 7.7).

Due to the rather low rainfall input during the post-burn period, modelled interception losses from the forest canopy (Gash, 1979) and litter layer (this study) were relatively low at 170 mm and 90 mm, as compared to those modelled for the same period a year earlier (294 and 138 mm, respectively) when rainfall (1536 mm) was closer to the long-term average (Section 6.3).

In this dry year, harvesting of the forest reduced catchment ET by some 0.2–0.4 mm day^{-1}, or 7–14%. Although the difference in water use seemed small, the gain in water yield was considerable, with the observed streamflow being 51% higher than that predicted for the forested catchment. In years with rainfall being closer to the long-term average, the difference between the forested and cleared situation can be expected to be even larger due to higher evapotranspiration losses from the forested catchment (see Table 9.2), as well as higher stormflow amounts from the cleared catchment (*cf.* Malmer, 1993).

15.6.2 Effect of Harvesting on Minimum and Peak Flows

Changes in minimum and peak flows are of particular interest, since it is under these conditions that changes in the hydrologic regime have the greatest economic implications, either through water shortages, or through damage to infrastructural works, property and crops by flooding and sedimentation.

If minimum flows at Oleolega would not be influenced by the change in forest cover, the below average rainfall in the post-harvesting period would have reduced the minimum flows from the catchment compared to those observed in the pre-harvesting period when rainfall totals were higher. A comparison of the observed minimum streamflow totals for periods ranging from 1 to 28 consecutive days before and after clearfelling and burning is shown in Table 15.12. Despite the lower rainfall during the post-harvesting period, minimum flows were between 80% (1 day) and 20% (28 days) higher than observed during the forested period. Even larger gains after clearing may be expected in years with rainfall totals closer to the long-term average. Therefore it is beyond doubt that forest clearing and subsequent burning of slash and undergrowth did have a marked effect on dry season flow, which is in agreement with findings elsewhere in the tropics (Bruijnzeel, 1990; Malmer, 1993).

The impact of harvesting on peak flows was studied by a comparison of regression equations obtained for the pre- and post-harvesting periods. The peak discharge (Q_p) could be related to corresponding rainfall amounts and 15-day API values using the following equation:

$$Q_p = \exp^{a \cdot P + b \cdot API_{15} + c} \tag{15.3}$$

which is similar to the equation used for stormflow volume prediction in the model developed by Schellekens (1992). The regression coefficients for the pre- and post-harvesting periods are shown in Table 15.13 whereas observed peakflows have been

Table 15.12: *Minimum streamflow totals (mm) in the forested Oleolega catchment for periods ranging from 1 to 28 days, and corresponding totals observed after harvesting and burning. Ratios illustrate the relative increase after harvesting.*

Treatment	**Period Length [days]**								
	1	**2**	**3**	**5**	**7**	**10**	**14**	**21**	**28**
	Cummulative streamflow totals [mm]								
Forested (A)	0.11	0.25	0.42	0.69	1.12	1.76	2.51	4.45	6.55
Harvested/burned (B)	0.21	0.42	0.63	1.06	1.55	2.31	3.70	5.83	7.96
Ratio B/A	***1.82***	***1.66***	***1.52***	***1.54***	***1.39***	***1.32***	***1.47***	***1.31***	***1.21***

Table 15.13: *Regression constants and statistics for predictive equations relating peakflows in the Oleolega catchment to rainfall and a 15-day API before and after harvesting and burning.*

Period	**a**	**SD**	**b**	**SD**	**c**	**SD**	**CD**	**n**
Pre-harvesting	0.058	0.004	0.008	0.002	-4.023	0.503	0.88	42
Post-harvesting	0.085	0.013	0.017	0.005	-4.049	0.764	0.75	25

plotted against rainfall in Figure 15.7. The pre- and post-harvesting regression lines for an average API_{15} of 45 mm are shown for comparison. The dummy variable technique and F-tests (Kleinbaum and Kupper, 1978) were used to test whether the slopes and intercepts of the two regression lines were significantly different. Differences between the intercepts (c) were not significant. However, the constants a and b of the post-harvesting equation were significantly higher than those of the pre-harvesting equation indicating that peakflows had indeed increased after clearfelling. Again, this finding corresponds with reports from other experiments in the humid tropics where pre-harvesting stormflow was dominated by subsurface flow (Bruijnzeel, 1990; Fritsch, 1992; Malmer, 1993)

15.6.3 Water Quality

Streamflow quality is affected by changes in amounts of dissolved solids as well as of particulate matter (sediment, organic matter) and changes in biological activity (*e.g.* bacteria, algae). Changes in the sediment load and biological activity were not quantified in detail during the present study. What follows below is largely based on visual observations and limited measurements of the suspended load during several storms. Logging activity in the catchment, and the associated disturbance of the soil by the construction of roads, tracks and landings, resulted in a large increase in the sediment load during stormflow events compared to that observed in the undisturbed situation. One landing (L7 in Figure 15.2) had been cut into a slope close to a first order streamhead, with the landing walls steeply sloping towards the stream channel. The access road to this landing was steep, and no sediment traps were constructed along the

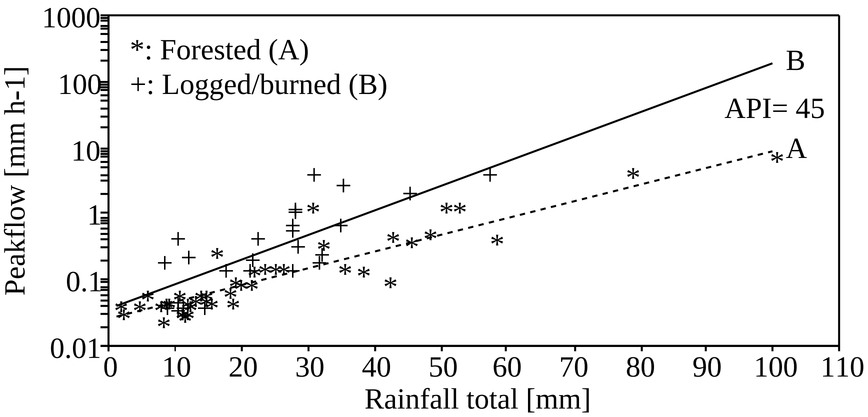

Figure 15.7: *Measured and predicted peak flows (for an average API_{15} of 45) for various storm sizes in pre- and post-harvesting periods in the Oleolega catchment.*

sides. Overland flow from the landing access road and the landing reached the main stream channel within a very short time, thereby producing a sharp, shortlived peak in the hydrograph before the peakflow as a result of the normal catchment response occurred. Gullies formed on this access road within a few weeks, and large amounts of sediment were washed into the stream. As such the peak sediment load was observed during the first runoff peak, rather than during the main peak flow resulting from the overall catchment response to rainfall (Assenberg, 1993). This suggested that most of the sediment in the streamflow may have originated from this particularly ill-constructed landing. Assenberg (1993) examined suspended sediment concentrations in water samples collected during several storms in January and February, 1991, shortly after a number of landings and roads had been constructed, including the one described above. He obtained an erosion rate of 2 tonnes ha^{-1}, which may seem modest in comparison to erosion rates found elsewhere after logging (*e.g.* Douglas *et al*, 1992; Malmer, 1993) but it should be remembered that most of the material came from a limited number of landings and roads, where on-site erosion rates must have been higher.

A large part of the eroded material went into temporary storage, filling pools in the creek and changing its bedding. Flushing of this stored material during large storms may affect the water quality for several years to come (*cf.* Malmer, 1993). In April 1992 gullies with depths up to 40 cm had formed on some of the steeper tracks and roads in the catchment (pers. comm. Dr. J.R.H. Heuch, Fiji Pine Ltd.) and because erosion seemed to remain active in these gullies at least for some time, a semi-permanent decrease in stormflow water quality may be expected as a result of the logging activities. The sediment load under baseflow conditions was not different from that before clearfelling started (Assenberg, 1993).

A lot of these sedimentation problems might have been avoided by a more careful selection of landing locations, as well as of their access roads. Sediment traps were constructed along the main roads in January – February, 1991, which improved the situation. However, some of these traps were spaced too far apart, particularly on steeper sections to prevent overland flow attaining high velocities. As such these traps were filled with sediment after one or two major storms, and their effect correspondingly shortlived.

Nutrient losses associated with the removal of particles of soil and organic matter in the streamflow could not be evaluated since no analyses were carried out on the solids in streamflow samples. However, a comparison between samples containing sediment which were filtered during sampling, and corresponding samples that were not filtered until after arrival in the laboratory, showed that concentrations of PO_4 in the latter were four times higher than those in the former (Table 15.1). This suggested that at least some of the 'available' P in soil was removed from the site absorbed on clay minerals or organic matter in streamflow.

Visual observation of the streamflow revealed that the number of algae in the stream increased after the catchment was deforested. This may have been caused by a combination of higher light inputs to the stream as a result of the removal of the forest canopy, and by higher nutrients concentrations (*e.g.* NO_3). Fresh-water prawns, which were present in the creek before harvesting started, had disappeared after the clearfelling of the forest. The decrease of the prawn population may be attributed to the increased sediment load after harvesting, which destroyed their habitat by filling the pools in the creek.

The impact of harvesting on the chemical composition of streamwater was studied in more detail. Because the quality of the discharge reflects the interactions of vegetation, soil, water and nutrients (Turvey, 1975), a disturbance of the ecosystem will be evident in the chemical composition of the streamflow (Likens *et al.*, 1977). The composition of baseflow differed from that of stormflow and the effects of harvesting on each of these components will therefore be discussed separately.

Chemical Composition of Baseflow

The decrease in nutrient uptake after harvesting and the transfer of large quantities of nutrients to the forest floor, first by cyclone Sina and later by harvesting, which were subsequently released by decomposition and burning of the slash can be expected to have influenced the nutrient concentrations in streamflow from the catchment. Details on the pre- and post-cyclone baseflow composition of the forested catchment have been given in Section 13.7.2. The temporal behaviour of the concentrations of Na, K, Mg, Ca, Cl, NH_4-N + NO_3-N, Mn and total P in baseflow, and patterns of rainfall and streamflow over the entire study period are illustrated in Figure 15.8, whereas average concentrations and corresponding baseflow discharges for various periods are given in Table 15.14. The concentration of Al remained below the detection limit during the whole study period and was therefore not included. The concentrations of PO_4 and total P in streamflow before the burn were also at or below the detection limits, which renders a comparison of the means for the pre-burn periods unreliable and differences were therefore considered not significant. Differences between mean baseflow levels were not significant, except for the post-cyclone period which showed significantly higher amounts of baseflow. Therefore differences between mean ion concentrations may be attributed to the various treatments rather than to differences in discharge. The impact of cyclone Sina on baseflow composition has already been discussed in Section 13.8 and it suffices to say here that the changes in nutrient concentrations in the first month after the event reflected the deposition of sea spray and fresh litter during the cyclone.

Significant changes in baseflow EC, pH, and concentrations of the major ions were

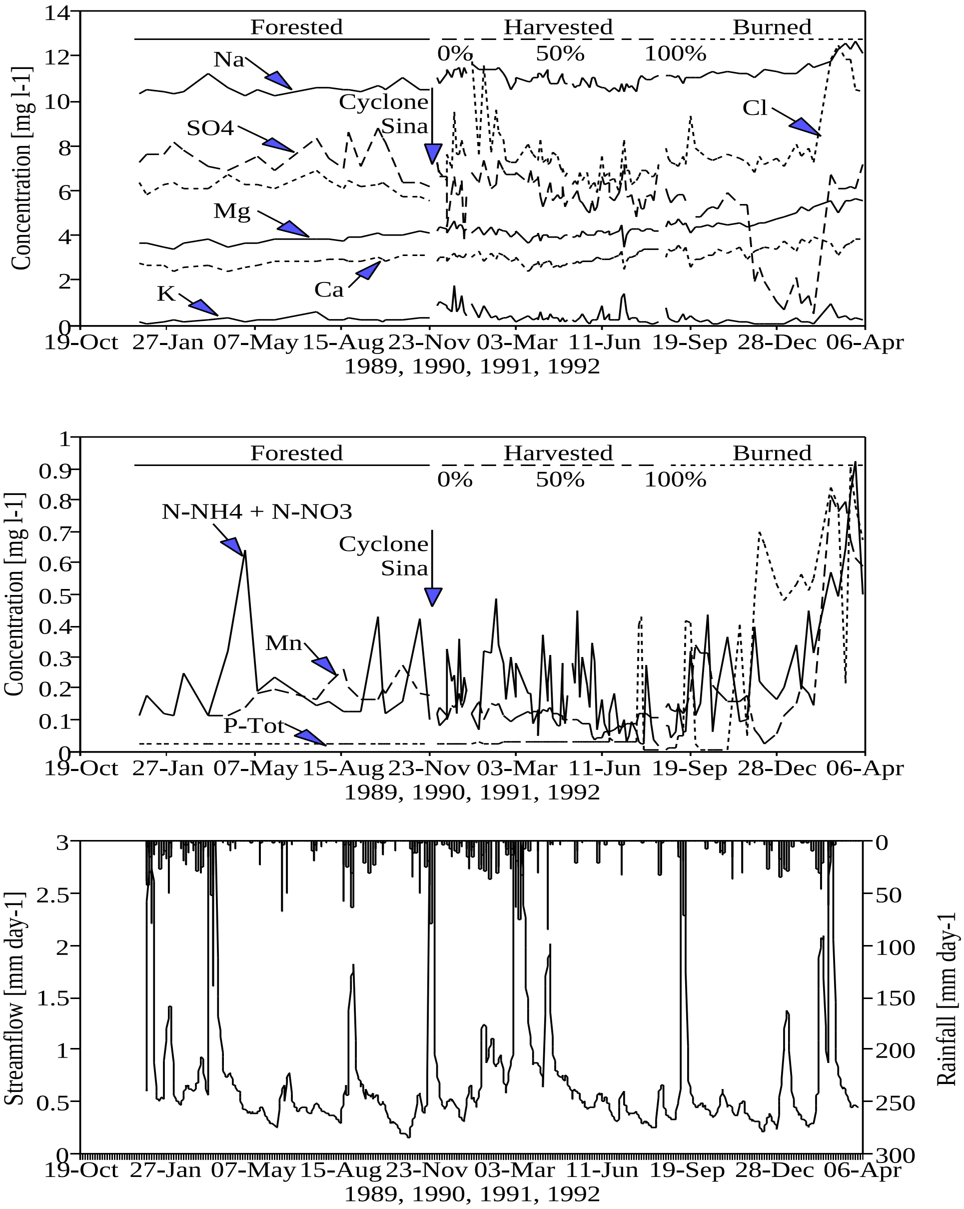

Figure 15.8: *Variations with time in concentrations of Na, K, Ca, Mg, Cl, SO_4, N-NH_4 + N-NO_3, total P, and Mn in baseflow, and corresponding total streamflow (solid line) and rainfall (hanging bars) patterns (bottom figure) before, during, and after clearfelling and burning of the Oleolega catchment.*

Table 15.14: *Average discharge (mm h^{-1}), electrical conductivity ($\mu S\ cm^{-1}$), pH and ion concentrations (mg l^{-1}) in baseflow (Q) from the Oleolega catchment at various stages during the study Significance levels (*Student's t *test) given for differences between mean ion concentrations in the undisturbed state (A) and those after various treatments (B, C, D, E).*

Period	Q	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO	SO4	NO3	PO4	Si	Fe-T	Mn	N-T	P-T
Pre-cyclone (A), 25 December 1989 - 26 November 1990																		
Average	0.017	91	6.73	10.5	0.24	3.82	2.79	0.22	6.19	36.3	7.47	0.16	0.02	13.7	0.35	0.18	0.08	0.02
SD	0.006	4	0.22	0.2	0.11	0.22	0.21	0.17	0.31	2.2	0.74	0.13	0.01	0.6	0.06	0.04	0.05	0.00
n	21	21	21	21	21	21	21	21	21	21	21	20	20	21	16	16	21	21
Post-cyclone (B), 2 December 1991 - 7 January 1991																		
Average	0.017	94	6.72	11.2	0.89	4.35	3.04	0.21	7.58	38.7	5.94	0.15	0.02	13.8	0.35	0.14	0.15	0.02
SD	0.005	4	0.12	0.2	0.39	0.14	0.12	0.13	0.81	2.3	1.02	0.19	0.01	0.3	0.10	0.03	0.13	0.00
n	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
0-50% harvested (C), 11 January 1991 - 2 May 1991																		
Average	0.031	92	7.10	11.1	0.36	4.02	2.81	0.19	7.85	35.1	6.28	0.27	0.02	14.2	0.32	0.12	0.10	0.02
SD	0.008	5	0.24	0.3	0.19	0.17	0.22	0.11	1.28	4.6	0.57	0.33	0.00	0.4	0.04	0.02	0.06	0.00
n	28	28	28	28	28	28	28	28	28	28	28	27	28	28	28	28	28	28
50-100% harvested (D), 6 May 1991 - 15 August 1991																		
Average	0.018	90	7.13	10.8	0.34	4.13	3.01	0.12	6.66	45.2	5.76	0.18	0.02	13.6	0.22	0.09	0.08	0.03
SD	0.004	3	0.10	0.2	0.33	0.18	0.23	0.12	0.47	2.9	0.58	0.25	0.01	0.4	0.10	0.02	0.11	0.01
n	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29
Burned (E), 22 August 1991 - 4 April 1992																		
Average	0.017	97	7.02	11.4	0.24	4.78	3.38	0.27	8.29	49.5	4.45	0.32	0.06	13.0	0.31	0.27	0.28	0.34
SD	0.007	4	0.34	0.5	0.20	0.45	0.32	0.29	1.69	5.8	2.10	0.35	0.05	0.7	0.11	0.23	0.32	0.31
n	31	31	31	31	31	31	31	31	31	31	30	31	31	31	31	31	31	31
Significance of differences between the means																		
A<>B	ns	<***	ns	<***	<***	<***	<***	ns	<***	<***	>***	ns	na	ns	ns	>***	<**	ns
A<>C	<***	ns	<***	<***	<**	<***	ns	ns	<***	ns	>***	ns	na	<***	>**	>***	ns	ns
A<>D	ns	ns	<***	<***	ns	<***	<***	>**	<***	<***	>***	ns	na	ns	>***	>***	ns	ns
A<>E	ns	<***	<***	<***	ns	<***	<***	ns	<***	<***	>***	<**	<***	>***	>*	<*	<***	<***
D<>E	ns	<***	>*	<***	>*	<***	<***	<***	<***	<***	>***	<**	<***	>***	<***	<***	<***	<***

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01; na: not applicable

observed shortly after the cyclone event. These again could be linked to the input of sea spray by the cyclone (particularly Na, Cl, Ca, Mg, K), as well as to the release of nutrients (mainly K) by leaching and decomposition of the fresh litter. After this initial flush of nutrients the EC decreased while harvesting progressed, and was not significantly different from that observed during the pre-cyclone calibration period, although the catchment had been logged completely at the end of period D (Table 15.14). Significant increases in baseflow EC were also observed by Malmer (1993) after clear-felling of rain forest on Gleyic Podsols and Orthic Acrisols (62% and 38% areal coverage respectively) in a paired catchment study in Sabah, Malaysia.

The pH of streamflow from the Oleolega catchment was near neutral during harvesting, which was significantly higher than that of the pre-cyclone baseflow from the forested catchment. A possible explanation for this increase is that a reduction in the release of H^+ ions by pine roots to balance nutrient uptake for biomass production may have occurred (Miller, 1984). Since these H^+ ions are important in the weathering process as well (Clayton, 1979), the increase in soil pH_{H2O} (Section 15.4), as well as that of the streamflow, suggested that weathering rates could have slowed down temporarily as a result of the removal of the trees. However, it could also be argued that the increased amounts of water percolating through the soil after clearfelling (Section 15.6.1) would tend to increase the rate of weathering.

The concentrations of Na, Mg, and Cl peaked at the height of the wet season (January – February 1991), which must be attributed to delayed leaching of salts deposited by cyclone Sina because only a small part of the area had been logged by then. This was followed by a gradual decrease and minimum concentrations were reached at the end of the wet season. A slight increase was again observed during the dry season which presumably represented the normal seasonal pattern in the concentrations of these elements, which tend to increase with decreasing baseflow levels (Table 15.15). However, in a paired catchment study in Sabah, Malaysia, Malmer (1993) also observed elevated concentrations of Na and Cl, but not of Mg, in the period between harvesting of rain forest and burning of slash, which suggests that a portion of these ions may also have been released from the slash during harvesting. Concentrations of Ca were highest shortly after cyclone Sina and returned to pre-cyclone levels during the wet season of 1991, after which they increased again during the dry season, possibly as a result of leaching from decomposing litter.

Concentrations of K showed a peak shortly after cyclone Sina but then decreased throughout the harvesting period. This is not surprising in view of the large amounts of foliage that had been deposited during the cyclone event. As logging proceded slowly, the amounts of K released from slash during harvesting were such that these only produced a relatively small increase of the concentration as compared to the pre-cyclone situation. Similar increases in baseflow concentrations of K after harvesting of tropical rain forest in Malaysia were reported by Zulkifli Yusop and Abdul Rahim (1991) and Malmer (1993).

Concentrations of NH_4 and SO_4 decreased after the cyclone event and during harvesting, which may be related to changes in biological processes taking place in the soil. However, the decrease in concentration of NH_4 was more than balanced by an increase in concentration of NO_3, suggesting that a conversion of NH_4 to NO_3 (nitrification) occurred (Robertson, 1989). This was also observed by Parker (1985) in soil solutions after clearfelling (but not burning) rain forest in Costa Rica. Higher NO_3, but unchanged NH_4, concentrations in streamflow were also observed by Swank (1987) after clearfelling mixed hardwood forest near Coweeta, Southeastern USA. Malmer (1993), on the other hand, observed a 20-fold increase in the concentration of NH_4 in baseflow after clearfelling of rain forest in Sabah, Malaysia, whereas no significant changes were observed in those of NO_3, total N and SO_4. Concentrations of total N and Si increased in response to cyclone Sina but not as a result of subsequent harvesting, whereas those of PO_4 and total P did not show any response to cyclone Sina or harvesting and remained below the detection limit for most of the time. Concentrations of Mn also decreased after cyclone Sina and during harvesting of the Oleolega forest. Malmer (1993) observed no change in total N or total P, but significant increases for PO_4 as well as Mn in the streamflow after clearfelling of rainforest.

Concentrations of all elements in baseflow changed significantly after prescribed burning of slash (Table 15.14) in August 1991, but these changes did not occur until three months after the burn. This may be attributed to the low rainfall during this intermediate period, which prevented the transport of any nutrients released by the burn to groundwater. Hence, increased leaching of ions into baseflow did not start until the soil had been wetted thoroughly during the rainy season of 1992 (December). The resulting higher concentrations of Na, Cl, Ca, Mg and HCO_3 caused a significant increase in the baseflow EC (Table 15.14). In the much wetter climate (P= 4000 mm year^{-1}) of Malaysia, Malmer (1993) observed similar increases in baseflow concentrations of Cl, Ca and Mg, but not of Na, immediately after burning of slash.

Concentrations of SO_4 dropped sharply after the burn from a pre-burn average of 5.8 mg l^{-1} to about 1 mg l^{-1} in January 1992 and increased again to pre-burn levels shortly after heavy rainfall in February 1992. It is difficult to explain the behaviour of SO_4 but as its concentration in stream water is known to be strongly influenced by biological sulfur transformations (Swank and Waide, 1987), the decrease may have been caused by changes in biological processes in the soil (activity of Mycorrhizas?) or in stream water after the burn (algae?). Relatively low concentrations of SO_4 were also observed in baseflow from the Ividamu grassland catchment (on average 2.4 mg l^{-1}) where mycorrhizas were presumably absent. Lower concentrations of Si were also observed in baseflow from the Oleolega catchment after the burn, whereas Malmer (1993) observed a significant increase after burning which may be related to leaching from the ash.

Some support for changes in soil biological activity comes from the fact that the decrease in the baseflow concentrations of SO_4 corresponded with a sharp increase in those of total P and PO_4, and with more gradual increases in those of Ca and Mg. In Malaysia, Malmer (1993) did not observe a response in the concentrations of SO_4 after clearfelling and burning of a rainforest catchment.

Changes in the concentrations of Na, K, Cl, total N, NH_4, NO_3 and Mn lagged several weeks behind those of SO_4, PO_4 and total P but showed a similar sharp increase at the height of the wet season of 1992 after replanting had begun. The decrease in concentrations of K to pre-cyclone levels during the wet season of 1992 may be linked to uptake by the rapidly returning grassland vegetation after the burn (Mr. T.T. Rawaqa, pers. comm.) which required large amounts of this nutrient compared to other nutrients (Section 10.4).

The present study ended before nutrient concentrations in baseflow declined to their pre-cyclone levels. However, Hudson *et al.* (1983b), Uhl and Jordan (1984) and Malmer (1993) all observed declines in nutrient concentrations to pre-treatment levels within two years after the treatment, and this may not be very different for those in baseflow from the Oleolega catchment.

Chemical Composition of Stormflow

Stormflow is defined here as a composite of baseflow, channel precipitation and various contributions of water from the hillslope (*cf.* Ward, 1984). As such, its chemical composition can be expected to vary much more with discharge than that of baseflow. Assenberg (1993) observed changes in nutrient concentrations in response to changes in stormflow were not the same for all elements. The EC, and concentrations of Na, Mg, Ca, HCO_3, Si and Mn decreased with increasing stormflow due to dilution with less concentrated waters. However, concentrations of K, NO_3, total P and total N showed the opposite behaviour and increased with discharge, possibly as a result of contributions of water enriched with nutrients after percolating through the canopy, litter layer and topsoil. Very little variation with discharge was observed for Cl, SO_4, PO_4 and Fe. Similar changes in ion concentrations during storms have been reported in catchment studies elsewhere both within and outside the tropics (Hem, 1970; Gregory and Walling, 1973; Likens *et al.*, 1977; Bruijnzeel, 1983a; Malmer, 1993).

Changes in the chemical composition of stormflow may be expected following a cyclone event, harvesting of timber and subsequent burning of slash, due to associated changes in the composition of baseflow (see previous section) and soil moisture on the hillslope (Table 15.10) as a result of changes in leaching and uptake rates in the surface layers (Malmer, 1993). Variations in stormflow with discharge can be expressed with solute rating curves, which usually relate the natural logarithm of stormflow discharge ($\ln Q_s$) to EC, pH or ion concentrations ($[X]$) according to:

$$[X] = a \cdot \ln Q_s + b \tag{15.4}$$

where a and b are regression coefficients (Gregory and Walling, 1973).

Separate solute rating curves were calculated from stormflow samples collected in the periods before harvesting, during harvesting, and after burning. Data for the first stormflow event of the post-burn period were excluded from the regressions as the concentrations of several elements (*e.g.* K, SO_4, Si, Cl) deviated considerably from those of subsequent stormflow events (Figure 15.9). The regression coefficients and their statistics for the respective periods are given in Table 15.15. The scatter in the data

Table 15.15: *Regression constants and statistics of solute rating curves for the forested catchment (n= 43, baseflow data included), harvesting period (n= 167, baseflow data excluded) and post-burn period (n= 59, data for the first storm and baseflow data excluded). EC in $\mu S\ cm^{-1}$, Q_s in $mm\ h^{-1}$ and concentrations in $mg\ l^{-1}$.*

Species	**Forested**					**Logged**					**Burned**				
	a	SE	b	SE	CD	a	SE	b	SE	CD	a	SE	b	SE	CD
EC	-4.465	0.944	75.88	5.25	0.35	-8.276	0.547	70.20	9.57	0.58	-7.638	0.459	74.62	5.96	0.83
pH	-0.084	0.036	6.37	0.20	0.12	-0.112	0.016	6.53	0.28	0.23	-0.198	0.022	6.43	0.29	0.58
Na	-0.507	0.085	8.20	0.47	0.46	-0.826	0.058	7.84	1.01	0.55	-0.681	0.041	8.30	0.54	0.83
K	0.269	0.061	1.53	0.34	0.32	0.113	0.047	1.49	0.83	0.03	0.299	0.039	2.10	0.51	0.51
Mg	-0.230	0.055	2.87	0.31	0.30	-0.505	0.034	2.28	0.59	0.57	-0.570	0.030	2.32	0.39	0.87
Ca	-0.220	0.052	1.89	0.29	0.31	-0.547	0.028	0.86	0.49	0.70	-0.553	0.037	1.09	0.47	0.80
NH4	0.006	0.026	0.22	0.15	0.00	-0.020	0.009	0.14	0.15	0.03	0.003	0.007	0.15	0.09	0.00
Cl	-0.030	0.097	6.03	0.54	0.00	0.451	0.108	10.08	1.89	0.10	1.076	0.112	12.62	1.45	0.62
HCO3	-2.572	1.259	23.07	7.00	0.09	-6.828	0.395	11.05	6.91	0.64	-9.161	0.443	9.73	5.76	0.88
SO4	-0.169	0.145	6.53	0.81	0.03	-0.053	0.069	6.59	1.21	0.00	0.371	0.086	7.65	1.12	0.25
NO3	0.327	0.102	1.57	0.57	0.20	0.475	0.057	2.14	1.00	0.29	1.242	0.099	4.99	1.29	0.73
PO4	0.004	0.006	0.04	0.03	0.01	0.002	0.001	0.03	0.02	0.01	-0.001	0.002	0.02	0.03	0.01
Si	-0.673	0.211	10.42	1.18	0.20	-1.099	0.081	9.27	1.42	0.52	-1.549	0.056	6.89	0.72	0.93
Al	0.017	0.008	0.12	0.05	0.09	0.073	0.011	0.35	0.19	0.22	0.045	0.006	0.24	0.08	0.50
Fe	0.006	0.013	0.36	0.07	0.01	0.006	0.010	0.34	0.18	0.00	-0.013	0.009	0.22	0.11	0.04
Mn	-0.026	0.007	0.06	0.04	0.25	-0.025	0.002	0.01	0.04	0.46	-0.002	0.003	0.02	0.04	0.58
N-tot	0.007	0.010	0.11	0.05	0.01	0.034	0.007	0.23	0.13	0.12	-0.015	0.019	0.26	0.24	0.01
P-tot	0.000	0.000	0.02	0.00	0.01	0.006	0.001	0.04	0.02	0.20	0.049	0.019	0.34	0.25	0.11

was large, partly because of hysteresis effects (*i.e.* differences in ion concentrations at similar discharge during the rising and falling limb of the hydrograph; Gregory and Walling, 1973), and partly because of other factors (*e.g.* time since the cyclone Sina, percentage of area cleared, initial moisture conditions, storm size and intensity), resulting in low to very low coefficients of determination for the regressions (Table 15.15; Turvey, 1975; Malmer, 1993). A selection of solute rating curves for several elements is presented in Figure 15.9. Due to the large scatter of the data and the limited number of stormflow samples collected during the pre-cyclone period differences between rating curves for the respective periods were not statistically significant, with the exception of the post-burn curves for total P and NO_3 which were significantly steeper than corresponding pre-burn curves. Harvesting only had little effect on the rating curves for PO_4 and total P, the concentrations of which remained close to or below the detection limits anyway, suggesting that P released from decomposing litter was retained in the soil. However, concentrations of PO_4 and total P increased greatly after the soil was thoroughly wetted during the wet season following the burn *cf.* Figure 15.8).

Although not statistically significant, the solute rating curves for the other constituents may give a good impression of the changes that occurred in the chemical composition of stormflow after cyclone Sina and harvesting. The pattern of the EC during stormflow reflected that of the major ions (HCO_3, Na, Ca, Mg, Si) of which the concentrations decreased with increasing discharge due to dilution of the baseflow by hillslope contributions and channel precipitation. Changes in the solute ratings of Na, Mg, and HCO_3 as a result of harvesting and subsequent burning were comparable to those shown for Ca in Figure 15.9, with higher concentrations at low discharges and lower concentrations at high discharges during harvesting and after burning than in the forested condition. The effects of burning on the rating curves for these solutes, and also on that for Mn, were smaller than those of harvesting and cyclone Sina combined. Concentrations of these constituents went down during high discharges after harvesting and burning, which suggests that the release of these elements from the litter layer and topsoil during storms was reduced. Concentrations of Mn decreased after harvesting started, but the response to variations in discharge remained similar to that of the forested state as the respective rating curves were roughly parallel (Figure 15.9).

Concentrations of K, NO_3, and SO_4 changed little with storm discharge during harvesting, but larger changes where observed after burning, particularly during the first storm event after the burn (Figure 15.9). Concentrations of Si, and to a lesser extent those of Ca, Mg, Mn and HCO_3, were lower than usual, but recovered again in the subsequent storms (Figure 15.9). The extremely high concentrations of K, SO_4 and Cl that were observed in the first stormflow after the burn indicated that these nutrients had been mobilized by the fire and were now leached from the hillslopes (*cf.* O'Loughlin *et al.*, 1980; Malmer, 1993). Burning had no apparent effect on the concentrations of total N, NO_3, Mn, PO_4, and total P during this first storm, but concentrations of NH_4 dropped below the detection limit.

After clearfelling and burning of rain forest in Malaysia, Malmer (1993) observed higher concentrations of NO_3, NH_4, PO_4, K and Mn in stormflow, whereas those of Si and Fe decreased compared to the forested situation. However, because of the higher biomass involved in this study, the results may not be directly comparable with those presently obtained for the Oleolega catchment.

In spite of the severe disturbance of the Oleolega catchment and the large nutrient inputs to the soil following the burn (*cf.* Section 15.2.2), changes in ion concentrations in streamflow were relatively small, suggesting that most nutrients were retained by the soil, at least during the period of observation. This view is supported by the observed increase in soil nutrient reserves (Table 15.9), which is probably related to a combination of relatively low rainfall following the burn and the relatively high nutrient retention capacity of the soil. Although the various treatments did not result in a deterioration of the chemical quality of the streamflow, a distinct decrease in water quality occurred as a result of increased erosion during and after harvesting (Assenberg, 1993).

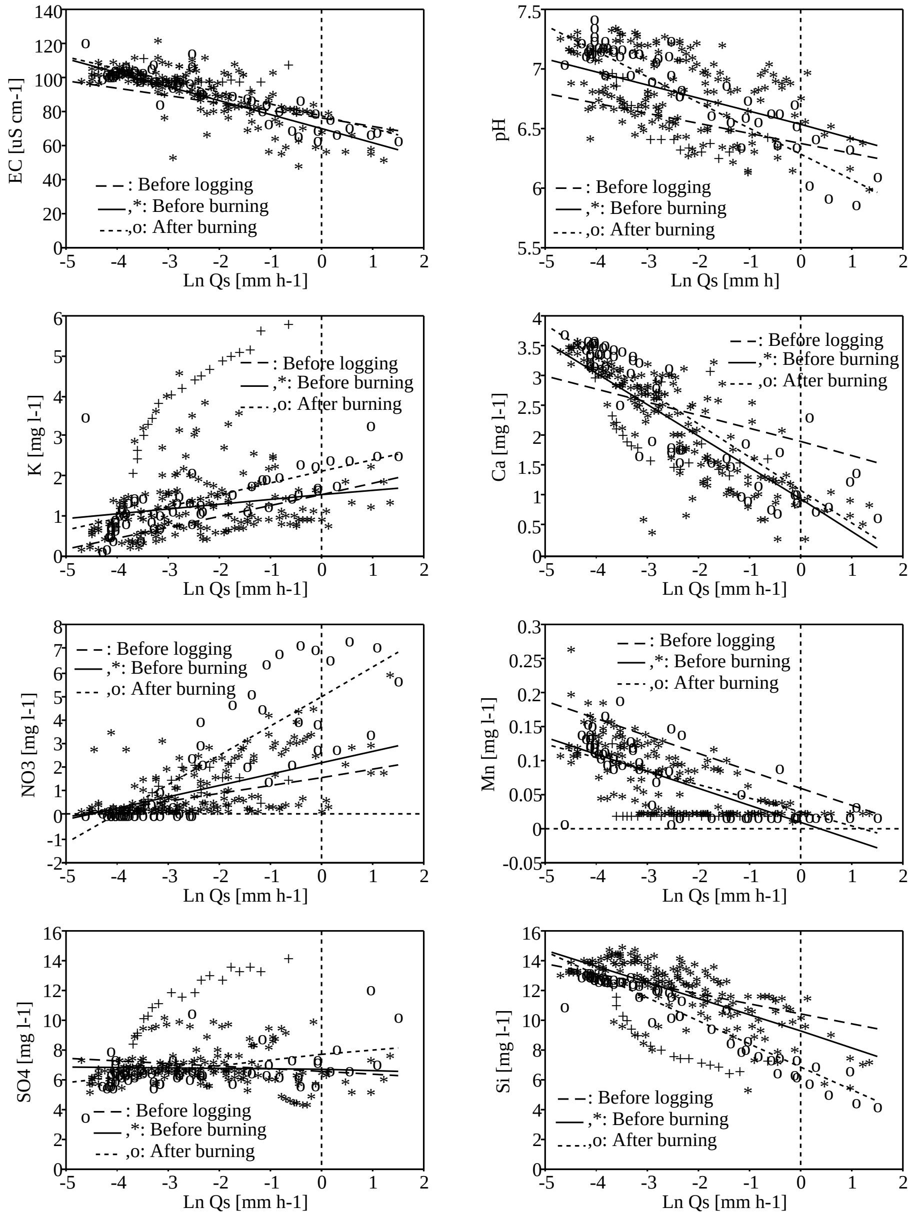

Figure 15.9: *Solute rating curves for the EC, pH and selected elements in stormflow. Data collected during harvesting and after burning included to illustrate the scatter. Data for the first storm after burning (+) not included in the calculation of the post-burn rating curves.*

Table 15.16: *Actual water (Q, in mm) and nutrient exports (kg ha^{-1}) for various periods during the Oleolega catchment experiment, together with the gains in water yield and export of nutrients associated with cyclone Sina, harvesting and burning (also expressed as a percentage of the exports from the forested catchment).*

	Q	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Exports from forested catchment (January 4 - November 26, 1990)																	
A	254	26.1	1.08	9.6	7.0	0.53	15.7	88.3	18.5	0.84	0.04	33.7	0.15	0.85	0.43	0.21	0.05
Exports during harvesting (November 27, 1990 - August 15, 1991)																	
B	282	26.6	2.41	9.3	6.0	0.45	22.5	78.3	18.1	3.47	0.06	33.1	0.59	0.97	0.23	0.40	0.10
Exports after burning (August 16, 1991 - April 4, 1992)																	
C	163	17.0	1.69	6.5	4.1	0.44	16.5	59.2	10.0	2.81	0.08	17.6	0.25	0.47	0.34	0.45	0.58
Observed exports during and after harvesting and burning (B+C)																	
D	445	43.5	4.1	15.8	10.2	0.89	39.0	137.5	28.2	6.28	0.14	50.7	0.83	1.45	0.57	0.84	0.68
Predicted exports from the forested catchment for postburn rainfall total																	
E	309	31.9	1.2	11.7	8.5	0.65	19.0	108.3	22.6	0.89	0.05	41.2	0.18	1.04	0.53	0.25	0.06
Gains in water yield and export of nutrients associated with cyclone effects, harvesting and burning																	
D-E	136	11.6	2.9	4.1	1.7	0.24	20.0	29.2	5.6	5.39	0.09	9.5	0.65	0.40	0.03	0.59	0.62
%	44	36	250	35	20	37	105	27	25	603	176	23	361	39	6	238	1072

15.7 Nutrient Exports in Streamflow Associated with Harvesting

Nutrient exports in baseflow from the Oleolega catchment were calculated by combining the concentration data with the corresponding flow volumes. Stormflow samples were collected during each major storm after harvesting started, and the exports during storms could therefore be calculated in a similar fashion.

Only few stormflow samples were collected from October 1991 onwards, and nutrient exports in stormflow until April 1992 were therefore estimated using the post-burn solute rating curves presented in Table 15.15. The resulting nutrient exports from the catchment during the respective periods are summarized in Table 15.16.

The impact of cyclone Sina, harvesting and subsequent burning on nutrient exports was studied by comparing the 'actual' exports with those that would have occurred if the catchment had remained under forest. The latter were obtained by simulation using the model developed by Schellekens (1992) to predict streamflow amounts for the forested catchment associated with post-burn rainfall totals (see Section 15.6). Because this model could not accurately predict the quickflow amounts for the extreme rainfall events in March, 1991, the ratio of the observed (82 mm) to the simulated quickflow volume (29 mm) during the calibration period was used to correct the simulated post-cyclone quickflow total (26 mm), resulting in a post-cyclone quickflow total of 75 mm. The simulated baseflow total during the calibration period agreed well with the observed total and no corrections were applied to the simulated post-cyclone baseflow (234 mm). The gain in water yield following clearfelling (0.3 mm day^{-1}) as derived from comparison of observed (cleared conditions) and simulated (forest conditions) water yields, compared well with the reduction in ET following harvesting (0.2–0.4 mm day^{-1}) discussed in Section 15.6, adding confidence to the simulated streamflow total. To estimate nutrient exports under forested conditions with post-burn rainfall totals, the simulated base- and quickflow totals were multiplied with the respective pre-cyclone baseflow and stormflow concentrations.

Nutrient exports from the catchment during and after clearfelling and burning were higher than predicted for the forested catchment. The higher exports of Na, Ca, Mg, NH_4, SO_4, Si, Mn and Fe could be ascribed completely to the higher water yield after harvesting. Exports of total P, PO_4, NO_3, K, and Cl, on the other hand, where much higher than expected from the increase in water yield alone (see bottom row in Table 15.16). These nutrients are intimately connected with biological activity (with the possible exception of Cl, although Khanna and Ulrich (1984) argued that this element could play a significant role in forest nutrient uptake by maintaining electrical neutrality), and were released in large quantities from slash deposited on the forest floor during harvesting (particularly K), and from the ashes following the burn (particularly P, NO_3). However, exports of N, P, K, Ca, Mg and Mn in streamflow (Table 15.16) were small compared to the amounts released from the slash during the burn (Table 15.4), ranging from 0.2% for Mn to 6% for P, indicating that the soil was capable of retaining most of the nutrients released during harvesting at least during the rather dry period of observation.

The export of nutrients in suspended sediment and organic matter was not quantified, and the values given in Table 15.16 should therefore be considered as minimum estimates.

In the next chapter the information presented in the previous chapters on the various nutrient gains and losses will be used to compile an overall nutrient budget for a full rotation cycle of *Pinus caribaea* in the Oleolega catchment.

Chapter 16

Nutrient Balance for the Oleolega Forest

One of the chief objectives of the present study was to evaluate whether pine plantation forestry in Fiji was sustainable under the current management practices, *i.e.* without fertilizing. The preservation of soil fertility is of course a prerequisite for sustained-yield forestry and this implies that nutrient inputs in rainfall and the release of nutrients by weathering of minerals in the rooting zone should match or exceed nutrient exports in streamflow and merchantable timber over a rotation period. If this is not the case, a gradual depletion of soil nutrient reserves will occur during subsequent rotations, eventually leading to nutrient deficiencies and poor growth.

Trends in soil fertility as a result of plantation forestry may be evaluated by solving the mass balance equation for a full rotation period according to:

$$P_x + W_x + F_x = Q_{xs} + Q_{xp} + \Delta S_{xv} + \Delta S_{xl} + \Delta S_{xs} \qquad (16.1)$$

where P_x, W_x and F_x are the amounts of nutrient x supplied by atmospheric deposition, mineral weathering, and biochemical fixation of nutrients in the gaseous phase, respectively, whereas Q_{xs} and Q_{xp} represent exports as solute and particulate matter in streamflow, respectively, and ΔS_{xv}, ΔS_{xl} and ΔS_{xs} the changes in amounts of nutrients stored in the biomass, litter layer and soil reserve, respectively. F_x may be neglected if the mass balance is solved for non-gaseous nutrients, but must be included for N, S and C. Fixation rates for gaseous nutrients were not determined in this study and the mass balance for these elements will inherently be incomplete. Furthermore, exports of nutrients as particulate matter (sediment, organic matter) were not determined either, which will have lead to an underestimation of the exports in streamflow.

Based on the hydrological and hydrochemical data presented earlier in combination with the information on biomass development and soil nutrient reserves, an attempt will now be made to quantify the water and nutrient budgets for the Oleolega catchment over the period of a full rotation (*i.e.* January 1975 – April 1992). Since records of precipitation and streamflow at Oleolega only spanned a 27 month period, several assumptions had to be made to approximate the mean annual rainfall and streamflow totals. Similarly, hydrochemical information was only available for the study period, and the long-term nutrient fluxes in rainfall and streamflow had to be estimated from these data in combination with the derived long-term climatic and hydrological estimates. The approximations were further complicated by uncertainties in the nutrient inputs and outputs during and following the passage of cyclones during the rotation period (six major cyclones between January 1975 and April 1992), and by uncertainties in both the in- and outputs of certain nutrients whose concentrations in water were often below the detection limits (*e.g.* P). The various assumptions and the resulting estimates will be discussed below.

16.1 Nutrient Inputs in Precipitation

The annual rainfall inputs into the catchment were assumed similar to those measured at Nadi Airport from 1975 until 1979 and at Nabou Station from 1980 until 1990. Rainfall data collected for the Oleolega catchment itself were used for 1990, 1991 and part of 1992. Assuming that annual fluctuations in the chemical composition of rain

Table 16.1: *Annual rainfall (mm) and derived atmospheric nutrient inputs (kg ha^{-1}) to the Oleolega catchment over the first rotation period (1975–1990), including harvesting and burning (1991, 1992).*

Year	P	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	N-T	P-T	Mn
1975	2069	13	3.1	1.4	2.0	5.8	25	20	18	3.7	0.5	1.9	3.1	0.41	0.7
1976	1601	10	2.4	1.1	1.6	4.5	20	16	14	2.9	0.4	1.5	2.4	0.32	0.5
1977	1802	11	2.7	1.3	1.8	5.1	22	17	16	3.2	0.5	1.7	2.7	0.36	0.6
1978	1178	7	1.7	0.8	1.2	3.3	14	11	10	2.1	0.3	1.1	1.8	0.24	0.4
1979	1787	11	2.6	1.2	1.7	5.0	22	17	16	3.2	0.5	1.7	2.7	0.36	0.6
1980+	1621	37	3.7	4.6	2.7	4.4	69	13	19	3.0	0.4	1.3	2.1	0.28	0.4
1981+	1932	40	4.2	4.8	3.0	5.4	74	17	23	3.6	0.4	1.6	2.6	0.35	0.6
1982	1973	12	2.9	1.4	1.9	5.6	24	19	17	3.5	0.5	1.9	2.9	0.39	0.6
1983+	1207	35	3.2	4.3	2.3	3.5	65	10	17	2.4	0.3	1.0	1.6	0.21	0.3
1984	1421	9	2.1	1.0	1.4	4.0	17	14	12	2.5	0.4	1.3	2.1	0.28	0.5
1985+	2013	67	5.4	8.2	4.0	5.1	122	14	27	3.6	0.4	1.4	2.2	0.29	0.5
1986	1844	11	2.7	1.3	1.8	5.2	23	18	16	3.3	0.5	1.7	2.8	0.37	0.6
1987	820	5	1.2	0.6	0.8	2.3	10	8	7	1.5	0.2	0.8	1.2	0.16	0.3
1988	1421	9	2.1	1.0	1.4	4.0	17	14	12	2.5	0.4	1.3	2.1	0.28	0.5
1989	2508	15	3.7	1.7	2.5	7.1	31	24	22	4.5	0.6	2.4	3.7	0.50	0.8
1990+	1867	40	4.2	4.8	3.0	5.4	73	17	22	3.6	0.4	1.8	3.1	0.50	0.6
1991	1370	8	2.0	1.0	1.3	3.9	17	80	12	2.5	0.3	1.3	2.0	0.27	0.4
1992*	407	2	0.6	0.3	0.4	1.1	5	24	4	0.7	0.1	0.4	0.6	0.08	0.1
Total	**28842**	**343**	**<50**	**<41**	**<35**	**<81**	**652**	**354**	**<284**	**<52**	**<7.0**	**<26**	**42**	**<5.7**	**<8.9**

+: Years with cyclones; *: January 1 - April 4, 1992

water were small and largely governed by amounts of rainfall, atmospheric nutrient inputs could be quantified by combining the annual rainfall totals with the bulk average chemical composition of rain water at Oleolega (excluding cyclone effects) obtained during the present study. The average concentration of HCO_3 in rainfall at Oleolega was presumably overestimated due to contamination of several water samples (see Section 13.3), and the more realistic estimate for Korokula forest was used instead. The concentrations of Zn and B in rain water (not measured) were estimated by assuming that these nutrients were derived from maritime sources exclusively. Drever (1982) provided average concentrations of Zn and B in sea water, and those in rain water were calculated using Equation 13.1 on the basis of the relative concentrations of Cl in rain and sea water, assuming that fractionation did not occur. Six major cyclones crossed Viti Levu between 1975 and 1992 (two cyclones in 1985) and the atmospheric inputs for these years were increased with the net nutrient input from cyclone Sina, as measured in the Oleolega catchment (*cf.* Table 13.4). The resulting estimates for the rotation period are given in Table 16.1. As the concentrations of K, Ca, Mg, NH_4, SO_4, NO_3, Mn and Total P were often below the detection limits, the inputs of these constituents may have been more or less seriously overestimated. However, the effect will be compensated to a large extent because tall forest vegetation tends to trap aerosols and dust more effectively than the rain water collectors used in the present study (White and Turner, 1970).

16.2 Nutrient Exports in Streamflow

Streamflow records for the Oleolega catchment were not available before 1990. A simple exponential model was developed therefore to relate daily streamflow totals (Q) to daily rainfall totals (P) and a 15-day API, with K in Equation 15.1 set to 0.90 instead of 0.82 to obtain more realistic streamflow outputs for periods without rainfall. Regression analysis was used on data for a 151-day period which included both dry and wet periods (15 February – 15 July 1990), and the following expression was obtained:

$$\ln Q = -0.921(\pm 0.297) + 0.022(\pm 0.002)P + 0.010(\pm 0.001)API_{15}$$
$$\text{n}= 151,\ \text{r}^2 = 0.77 \qquad (16.2)$$

To test whether this simple model could predict long-term streamflow totals accurately, the model was run on an independent 211-day dataset during 1990. The predicted streamflow total for this period was within 1% of the measured streamflow total. However, when the model was applied to the complete data set for 1990, the predicted streamflow total was 7% lower than the measured total due to underestimation of the stormflow associated with the passage of cyclone Rae (March, 1990). Since errors in measurements of stormflow during cyclone events are probably as high as 10% anyway, the model was considered sufficiently accurate for the prediction of annual streamflow totals for the forested catchment. The data presented in Chapters 6 and 7 suggested that evapotranspiration by the pine forests reached a maximum before age six, and remained fairly constant afterwards. As such the current model could presumably provide fairly accurate annual streamflow totals from 1979 onwards.

Annual streamflow totals for the first 4 years after planting, during which ET losses were presumably lower than later in the rotation period, would be underestimated by Equation 16.2. The lower water use of grassland vegetation compared to pine forests is mainly caused by lower dry season transpiration rates as well as lower rainfall interception during the rainy season. To account for the difference in interception losses between the two vegetations, the canopy and litter layer interception models discussed in Sections 6.4.1 and 6.4.2 were run for the daily rainfall data for the years 1975–1990, using the model parameters obtained for Koromani forest (Section 6.4.2) and for Nabou grassland (Section 5.5). The annual difference in interception loss between the two vegetation types ranged from 132 mm in 1987 (a dry year) to 370 mm in 1990 (which was quite wet), and averaged 261 mm. The calculated annual differences in interception loss between grass and pine forest for the years 1975–1978 were added to the annual streamflow totals predicted by Equation 16.2 to obtain a more realistic annual streamflow output for these years. To account for differences in dry season transpiration rates between pines and grassland, the daily streamflow amounts for dry days during the dry seasons of 1975–1978 were increased with the observed difference in daily ET rates from grassland and Koromani forest in 1991 (2.0 mm day^{-1}). This added another 286–382 mm to the predicted streamflow totals for these years. The resulting estimates of annual streamflow totals are given in Table 16.2.

Table 16.2: *Annual streamflow outputs (Q, mm) and nutrient exports (kg ha^{-1}) from the Oleolega catchment over the first rotation period (1975–1990), including harvesting and burning (1991, 1992).*

Year	**Q**	**Na**	**K**	**Mg**	**Ca**	**NH4**	**Cl**	**HCO3**	**SO4**	**NO3**	**PO4**	**Si**	**N-T**	**P-T**	**Mn**
1975	946	98	3.1	35.8	26.2	2.0	58	336	70	2.3	0.2	127	0.7	0.17	1.7
1976	787	82	2.4	29.9	21.8	1.7	49	281	58	1.7	0.1	107	0.6	0.14	1.4
1977	1027	106	3.6	38.8	28.4	2.2	63	362	75	2.7	0.2	138	0.8	0.19	1.8
1978	754	79	2.1	28.7	21.0	1.7	47	272	56	1.5	0.1	103	0.6	0.14	1.4
1979	367	67	2.4	24.3	17.7	1.4	40	226	47	1.8	0.1	86	0.5	0.12	1.1
1980	249	26	1.8	10.1	7.2	0.5	16	90	16	0.8	0.0	33	0.3	0.05	0.4
1981	327	35	2.7	13.2	9.4	0.6	22	117	21	1.2	0.1	43	0.4	0.07	0.5
1982	291	30	1.3	10.9	8.0	0.6	18	100	21	1.0	0.0	38	0.2	0.06	0.5
1983	216	23	1.7	9.0	6.3	0.4	15	80	14	0.6	0.0	29	0.3	0.04	0.3
1984	239	25	1.0	9.0	6.6	0.5	15	83	17	0.7	0.0	32	0.2	0.05	0.4
1985	525	54	4.4	20.6	14.7	1.0	34	180	34	2.4	0.1	68	0.6	0.11	0.7
1986	306	31	1.4	11.5	8.4	0.6	19	105	22	1.1	0.1	40	0.3	0.06	0.5
1987	189	20	0.6	7.2	5.2	0.4	12	67	14	0.4	0.0	25	0.1	0.03	0.3
1988	230	24	0.9	8.7	6.3	0.5	14	80	17	0.7	0.0	31	0.2	0.04	0.4
1989	402	41	2.1	15.0	10.9	0.8	25	136	29	1.7	0.1	52	0.3	0.08	0.7
1990	300	30	1.5	10.0	7.0	0.7	19	95	21	2.3	0.1	40	0.3	0.06	0.4
1991	312	30	2.7	10.5	6.8	0.4	27	92	20	4.6	0.1	36	0.5	0.25	0.3
1992*	86	9	0.9	3.5	2.2	0.3	9	32	5	1.4	0.0	9	0.3	0.42	0.2
Total	**7553**	**810**	**36**	**297**	**214**	**<16**	**500**	**2734**	**557**	**<29**	**<1.4**	**1036**	**<7**	**<2.1**	**<12.9**

*: January 1 - April 4, 1992

The predicted annual streamflow totals over the period 1975–1991 ranged from 189 mm during the dry year of 1987 (P= 820 mm) to 1027 mm in 1977 (P= 1802 mm), with an average of 446($\pm$276) mm. Rainfall during this period averaged 1695($\pm$412) mm, resulting in an average annual ET of 1246($\pm$441) mm, or 3.4($\pm$1.2) mm day^{-1}. Combining this figure with the annual Penman open water evaporation observed at Tulasewa forest in 1990 (1681 mm) would imply an ET/E_0 of 0.74 for the full rotation period. The average ET value is within the range presented by Bruijnzeel (1990, Table 1) for lowland tropical forests, adding confidence to the model predictions. The calculated ET/E_0 ratio is also close to the value of 0.77 calculated by Blackie (1979) from 16 years of rainfall, streamflow and micro-meteorological data collected in a small upland catchment (2400 m a.s.l., 36 ha) in Kenya planted to *Pinus patula* in the first year of data collection.

Because concentrations of several ions in baseflow were different from those in stormflow, separate estimates had to be obtained for the annual totals of the two streamflow components. During the calibration period, stormflow contributions to streamflow were usually observed on days with rainfall inputs higher than 10 mm only. Hence the annual stormflow total was approximated by the sum of the streamflow totals for days with rainfall above this treshold. The result of this rather crude method, when applied to daily rainfall and stormflow data collected in 1990, was within 8% of the actual stormflow total. This suggested that overestimation of the stormflow on days with relatively low rainfall was more or less compensated by the underestimation of stormflow for periods during which stormflow events lasted longer than one day. The annual baseflow total was obtained by subtracting the annual stormflow total from the predicted streamflow total.

Afforestation did not seem to change the concentrations of the most important nutrients (*e.g.* N, P, K, Ca and Mg) in baseflow significantly (Section 13.7.2) and the nutrient export for the years 1975 until 1989 was therefore estimated by combining the annual baseflow totals with the average nutrient concentrations in baseflow from the forested catchment in 1990. To estimate the nutrient output in baseflow for years with cyclones, the baseflow total in the period after the cyclone event until the end of the year was multiplied with the concentrations of the baseflow observed at Oleolega after the passage of cyclone Sina (Table 13.15). The cyclones all occurred in the months January until April, resulting in 8–11 month periods with elevated baseflow concentrations during these years. Afforestation may have affected concentrations in stormflow, but no information was available on this subject and the nutrient outputs via stormflow were therefore approximated using the average stormflow concentrations observed in the forested catchment in 1990. No corrections were made for stormflow outputs in years with cyclones. The calculated nutrient exports in streamflow are presented in Table 16.2. As indicated previously, concentrations of NO_3, PO_4, Total N and Total P were often below the detection limits and estimates for the exports of these nutrients must therefore be considered too high.

The reduction in water yield following the conversion of grassland to pine plantation also reduces corresponding nutrient exports in streamflow. Assuming a reduction of 50% in streamflow after the fifth year after afforestation (Section 9.2) and neglecting any cyclone effects, such 'gains' from reduced water yields could be in the order of 8, 0.8, 11, 92, 124 and 6 kg ha^{-1} for N, P, K, Ca, Mg, and Mn, respectively. However, it is uncertain whether these 'gains' are realistic since the lower soil moisture status and drainage rates below forest vegetation during dry periods may affect weathering rates negatively compared to those below grass vegetation.

16.3 Quantification of the Nutrient Balance

The catchment solute budget was calculated from the information given in the previous sections and the results are presented in Table 16.3. There were considerable losses of Si, Na, SO_4, Mg, Ca, and to a much lesser extent of Mn, which presumably reflects the release of these elements by weathering in excess of the demands from the vegetation. The budgets for K and P, on the other hand, suggested that these elements accumulated in the catchment. However, this may be an artefact of the large difference between inputs and outputs of water, which automatically results in larger inputs than outputs for nutrients with concentrations below the detection limits, because the latter was used as an approximation for the actual concentration in the calculations. No measurements were made of nutrients removed from the catchment with particulate matter in the streamflow and the budget of Table 16.3 must be considered incomplete. These exports will have been negligible for the forested catchment when the sediment load was low even during stormflow events. However, considerable amounts of nutrients will have been removed from the site in suspended particulate matter in stormflow after harvesting started. Some indication for the removal of P with particulate matter can be obtained from the fact that stormflow water samples which had not been filtered in the field showed significantly higher PO_4 levels than corresponding samples that had been filtered during collection (Section 15.6.3). This suggested that some of the available P adsorbed to sediment (clay) particles or organic matter had been released during transport and storage of the samples. For these reasons it may be more realistic to assume a more neutral water budget for P, and possibly also for K.

Nutrient exports in merchantable timber (ΔS_{xv}) from any site in the Nabou forest estate, or from any one of the pine estates in Fiji for that matter, are likely to be highly variable due to the impact of previous cyclone damage and site differences (*e.g.* soil fertility) determining biomass production. At present only stemwood and bark are removed during harvesting, whereas other tree components remain in the field. The nutrient exports associated with harvesting of timber in the Oleolega catchment have already been quantified in Section 15.2.1. However, to study the potential effects of branch and foliage (*i.e.* total tree) removal on the nutrient balance, the exports of nutrients in these components were estimated as well using the appropriate concentration data and ratios of branch mass/stem mass and foliage mass/stem mass observed in Koromani forest. The nutrient exports associated with the removal of the respective components are included in Table 16.3.

Immobilization of nutrients in the litter layer over the rotation period (ΔS_{xl}) could not be determined since no ash layer nutrient data had been collected in burnt grasslands, and neither in the Oleolega catchment at the end of the study (April 4, 1992; 7.5 months after the burn). Although the ash layer contents of P, Zn and Mn immediately after burning the Oleolega catchment in August 1991 (Table 15.4) were higher than corresponding totals in the vegetation – litter complex at the Nabou grassland plot (Table 10.4), subsequent decomposition and leaching of the burnt litter during the wet season of 1992 may well have transferred a large part of these nutrients to the soil. As such, it may be expected that immobilization of nutrients in the litter layer during the rotation period may have been small and ΔS_{xl} was therefore neglected. If the site would not have been burned a large accumulation of nutrients would have been recorded in the litter layer over the period of a rotation. However, since decomposition rates are likely to be higher after harvesting (Gadgil and Gadgil, 1978) than under forested conditions, these nutrients would presumably have become available for use by pine seedlings within the first two years after replanting and must therefore not be considered to be lost permanently.

Some evidence of losses of N due to volatilization during the burn was obtained from a comparison of the amount of N lost from the litter layer during the burn (232 kg ha^{-1}, Table 15.9) and the observed gain in the soil (141 kg ha^{-1}, Table 15.5) after the burn. This suggested that 91 kg ha^{-1}, or 39 % of the total, had been lost through volatilization or in smoke particles.

Whether nutrient depletion at a site occurs depends for a large part on the capacity of the soil to satisfy the nutrient requirements of the forest through weathering of primary minerals. No information has been presented yet on the nutrient input by weathering of soil and rock minerals. The nutrient supply by weathering is usually

Table 16.3: *Quantification of the components of nutrient the mass balance for a full (17.25-year) rotation period in the Oleolega catchment. The budget has been extended to include effects of (a) varying intensities of biomass harvesting and (b) various assumptions on weathering inputs. The maximum possible number of rotations for the worst case scenario was calculated using estimates of available N, K, Mg, and Ca in the soil at the end of the rotation after harvesting and burning and estimates of P reserves (P Bray II) taken from Koromani forest.*

	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	N-T	P-T	Mn	Zn+	B+
Water solute budget [kg ha-1]																
P input	343	<50	<41	<35	<81	652	354	<284	<52	<7.0	<26	42	<5.7	<9	0.1	0.2
Q output	810	36	297	214	<16	500	2734	557	<29	<1.4	1036	<7	<2.1	<13		
P-Q	-467	14	-256	-179	65	152	-2380	-273	23	6	-1010	35	3.6	-4	0.1	0.2
Nutrient exports with particulate matter in streamflow [kg ha-1]																
		?	?	?								?	?	?	?	?
Nutrient exports in biomass components [kg ha-1]																
Stemwood & bark		29	11	23								45	5.3	3	0.6	0.1
Branches*		9	4	9								13	1.3	1	0.1	0.0
Foliage*		24	8	17								51	3.2	4	0.2	0.1
Contribution of nutrients by weathering [kg ha-1]																
Scenario 1: All nutrients provided by weathering																
Weathering input		48	279	228								73	6.2	11	0.8	0.1
Scenario 2: No nutrients provided by weathering																
Weathering input		0	0	0								0	0.0	0	0.0	0.0
Net gains (+) or losses (-) during a rotation period [kg ha-1]																
Scenario 1: All nutrients provided by weathering																
Harvesting of:																
Stemwood & bark		33	12	26								63	4.5	4	0.3	0.1
+ branches		24	8	17								51	3.2	4	0.2	0.1
+ foliage		0	0	0								0	0.0	0	0.0	0.0
Scenario 2: No nutrients provided by weathering																
Harvesting of:																
Stemwood & bark		-15	-267	-202								-10	-1.7	-7	-0.5	0.0
+ branches		-24	-271	-211								-23	-3.0	-8	-0.7	0.0
+ foliage		-48	-279	-228								-73	-6.2	-11	-0.8	-0.1
Soil Nutrient Reserves at the end of the rotation [kg ha-1]																
Available	213	280	2011	1069								110	16			
Predicted number of rotations for scenario 2 and various harvesting intensities																
Stemwood+bark		19	8	5								11	9			
+ branches		12	7	5								5	5			
+ Foliage		6	7	5								2	3			

+: Atmospheric inputs from marine sources exclusively, based on Zn/Cl and B/Cl ratios in seawater (Drever, 1982)
*: Calculated using branch/stem and foliage/stem biomass ratios observed in Koromani forest

approximated by solving the mass balance equation for each of the elements under concern, using data collected in small watersheds (Clayton, 1979). A number of studies have presented estimates of weathering rates obtained with this method (Likens *et al.*, 1977; Clayton, 1979; Johnson *et al.*, 1981; Bruijnzeel, 1983a,b, 1990). However, such wheathering rates were always calculated with the implicit assumption that ΔS_{xs} could be neglected. This is a fair assumption for soils where easily weatherable primary minerals releasing nutrient x are abundant in the soil, or where the vegetation is in a steady state so that the nutrient demands on the soil are low. However, in fast-growing short-rotation plantation forests on less fertile soils the uptake of nutrients for biomass production is likely to exceed the contributions from the atmosphere and perhaps those by weathering at some stage during the rotation, or throughout the rotation period, particularly on poor soils (Lundgren, 1978; Chijioke, 1980; Russell, 1983). Hence under these circumstances ΔS_{xs} cannot be neglected, and should be accounted for. The mass balance approach does not give reliable results for N and P for the following reasons. Nitrogen is a trace element in rocks and the release of this nutrient by weathering can be assumed negligible. Therefore values of N obtained from a mass balance reflect the gains and losses of N through biochemical processes (Robertson, 1989), rather than release by mineral weathering. Determination of the weathering rate for P, and the fraction of total P available for plants, is difficult because of the low mobility of this element (Clayton, 1979). Hence a large proportion of P released by mineral weathering is immobilized in organic soil compounds, inorganic soil compounds (associated with Ca, Fe and Al), and in clay minerals. The amount of P available for plants depends therefore mainly on microbial transformations of P, the ionic activities of Ca, Fe and Al (Clayton, 1979) in the soil solution, and soil pH (Khanna and Ulrich, 1984).

One of the main reasons for studying a pine chronosequence was to obtain information on ΔS_{xs} through comparisons of the available nutrients in the soil of the various plantations. Such information was also obtained by Gholz *et al.* (1985) who observed a general decrease in the soil macronutrient content (N, P, K, Ca and Mg) in an age sequence of slash pine (*Pinus elliottii*, 2–34 years old) on nutrient-poor sandy soils in the coastal plains of Florida. Similarly, Bruijnzeel (1983a) found evidence of soil depletion of Ca, Mg, K and P in a chronosequence (*Agathis dammara*, 7–35 years) planted on volcanic ashes in Java, Indonesia. Although Bruijnzeel (1983a) did take into account the effect of nutrient accumulations in aggrading biomass, the changes in soil nutrient reserves over time were not included in his calculations of the weathering rates. Amounts of nutrients taken up by the vegetation in the studies of Gholz *et al.* (1985) and Bruijnzeel (1983a) were much larger than those taken up by the pine forests in Fiji, partly due to the extended rotation length and partly due to the absence of cyclone disturbance in the former studies. Unfortunately, the high spatial variability in the soils of the Nabou forest estate made it impossible to carry out the study in forests which satisfied both the age (5, 10 and 15 years) and soil criteria (identical chemical and physical properties). As such ΔS_{xs} could not be evaluated properly from the soil nutrient reserves in the study plots, and it remained uncertain what proportion of the nutrients taken up for biomass production was provided by weathering, and what was provided by depletion of soil nutrient reserves.

The capacity of a soil to satisfy the demands for nutrients for biomass production by weathering depends on several factors, including the amount of weatherable minerals, the nature of these minerals, the soil moisture regime, and the soil pH. Weathering may well provide most of the nutrients for biomass production in relatively young soils, such as those in the Tulasewa and Korokula forest plots and in part of the Oleolega catchment, where the zone of active weathering was relatively close to the surface and in reach of the pine roots. However, in older, more deeply weathered soils such as that at Koromani forest and those in other parts of the Oleolega catchment, where primary minerals were less abundant and the pine roots may not reach the zone of active weathering, some portion of the nutrients may have been provided by depletion of soil nutrient reserves. One way to evaluate the possible effects of weathering inputs (W_x) on the nutrient budget is to present budgets for best and worst case scenarios. In the former, all nutrients taken up by the trees are assumed to be provided by weathering, and ΔS_{xs} is therefore zero. In the worst case scenario the nutrients accumulated in the trees are assumed to be supplied from the soil nutrient reserves exclusively, which implies that W_x is zero. Estimations of the net gains or losses for both scenarios are presented in Table 16.3.

If all nutrients for biomass production were provided entirely by weathering, net gains were calculated for all nutrients as long as some portion of the biomass remained at the site. This budget may be appropriate for Ca and Mg which were released in the weathering process, but less so for P, and possibly K and N, which had near neutral or positive hydrochemical budgets (Table 16.3). The losses of Mg, Ca and possibly K, largely reflected the release by weathering and subsequent removal in streamflow, and nutrient deficiencies for these elements are unlikely in view of the large quantities of exchangeable Ca, Mg and K in the soil (Table 4.10). The budget for P may be approximated better by the worst case scenario. The derived loss of P is more critical in view of the large uncertainties in the water budget, the availability of P in the soil at Oleolega, and the fact that enhanced leaching of P during the post-burn phase may have continued for some time after the study ended. Net losses were small for timber removal only, but whole tree removal would result in a sharp increase of these losses due to the high P content of foliage (Tables 11.14–11.16, *cf.* Bruijnzeel and Wiersum, 1985).

Estimations of the maximum possible number of rotations at Oleolega without the necessity for fertilizing can be calculated from the net losses observed over a rotation period and the soil nutrient reserves present at the end of the rotation. If weathering would satisfy the nutrient requirements of the vegetation the number of rotations would be unlimited since the ecosystem would experience net gains of nutrients during each rotation. Because this variant of the budget seems appropriate for Ca and Mg, and possibly also for K, no deficiencies of these elements are likely to occur.

The number of rotations that are possible with the worst case budget ($W_x = 0$) depends strongly on the amount of biomass exported from the site and remaining soil nutrient reserves. The Ca-lactate method for P extraction did not show an increase in soil P after the catchment was burned even though 10.5 kg ha^{-1} had been released from the litter layer (Table 15.4). This suggests that most of the P was stored in a form that could not be extracted with this method and presumably bound to organic matter or less soluble Fe and Al compounds (Dr. V.J.G. Houba, pers. comm.). Assuming that the water budget was correct, and that the long-term available P in the soil of the Oleolega forest may be approximated by the amount of P obtained with the P-Bray II method for the soil of Koromani forest (16 kg ha^{-1} for the upper 60 cm of soil), some 11% of soil P reserves would be lost over a rotation period as a result of timber removal. However, the result for the more realistic neutral hydrochemical budget indicated that P could be depleted already after the third rotation. The soil P content in Oleolega forest may have been higher than that in Koromani forest, and the number of potential rotations may therefore be higher than that suggested in the present budget. On the basis of the calculated hydrochemical budget for K this element would be depleted within fifteen rotations, whereas the neutral budget would reduce the number of rotations to seven. Nitrogen soil reserves were large enough to sustain 16 rotations, without contributions from fixation of N. Hence no N deficiencies are expected in future rotations. No information was obtained on amounts of available Mn in the soil and the corresponding maximum number of rotations could not be calculated. However, because Mn showed a net loss on the basis of the hydrochemical budget, the inputs of Mn by weathering may be sufficient to satisfy the demands by the vegetation. Hydrochemical budgets and soil reserves of Zn and B were not quantified. However, because of the relatively large export of Zn in merchantable timber, this element may become critical in future rotations if the availability in the soil is low.

Some caution should be taken when interpreting these budget estimates. First, the budget does not include amounts of nutrients (*e.g.* P) removed as, or adsorbed to particulate matter produced by surface erosion upon harvesting and burning in streamflow and may therefore be too optimistic. Second, local nutrient deficiencies may occur earlier than predicted for the whole catchment for the following reasons:

- The soil chemical properties showed a large spatial variation and nutrient deficiencies may therefore occur earlier on relatively poor soils in the catchment.
- The disturbance of the litter layer during harvesting had been severe, and slash had not been left *in situ*, but was concentrated around the landings. As such the input of nutrients to the soil as a result of burning showed a very large spatial variation, and deficiencies may occur on locations where the slash and litter layer had been completely removed during harvesting or where leaching could be prolonged due to continued decomposition of slash piles beyond the capacity of the surrounding soils to absorb the surplus supply.

The disturbance of the litter layer, and the deposition of slash are strongly determined by the techniques of harvesting, and changes in these techniques could well minimize these adverse effects (Pearce and Hamilton, 1986).