Part V

Conclusions and Recommendations

Chapter 17

Conclusions

The main objectives of the study were to evaluate changes in the hydrological cycle, with emphasis on changes in water yield, after converting seasonal *Pennisetum polystachyon* grasslands to *Pinus caribaea* plantations, and to determine the sustainability of plantation forestry in SW Viti Levu from a nutrient point of view. Furthermore, several new instruments and techniques were to be tested over longer periods of time in this tropical environment.

Time and financial constraints precluded the monitoring of a single forest over a rotation period (15–20 years) and hydrological, micro-meteorological and ecological studies were therefore carried out between November 1989 and April 1992 in a 'false time series' represented by a grassland plot (Nabou grassland), 6 (Tulasewa forest), 11 (Korokula forest) and 15-year-old (Koromani forest) pine plantations, and a catchment (Oleolega catchment) under 15-year-old pine forest which was logged during the study. The data collected at these sites provided information on the water use and nutrient cycling at several stages of plantation development, as well as on the effects of harvesting and subsequent burning of slash (catchment study). The 'false time series' approach worked well for the quantification of the various components of the water cycles, but proved less satisfactory for the evaluation of changes in the nutrient cycles with forest age because differences in soil properties between the selected study sites affected the components of the nutrient cycles sometimes in such a way that age effects could not always be distinguished from environmental effects.

Interpretation of the results was further complicated by the passage of cyclone Sina over the Fiji group in November 1990, which caused considerable damage to the forest stands and restricted the study periods for pre- and post-cyclone conditions to less than a year each. The occurrence of cyclones, and the amount of damage they afflict to a forest stand are unpredictable and this introduced uncertainties in the long-term predictions of biomass production and nutrient requirements of the plantation forests in Fiji, on top of those originating from spatial and temporal variations in other environmmental variables (particularly soil properties).

It should be stressed that the conclusions listed below apply first to the situation in Fiji, where forest productivity and the intra-system nutrient cycle are strongly influenced by the occasional occurrence of cyclones and soils are relatively fertile compared to the Oxisols and Ultisols which are far more common elsewhere in the tropics (Vitousek and Sanford, 1986). Furthermore, caution should be taken when extrapolating the present conclusions to other plantation species (*e.g. Eucalyptus* sp.) because of possible differences in water use and/or nutrient requirements.

Information on the soils of the study sites was presented in Chapters 3 and 4, whereas effects of harvesting and burning on soil physical and chemical properties have been discussed in Chapter 15. No major improvements in soil physical characteristics were observed as a result of afforestation. Hydraulic conductivities of fire climax grassland and forest soils were generally high in the granular top 20–30 cm, but decreased sharply deeper in the profiles. This will restrict the occurrence of overland flow to only the most extreme rainfall events. However, in areas where the topsoil was removed or severely compacted during harvesting (tracks, roads and landings), overland flow and associated erosion (rill formation) became widespread (Chapter 15). The water holding capacities of the soils were generally sufficiently large to meet the water demands of the forest during dry periods of several weeks, provided that soil depth exceeded 60 cm. Changes in soil chemical properties as a result of afforestation could not be evaluated properly due to the large variation between sites. The soils were moderately fertile with CECs higher than 6 meq 100 g^{-1} and, because roots were observed to penetrate the weathering zone and saprolite, weathering may continue to supply considerable amounts (particularly Mg and Ca) of nutrients for tree growth (Chapter 16).

From the data presented in Chapters 5–8, which deal with changes in the hydrology and micro-meteorology after converting *Pennisetum polystachyon* grasslands to *Pinus caribaea* plantations, the following conclusions can be drawn:

- A decrease in dry season water yield (300–380 mm) will occur within six years after converting grasslands to pine plantations. As indicated in Chapter 9, the main reason for this reduction lies in the fact that the grassland vegetation dies during the dry season, thereby strongly reducing its transpiration losses, whereas transpiration by pine forest continues as long as sufficient moisture is available in the subsoil
- Wet season water yields may also be reduced several years after afforestation for the following reasons:

    1. Evapotranspiration rates (ET) for pine forest are presumably larger than for grass because net radiation above the canopy of the former is higher due to the lower albedo of the pine forest (0.10–0.13 *versus* 0.19 for grass).
    2. Rainfall interception losses from the forest canopy and litter layer (25–30% of rainfall) are higher than those from the vegetation – litter complex in grassland (about 12% of rainfall).

  Therefore the annual decrease in water yield may well be much higher than 400 mm for years with rainfall close to the long-term average (1700 mm). It should be noted here that the impact of afforestation on water use may be somewhat less pronouced in the case that catchments are afforested in which native forest is present in the riparian zone. This riparian forest does not show a seasonal pattern in ET as moisture is never limiting and the dry season water use from the grass and forest vegetation in such a catchment may therefore be somewhat higher than that obtained presently from the grassland plot.
- Pre-cyclone evapotranspiration rates, as determined from micro-meteorological measurements in the 6-year-old Tulasewa forest (Section 7.7) and the catchment water balance method in the 15-year-old Oleolega forest (Section 8.3), indicated that annual ET was somewhat lower in the mature forest (1512 *versus* 1772 mm).

This was presumably caused by reduced transpiration and rainfall interception losses as a result of the lower stocking of the latter (cyclone damage!; see also Chapter 9).

- Forests planted on shallow soils (depth to bedrock < 60 cm) suffered from water stress during the dry season (Section 8.3). This induced high litterfall (Section 12.3.1) and limited forest productivity (Section 11.5.1).
- Damage afflicted to the pine forests by Cyclone Sina resulted in a more or less permanent decrease in ET for Tulasewa forest where 40% of the trees were destroyed, and more temporary decreases (presumably during 1–2 years of canopy recovery) at the Korokula and Koromani sites where trees were only defoliated. The soil moisture depletion technique suggested a 32% reduction in transpiration in the post-cyclone dry season at the Tulasewa plot. Comparison of pre- and post-cyclone dry season ET_{sm} was complicated (particularly for the Korokula site) by the difference in rainfall between the periods but indicated an 8% reduction at Koromani forest where rapid regrowth of foliage was observed after cyclone Sina (Section 11.3.6). Post-cyclone wet season interception losses from the canopy and litter layer at the Tulasewa (23% of rainfall) and Korokula (21% of rainfall) sites were lower than those observed during the pre-cyclone wet season (29 and 30% of rainfall, respectively).
- Harvesting of the mature pine forest and subsequent burning of slash in the Oleolega catchment increased water yield by about 50% during a rather dry period. Even higher gains in water yield might therefore be expected in years with rainfall closer to the long-term average. Increases were observed in both minimum and peak flows (Chapter 15).

In combination with data on nutrient inputs via atmospheric sources and losses in drainage water (Chapter 13) the information on forest productivity, litter production and decomposition presented in Chapters 10 – 12 has been used to compile pre- and post-cyclone nutrient budgets for the respective forest sites (Chapter 14). In addition, a budget for the Oleolega catchment over a full rotation (January 1975 – April 1992) has been given in Chapter 16. The following conclusions can be drawn from the information presented in these chapters:

- Afforestation resulted in an increase in above-ground biomass from about 8 t ha^{-1} for grassland at the end of the wet season to about 150 t ha^{-1} for a mature (cyclone damaged) pine forest. The corresponding nutrien accumulation rate was highest around age six just before canopy closure due to the rapid development of the nutrient-rich crown, whereas it slowed down after canopy closure when nutrient accumulation occurred mainly in nutrient-poor woody tissue.
- Amounts of pre-cyclone litterfall generally increased with forest age, but also showed a dependency on stand density and soil water holding capacity. Litterfall constituted the main pathway for the return of nutrients from the living biomass to the forest floor, with the exception of K, which was returned mainly in canopy wash. Amounts of Litterfall and associated nutrient returns to the forest floor during cyclone Sina were up to three times larger than annual pre-cyclone values. Because cyclones are a regular phenomenon in Fiji nutrient

returns to the forest floor in cyclone litterfall may be as important as those in periods between cyclones.

- The pre-cyclone mass of the litter layer increased from about 7 t ha^{-1} for grassland at the end of the wet season to 13.5 t ha^{-1} for mature pine forest at Koromani. Immobilization of nutrients in the pre-cyclone litter layer occurred but the rates of accumulation were low compared to the available amounts of nutrients in the soil (typically less than 1%). The post-cyclone litter layer mass and nutrient content reflected the large amount of litter and associated nutrients added to the forest floor during cyclone Sina.
- Needle decomposition in the forest plots was fairly rapid with 43–48% mass loss in the first year. Relatively large fractions of K (over 60%) and P (20–50%) in needle litter were released within three months after incubation, whereas rates of release of N, Ca and Mg were much lower with less than 50% being released after a year.
- Despite low atmospheric nutrient inputs, positive (*i.e.* accumulation) or near neutral hydrochemical budgets were calculated for N, P, K and Mn. Budgets for Mg, and to a lesser extent Ca (only at the Korokula and Oleolega sites), were negative due to relatively high exports of these nutrients in drainage and streamflow, suggesting that these ions were released by weathering in excess of the requirements of the vegetation.
- Nutrient losses associated with harvesting and burning in the Oleolega catchment were relatively low, with losses in merchantable timber removed from the site exceeding those by leaching in streamflow. A large proportion of the nutrients that were released from the slash, initially through decomposition and later during the burn, were retained by the soil and losses by leaching in streamflow mainly concerned P, N and K. The water quality decreased markedly during storms as a result of increased sediment loads due to erosion of places with severely disturbed soil in the catchment (log landings, extraction roads).
- The nutrient budget presented for a full rotation period in the Oleolega catchment indicated that for a 'worst case' scenario (no nutrient inputs by weathering) and removal of merchantable timber only as opposed to whole tree removal, no deficiencies of N, P, K, Ca, Mg or Mn were likely to occur within 5 rotations. However, if whole tree harvesting would be practised N and P deficiencies could be expected by the third rotation. Therefore the main threat to the productivity of pine plantation forests in Fiji is cyclone damage.
- The productivity of second rotation forest in the Oleolega catchment will be lower than that of the first rotation due to the increase in area (from 2% to 10%) with severely compacted soils (Section 15.1.2), although differences in cyclone damage between rotations may mask the effect.

As for the testing of commonly used measurement techniques in this humid tropical environment, several micro-meteorological methods were used to determine forest evapotranspiration rates. The temperature fluctuation energy balance method, with which half-hourly ET rates were obtained from measurements of above-canopy temperature at a single level in combination with estimates of available radiant energy, gave results that were comparable to those obtained with the more conventional (and data demanding) Bowen Ratio Energy Balance method (Section 7.6.2). Using the results of the former method to derive relationships between various climatic and soil moisture variables on the one hand, and the surface resistance parameter on the other hand, enabled the calculation of long-term ET rates with the Penman-Monteith method from routine measurements of micro-meteorological parameters. This approach seems quite promising for use in developing tropical countries in view of the simple and relatively cheap micro-meteorological set-up that is required for its application.

The Didcot capacitance soil moisture probe provided fairly accurate measurements of volumetric soil moisture content, in spite of the high volumetric moisture contents of the soil (often higher than 35%). Reliable estimates of the rates of ET during dry periods were derived from the soil moisture depletion method using soil moisture data collected in the Nabou grassland . However, the impossibility to install access tubes beyond the maximum depth of pine roots prevented accurate determinations of transpiration rates in the forest plots in this way.

Finally, with respect to the testing of existing catchment hydrological models in the study environment, climatic and streamflow data collected at the Tulasewa and Oleolega sites, respectively, were used to test the TOPOG model (O'Loughlin *et al.*, 1989) developed by the Cooperative Research Centre for Catchment Hydrology of the CSIRO Division of Water Resources, Canberra, during a two-week visit by the author to the Canberra laboratory in October 1991. The results looked promising but further work is necessary as most of the data had not been processed at that time. Unfortunately, processing of data and writing of this dissertation left no time for further applications.

Chapter 18

Recommendations

18.1 Research Targets

The following aspects of plantation forestry in SW Viti Levu need further attention:

1. One of the main gaps in our knowledge concerns the water use of unproductive (seasonal) grasslands in the tropics. The present study has partly filled this gap by determining the water use during part of the dormant (dry) season. However, the seasonal variation in hydrological, plant physiological and micro-meteorological parameters (*e.g.* interception characteristics, albedo, net radiation, stomatal resistance) could not be quantified due to time and material constraints. Since an increasingly larger area in the tropics will be covered with grassland as a result of deforestation, and the demand for forest products is still increasing, such areas may be targeted for reafforestation in the future (Evans, 1992). A study which would improve our understanding of the hydrology and micro-meteorology of these grasslands seems justified therefore.

2. Whether plantation forestry is sustainable depends for a large part on the capability of the soil to supply the nutrients required for biomass production in subsequent rotations. However, very little is known on the amounts of nutrients supplied by weathering in tropical soils. Published estimates of weathering rates that are based on nutrient input – output budgets for forested catchments may well be overestimates as the depletion of soil nutrients with time has usually not been taken into account. To properly evaluate weathering inputs within the context of plantation forestry on soil nutrient reserves, soil surveys should be carried out periodically, preferably in permanents sample plots. On the basis of the present findings nutrient deficiencies are not expected for the plantations in the Nabou estate. However, to determine the risks for other estates on geologically different substrates, the pedological studies conducted earlier by the Fiji Pine Commission and the University of the South Pacific should be reviewed in this respect.

3. Additional research is necessary to determine which methods commonly used for the determination of 'available' nutrients in the soil accurately describe the response of tree growth.

4. Fairly reliable estimates of atmospheric nutrient inputs for periods without cyclones have been presented in Chapter 13. However, large uncertainties exist with respect to the magnitude of inputs during cyclone events. It is therefore recommended that the rainfall collected at a selected number of rainfall stations (including coastal and inland stations) of the Fiji Meteorological Service during such events be analysed to obtain more information on the spatial variablility and the magnitude of such inputs.
5. Nutrient losses in suspended sediment during and after harvesting were not quantified in the present study and further research is necessary.
6. The testing of the TOPOG model (O'Loughlin *et al.*, 1989) on preliminary data collected in the Oleolega catchment indicated that the model may well be used to identify areas where plantation forest would be prone to moisture stress, or areas sensitive to erosion during and after harvesting. Furthermore, it may be used to predict the effects of land-use conversion on the hydrology of a given area and could therefore be an excellent tool in the planning of forestry activities (selection of future plantation areas, planning of locations of roads and landings at the end of a rotation). However, further testing of the model and quantification of the model parameters with respect to the situation in Fiji is necessary.

18.2 Forest Management

Based on the information presented in this dissertation, the following recommendations can be made:

- Grassland catchments which are presently used for the water supply of urban or rural areas should preferably not be converted to plantation forest for the following reasons:

  1. Afforestation of grassland catchments will lead to reduced water yields to such an extent that water shortages are likely to occur during dry periods, as has been the case with the Varaciva catchment (Kammer and raj, 1979).
  2. Unless exceptional care is taken during harvesting (*e.g.* sky line or manual extraction of logs), the construction of roads and landings associated with the removal of merchantable will almost certainly lead to increased erosion and therefore higher sediment loads in streamflow during storm events. This reduces the quality of the water and creates problems for the water supply to downstream villages.

  It is recommended therefore that water authorities participate in the planning of afforestation projects in such grassland areas.

- To minimize the extreme spatial heterogeneity in amounts of logging debris during harvesting, trees should be stripped from their crowns immediately after felling and the slash should be left *in situ* as a mulch. From a soil conservation point of view burning of the slash should be avoided for the following reasons:

  - The slash and litter layer protect the soil from direct raindrop impact, thereby reducing chances of physical degradation of the topsoil to a large extent.

  - Nutrient release from the slash and litter layer by decomposition are gradual and this will prevent the losses via leaching in streamflow (particularly K, P, N) and volatilization (N), as were observed after the burn in the Oleolega catchment. Furthermore, newly planted pines may profit from the slow release of nutrients from the mulch

  Site accessability for planting could be improved by the cutting of large pieces of woody debris (such as tree tops, large branches) into small pieces when the crowns are stripped at the stump. This would have the additional advantage of speeding up the decomposition of these components, thereby reducing the fuel load and thus subsequent fire hazard. The presence of a mulch cover after planting has the additional advantage that evaporation from the wet soil is reduced, although this may partly be compensated by higher rainfall interception losses from the litter. This would reduce the chance of water stress occurring shortly after planting. When planting and mulching is done immediately after harvesting, the competition between the young pines and the returning grassland vegetation may not be too large. A rapid return of the grasland vegetation was observed after burning in the Oleolega catchment and the effect of burning with respect to weed suppression may therefore be limited anyway.

- Since nutrient deficiencies are not likely to occur in subsequent rotations in the Oleolega forest, the largest threat to the sustainability of the plantation forests comes from a degradation of the physical properties of the soil (depth, water holding capacity, permeability) by compaction and erosion. This may lead to water stress as well as problems with root development (Van der Weert, 1974) Roads and landings should therefore preferably be located on the ridges where the soil is already shallow, and cutting of roads in steep hillslopes should be avoided as much as possible to avoid soil degradation which may also affect adjacent, relatively undisturbed, areas downhill.
- Forests should preferably be planted on soils with depths over 60 cm since the productivity may otherwise be affected by frequent water stress and possibly also by problems with root development.
- Soils were observed to remain moist throughout the dry season after harvesting, and planting may therefore start after the first rainy period at the end of the dry season without the risk of moisture stress for the saplings.

Chapter 19

Summary

The destruction of natural forest, presumably by fire, shifting cultivation and overgrazing in the previous century has lead to a fire-climax grassland vegetation cover in West Viti Levu, Fiji (Twyford and Wright, 1965), where rainfall exhibits a seasonal pattern with an annual total of about 1800 mm. To meet increasing demands for pulpwood on the world market and local demands for timber, as well as to provide business opportunities for the land owners, extensive areas of these *Pennisetum polystachyon* grasslands have been afforested to *Pinus caribaea* since the 1960s by the Fiji Pine Commission. This afforestation allegedly led to reduced water yields from catchments in the North of Viti Levu within six years after planting (Kammer and Raj, 1979) in turn producing shortages in the urban water supply during dry periods. When these forests were harvested in the 1980s, a deterioration of the water quality was observed due to enhanced erosion leading to high suspended sediment loads during rainstorms. In addition, nutrient deficiencies (shoots without needles) became apparent in second rotation forests in the 1980s, which raised the question if plantation forestry was sustainable at all without the application of fertilizers. With respect to these issues, a study was initiated in 1989 as part of a collaboration between the Free University of Amsterdam and the Fiji Pine Commission (now Fiji Pine Ltd.), funded by the Netherlands Foundation for the Advancement of Tropical Research (WOTRO, grant no. W84-295) with the following objectives:

- to quantify any changes in the hydrological cycle as a result of converting *Pennisetum polystachyon* grasslands to *Pinus caribaea* plantations
- to evaluate the sustainability of pine plantation forestry in SW Viti Levu from a nutrient point of view
- to study the impact of harvesting and subsequent burning of slash on catchment water yield and quality, as well as on soil physical and chemical properties

Since it was not feasible to monitor a single plantation over a full rotation period (16–20 years), the 'false time series' approach (Hase and Fölster, 1982; Bruijnzeel, 1983a; Gholz *et al.*, 1985) was used to study the water and nutrient dynamics at several stages of plantation development. Hydrological, micro-meteorological and ecological studies were carried out between November 1989 and October 1991 in a grassland plot at Nabou, in three forest plots carrying six, eleven and fifteen year old forest (at Tulasewa, Korokula and Koromani, respectively). In addition, hydrological

Table 19.1: *Characteristics of the vegetation at the respective sites. Biomass and CAI data are for the pre-cyclone period.*

Research Site	**Age** [yr]	**Stocking** [ha-1]	**Dbhob** [m]	**h** [m]	**BA** [m2 ha-1]	**Living biomass** [t ha-1]	**CAI(1990)** [t ha-1 yr-1]
Nabou grassland	0	na	na	na	na	8	na
Tulasewa forest	6	825	0.16	11.6	18.1	70	22.5
Korokula forest	11	822	0.20	14.7	27.5	111	7.6
Koromani forest	15	621	0.25	17.5	31.6	148	9.6
Oleolega forest	15	459	0.25	18.3	15.8	109*	-

Dbhob: diameter at breast height (1.35 m); h: tree height; BA: Basal area; CAI: Current annual increment
na: Not applicable; *: Biomass of riparian forest not included

measurements were made between January 4, 1990, and April 5, 1991, in the Oleolega catchment which had been planted to pines in 1975 and was logged and burned in 1991 as a salvage operation after the forest had been severely damaged by cyclone Sina in November, 1990. This cyclone had a large impact on both the hydrological and nutrient cycles. The sites were all located in the Nabou Forest Estate (Figure 2.2) in SW Viti Levu, which was established in 1975. Some information on vegetation characteristics of the grassland and forest sites are presented in Table 19.1.

The *Pennisetum polystachyon* grassland vegetation is highly seasonal, with active growth during the wet season (November – April) and low productivity during the dry season. Since it is during the dry season that water shortages as a result of afforestation become acute, measurements at the Nabou grassland site were carried out mainly during the dry season of 1991. The results of the studies made at the respective sites will be summarized below.

Soil Physical and Chemical Aspects

The grassland and forest soils differed markedly in their physical and chemical characteristics, which could be attributed to differences in parent rock (dacites, andesites, and basalt–diabase), weathering processes and the degree of erosion. The forest soils were classified as Mollisols (Nabou grassland, Tulasewa and Korokula forests) and Oxisols (Koromani forest), of which the fertility was moderate (Koromani forests) to good (Tulasewa forest). Soil properties in the Oleolega catchment were highly variable but two major soil groups could be distinguished based on soil texture, depth and colour, which were associated with changes in the underlying parent rock (dacite–trachite, basalt–diabase). The soil in Korokula was shallow (bedrock between 30 and 80 cm) and still contained fairly large amounts of strongly weathered primary minerals, suggesting that this soil was relatively young. Weathering had progressed somewhat further in the soil of Tulasewa forest (bedrock at 80–150 cm), whereas the soil at Koromani forest (bedrock deeper than 150 cm) was in an advanced state of weathering and was considered to be relatively old. The soils in the Oleolega catchment ranged from those similar to that at Korokula forest (mainly on ridges in the north of the catchment on dacite rock) to that at Koromani forest (on hillsopes in the south of the catchment on basalt–diabase rock).

The soils were well-drained, with generally high hydraulic conductivities in the topsoil, but much lower values in the subsoil. Bulk densities ranged from 0.97 to 1.16

g cm^{-3} in topsoil, and increased to values between 1.1 and 1.5 g cm^{-3} in subsoil. Porosities were relatively high, both in topsoil (46–51%) and subsoil (39–64%). Data collected in the grassland and forest plots and in the Oleolega catchment did not suggest that any major changes in soil physical properties had occurred as a result of afforestation because differences in bulk density and saturated hydraulic conductivity between soils under forest were as large as those between forest and grassland soils (Tables 4.2 and 4.3). Some evidence was found which suggested that the higher root activity of pines did improve the soil structure of subsoil below the rooting zone of grass (0–80 cm), contrary to the findings of Latham (1983) and Bayliss-Smith (1983) who observed improvements in topsoil after afforestation with pines in Fiji. It must be noted that the evaluation of changes as a result of afforestation from a comparison of sites remains difficult due to the large spatial variation in properties of the soils in Fiji.

The water holding capacity (59–123 mm) of the shallow (0.3–0.8 m) soil in Korokula forest was insufficient to supply moisture for sustained transpiration by the pines during a dry period in April–May 1990 and water stress, as indicated by high litterfall, was observed. No water stress was observed during the same period in the other forests where the soils were deeper (1–2 m) and therefore had a higher storage of soil moisture (>150 mm). This illustrates the importance of soil depth in determining whether a particular forest is likely to suffer from water stress or not under the prevailing climatic conditions. Frequent water stress may be expected on soils with depths less than 0.5 m, and the forest productivity on such sites will be low, regardless of the nutrient content of the soil.

Significant changes in soil physical properties were observed following harvesting and burning in the Oleolega catchment. The mean bulk density of the topsoil increased from 1.07 to 1.13–1.17 g cm^{-3}, but the increase was not such that it fell outside the normal range observed in the forest study sites (0.99–1.16 g cm^{-3}). This coincided with a drop in the saturated hydraulic conductivity of the topsoil, with the largest decreases being observed on the landing and road surfaces. However, reductions in hydraulic conductivity in areas that had been harvested and burned, but not disturbed otherwise by heavy machinery, were not so large that overland flow occurred or reductions in the growth of second rotation forest were to be expected. Overland flow and associated erosion was observed on the severely compacted surfaces of landings and roads where the removal of topsoil often had decreased the soil depth to such an extent that the C-horizon or bedrock became exposed. The productivity of second rotation forest planted on these areas may be impaired for the following reasons:

- The soil depth, and therefore the water holding capacity was reduced. Pines planted on these surfaces are therefore likely to experience water stress during dry periods
- The compaction and the massive structure of the soil may have a detrimental effect on the root development of the pines (Van der Weert, 1974)

The fertility of the soils was moderate (Koromani forest) to good, with the highest nutrient contents in the soil of Korokula forest. The Bray-II method (Bray and Kurtz, 1945) and the Ca-lactate extraction methods for the determination of soil 'available' P produced widely differing estimates. The results of the latter (3.5–5 kg ha^{-1}) seemed unrealistically low in view of the amounts already accumulated in the trees and litter layer. The Bray-II method was thought to provide more realistic estimates (24–164 kg ha^{-1}).

Grassland *versus* Forest Water Use

Estimates of evapotranspiration from grassland for selected dry periods (n= 59 days) during the dry season of 1991 were derived from soil moisture depletion measurements with a Didcot soil moisture capacitance probe. Surface resistances (r_s) for grass were calculated for these periods by inserting the ET_{sm} values and micro-meteorological data collected above the grass in the inverted Penman-Monteith equation. These surface resistances were in turn related to the LAI of grass via a simple linear regression model. The latter equation was subsequently used to calculate the average daily ET_{pm} rate for a 131-day period during which the grass was dead, resulting in a value of 1.0($\pm$0.3) mm day^{-1}. The corresponding Penman open water evaporation (E_0) was 3.7 mm day^{-1} resulting in a very low ET/E_0 ratio of 0.26. The same approach for the derivation of r_s could not be used in the forest plots where ET_{sm} values were underestimated because soil moisture measurements could not be made down to depths below the rooting zone.

Therefore, a combination of various micro-meteorological techniques (Bowen Ratio and Temperature Fluctuation Energy Balance methods and Penman-Monteith method) was used for the determination of forest ET on a half-hourly basis in the Tulasewa and Koromani forest plots, whereas the water balance method was used to derive estimates of wet and dry season ET for the forested Oleolega catchment. As indicated earlier, the study sites were struck by cyclone Sina in November 1990. This resulted in large changes in foliar biomass and, indeed, total forest biomass in the case of Tulasewa forest where the stocking decreased overnight from 835 to 489 trees ha^{-1}. Needless to say that pre- and post-cyclone ET rates differed rather strongly. Calculated pre-cyclone dry season ET rates ranged from 3.3 mm day^{-1} for the mature pine forest in the Oleolega catchment to 4.0 mm day^{-1} for the young forest at Tulasewa. Corresponding Penman open water evaporation rates (E_0) were 3.8 and 3.5 mm day^{-1}, resulting in ET/E_0 ratios of 0.9 and 1.1, respectively. After Koromani forest had been defoliated by cyclone Sina, a relatively low ET value of 3.0 mm day^{-1} was derived for the dry season of 1991, in spite of a higher E_0 (4.2 mm day^{-1}) compared to those calculated for the other sites a year earlier. This resulted in the relatively low dry season ET/E_0 ratio of 0.7 for mature, cyclone damaged pine forest. The low post-cyclone ET in Tulasewa forest resulted in high soil moisture levels throughout the dry season.

Micro-meteorological measurements above grass and pine forest indicated that the albedo decreased from 0.18 for grass to 0.10–0.13 for pine forest, resulting in higher net radiation totals above the latter. Soil heat flux totals were low in a dense grass stand at Oleolega, but even lower values were observed in the pine stands. Energy storage within the pine canopy and biomass was low. These observations indicate that the available energy for partitioning over the latent and sensible heat fluxes is higher above pine forest than above grass. Afforestation also caused an increase in the aerodynamic roughness of the vegetation, resulting in a decrease of the aerodynamic roughness from 31 s m^{-1} for grass to about 14 s m^{-1} for pine forest. These changes suggest that the forest ET will be higher than the grassland ET during the wet season as well. Observed diurnal ranges of temperature and humidity above grass were larger than above pine forest.

Rainfall Interception losses in the canopies and litter layers of the respective forest sites were estimated from above- and below-canopy/litter layer measurements of rainfall. Interception losses in the forest chronosequence varied little, ranging from 26% of total rainfall in the 15-year-old Koromani forest to 29% in the 11-year-old Korokula forest, of which some 10% was lost in the litter layer. The (modelled) interception loss for grassland (Gash's analytical model and litter layer interception model developed in this study; Section 5.5) was much lower at 12% of total rainfall. As rainfall interception in the 6-year-old stand at Tulasewa amounted to 27%, this suggested that interception losses increased by some 14% of total rainfall in the period between planting and canopy closure around age six. Not surprising, interception losses decreased by several percent as a result of damage afflicted by cyclone Sina (gap formation, defoliation). These changes were presumably only temporary in the older forests where the stocking had not changed to a large extent. However, a permanent decrease may be expected for the stand at Tulasewa where 40% of the trees were destroyed.

Comparison of dry season evapotranspiration losses from *Pennisetum polystachyon* grassland and from *Pinus caribaea* plantations suggested an increase in these losses of 300–400 mm, and therefore corresponding decreases in water yield, within the first six years after afforestation. Evapotranspiration losses remained fairly constant thereafter. The change in the dry season water use after afforestation must be attributed to differences in transpiration between the (then largely dormant) grassland vegetation and the actively growing pines. Differences in rainfall interception characteristics are less important during the dry season but will play a significant role during the wet season.

Water balance measurements in the Oleolega catchment indicated that a modest reduction in ET (7–14%) occurred during a rather dry period following harvesting of the mature pine forest and subsequent burning of the slash. However, this reduction was sufficient to produce a 51% increase in water yield compared to that modelled for the forested catchment using post-harvesting rainfall data as input (Chapter 15). Harvesting of the forest and subsequent burning of slash increased minimum flows, which were 20–80% higher than those measured a year earlier for the forested catchment, as well as peak flow levels. Because the period after harvesting was much drier than usual (887 mm *versus* 1418 mm), larger reductions in ET, and therefore higher increases in the water yield may be expected with rainfall conditions closer to the long-term average.

The present study indicates that afforestation of areas under seasonal grass cover in SW Viti Levu does lead to reduced water yields during the dry season due to increased transpiration losses, and presumably during the wet season as well due to differences in interception characteristics. In turn, harvesting of the forest at the end of the rotation followed by burning results in increased water yields. Since the grassland vegetation returned within a few months after burning, and the disturbance to the soil associated with the logging activities did not result in the occurrence of overland flow on a large scale, the water use by the regenerating vegetation shortly after harvesting may be fairly similar to that of the catchment before afforestation.

Nutrient Cycling

All study forests were accumulating biomass at a high rate during the pre-cyclone period, with the above-ground tree and undergrowth biomass increasing from about 8 t ha^{-1} in grassland to 150 t ha^{-1} in 15-year-old forest (Table 19.1). The corresponding nutrient requirements were largest in the period before canopy closure, and decreased sharply between age 6 and 11 due to the release of nutrients (particularly K) from the undergrowth, the biomass of which decreased to about 3 t ha^{-1}. The grassland vegetation contained about 35 kg ha^{-1} of N, 3 kg ha^{-1} of P, 95 kg ha^{-1} of K, 16 kg ha^{-1} of Ca, 29 kg ha^{-1} of Mg and 2 kg ha^{-1} of Mn. Corresponding pre-cyclone amounts in the biomass of mature pine forest (Koromani) were 235, 23, 133, 165, 53 and 14 kg ha^{-1}, respectively. Cyclone Sina had a large impact on forest biomass and nutrient content, causing reductions of 30% in biomass and nutrient content at Tulasewa, and of 10% at Koromani, as measured at the end of the study in September 1991 compared to the initial values determined in January 1990. There were no indications that any of the study forests to suffered from nutrient deficiencies.

Amounts of litterfall (mainly needles) generally increased with forest age, but were also dependent on soil characteristics and stocking. Pre-cyclone pine litterfall amounts ranged from about 5 t ha^{-1} in the Tulasewa and Koromani plots to 9 t ha^{-1} in the Korokula forest plot. The associated nutrient returns to the forest floor formed a considerable proportion of the net annual uptake of the pines, particularly of Ca, Mg, Mn and B. Most of K, however, was returned to the forest floor in throughfall and stemflow. Litterfall deposited by cyclone Sina alone exceeded the pre-cyclone annual total by a factor 2 (Korokula forest) to 4 (Tulasewa forest). However, because of the higher nutrient concentrations in fresh material, the associated returns of N, P and K were 3 – 4 times (Korokula) and even 4 (N) to 10–11 (K, P) times (Tulasewa) higher than corresponding annual pre-cyclone returns. Post-cyclone litterfall was low at all sites.

Litter decomposition was fairly rapid, with a 70% decrease in needle litter mass over an 18–20 month period, as measured in a litter bag experiment. Pre-cyclone litter turnover rates (K_L) ranged from 0.4 in Korokula forest to 0.6 in Koromani forest. Decomposition of woody material, however, was much slower as indicated by the presence of severely decomposed wood from a forest stand which had been destroyed seven years earlier in the Tulasewa forest plot. Rates of nutrient release fromn decomposing litter varied between nutrients. More than 60% of the K present in fresh needle litter was released within the first three months after incubation, but the release of N, Ca, and to a lesser extent P and Mg, was much slower, with less than 50% released 1.5 year after incubation in the Koromani forest plot. Due to the differences between the stands it was not possible to detect if decomposition rates changed with age, although the lowest rates were found for litter in the mature forest.

Pre-cyclone measurements of litter standing crop in the forest chronosequence suggested that a slight accumulation of litter (from 10.5 to 13.5 t ha^{-1}) occurred with age. This coincided with a change in the litter layer composition from mainly grass litter in the Tulasewa forest plot to mainly needle litter at the older sites. The large amount of fresh litter deposited by cyclone Sina more than doubled the litter layer mass and nutrient content at all sites. Because such cyclones are a regular phenomenon in Fiji, the litter layer mass and nutrient content will fluctuate considerably during a rotation period.

Under normal weather conditions, the atmospheric nutrient inputs in Fiji are in the lower range of those measured for tropical forests elsewhere (Bruijnzeel, 1989a, 1991). However, during the passage of a cyclone, maritime elements (particularly Na, Cl, Mg and SO_4) may be deposited in quantities far exceeding the normal annual inputs, at least in the coastal areas. Losses of nutrients in water draining from the sites were low, with the exception of elements released by weathering (Na, Mg, Ca, Si, SO_4). Combining these losses with the atmospheric nutrient inputs indicated apparent accumulations of N, P, K and Mn at all sites under investigation, and near neutral budgets or net losses for Ca and Mg. The deposition of seaspray and large quantities of fresh litter during cyclone Sina resulted in increased concentrations of ocean-derived elements in the soil moisture and this, in combination with higher percolation rates due to reduced evapotranspiration, resulted in nutrient losses during the post-cyclone period which were several times higher than pre-cyclone losses.

The atmospheric nutrient input was insufficient to meet uptake by the actively growing forests, the accumulation of nutrients in the litter layer and losses by drainage. Therefore, most of the nutrients taken up by the biomass were supplied by the soil, either by weathering of primary minerals or by depletion of soil reserves. Rates of nutrient uptake from the soil were highest in the period before canopy closure but dropped to a minimum shortly after canopy closure (between age 6 and 11) when substantial amounts of nutrients (particularly K) were transferred from the undergrowth biomass to the soil. Nutrient use efficiency indices (*i.e.* ratio of litterfall mass to the return of nutrients to the forest floor, Vitousek, 1984) indicated that the forests were very efficient in their use of N and P, but less efficient in their use of Ca, Mg and K. The nutrient use efficiency of P, K and Mg decreased considerably after the cyclone event, which was attributed to a less efficient retranslocation of nutrients before abscission of relatively young needles.

The foregoing shows that effects of cyclones on the intra-system nutrient cycle are large and may well last several years during which nutrient requirements of the regenerating forest can be met entirely by release through decomposition of cyclone debris. The fact that the number of cyclones during a rotation and the amount of damage they afflict are unpredictable complicates the evaluation of forest nutrient budgets considerably. Soils in SW Viti Levu are relatively shallow and pine roots were observed to penetrate the zone of active weathering in most instances. This suggests that weathering may provide a significant portion of the nutrients required for biomass production, with the possible exception of P as this element becomes rapidly immobilized in the soil (Clayton, 1979).

Effects of Harvesting and Burning

The Oleolega forest was harvested between December 1990 and July 1991 as a salvage operation after the forest suffered severe damage by cyclone Sina. About 55 t ha^{-1} of merchantable timber were extracted from the catchment and the associated nutrient losses amounted to 45 (N), 5 (P), 29 (K), 23 (Ca), 11 (Mg), 0.6 (Zn), 3.1 (Mn) and 0.1 kg ha^{-1} (B). Cyclone Sina increased the litter layer mass from about 14 t ha^{-1} to 29 t ha^{-1} and a further increase to 37 t ha^{-1} occurred during harvesting. Nutrient concentrations in streamflow from the forested Oleolega catchment were low. The deposition of sea spray and fresh litter during cyclone Sina temporarily increased the EC and pH, as well as the concentrations of most nutrients in streamflow, with the exception of NO_3, NH_4, PO_4 and total P, which showed no significant changes, and those of SO_4 and Mn, which decreased after the event. Concentrations in baseflow tended to return slowly to their pre-cyclone levels during the harvesting operation which lasted until August 1991, although those of NO_3 increased (albeit not significantly). Changes in the chemical composition of streamflow and soil moisture after cyclone Sina were such that any effects of the subsequent harvesting were largely masked. No large changes occurred in the amounts exported from the catchment as a result of cyclone effects and timber extraction. However, although the exports remained low in an absolute sense, exports of K, NO_3 total N, PO_4 and total P were 1.5 (PO_4) to 2.2 (K) times higher than their pre-cyclone values.

Burning of the slash in August 1991 reduced the litter layer mass from 37 to 6 t ha^{-1} and its nutrient content by 245 (N), 10 (P), 72 (K), 95 (Ca), 37 (Mg), 0.8 (Zn), 19.1 (Mn) and 0.3 kg ha^{-1} (B). Comparison of the nutrient contents of soil samples collected before harvesting and after burning showed that most of the nutrients released from decomposing slash and by the burn were retained by the soil. Concentrations of most nutrients in baseflow after the burn only changed significantly when the soil had been thoroughly wetted at the start of the wet season in December 1991. At that time, significant increases were observed in the EC and concentrations of Na, Mg, Ca, NH_4, Cl, HCO_3, NO_3, PO_4, Mn, total N and total P. However, relatively high concentrations of K and SO_4 were already observed in streamflow during the first storm after the burn, but not during subsequent storms, suggesting that these nutrients were rapidly leached from the ash layer. Concentrations of SO_4 in baseflow after the burn were lower than those before the burn, possibly due to increased biological activity in the streamwater (algae). Post-burn exports of Na, Ca, Mg, NH_4, SO_4, Si, Mn and Fe were higher than those obtained from model simulations for the forested situation but the increases could be attributed almost completely to the higher water yield after harvesting and burning. Exports of total P, PO_4, NO_3, K, on the other hand, were higher than would be expected from the increase in water yield alone. However, the absolute nutrient exports in streamflow as a result of harvesting and burning were low in view of the large amounts released from the slash and subsequently retained by the soil. The largest losses were associated with the removal of merchantable timber from the site.

Sustainability of the Pine Plantation Forestry in Fiji

Full rotation (January 1975 – April 1992) nutrient budgets were compiled for the Oleolega forest for various harvesting intensities and two weathering scenarios. Atmospheric inputs were obtained by combining the concentration data collected during the present study with daily rainfall amounts measured at Nadi Airport (1975–1979), Nabou station (1980–1989) and at the Oleolega catchment (1990–1992). Corresponding nutrient exports in streamflow were obtained by combining nutrient concentrations in streamflow before harvesting with simulated streamflow amounts using daily time steps. Weathering inputs could not be evaluated from the soil chemical data collected in the 'false time series' due to differences in soils between the respective sites. Therefore 'pessimistic' (no weathering inputs) and 'optimistic' (all nutrients required for forest growth supplied by weathering) scenarios were computed. Combining the forest's nutrient requirements over the rotation period with estimates of nutrient reserves in the soil (weathering inputs assumed negligible) suggested that nutrient deficiencies were unlikely to occur within the next 5 (Ca) to 19 (K) rotations, provided that harvesting would remain limited to merchantable timber only, and that erosion and associated losses of nutrients with sediment in the streamflow would be minimized. Whole tree harvesting would reduce the number of possible rotations to 2 or 3, before N or P deficiencies could become apparent. Since weathering may provide substantial amounts of nutrients to the ecosystem and because our estimates of N inputs must be underestimates, it may be concluded that plantation forestry with the current management practices is sustainable from a nutrient point of view. Therefore, cyclone damage must at present be considered to be the main factor limiting the biomass production in SW Viti Levu. However, to maintain the current rates of productivity, care should be taken to avoid severe physical deterioration of the shallow soils as a result of soil disturbance during harvesting and subsequent erosion.

Chapter 20

Samenvatting van het Proefschrift 'Water en Nutriënten Dynamiek van *Pinus caribaea* Plantages op Voormalige Graslanden in zuidwest Viti Levu, Fiji'

Het verdwijnen van de natuurlijke bosvegetatie, waarschijnlijk door zwerflandbouw, bosbranden en een te intensieve begrazing in de vorige eeuw heeft geleid tot het ontstaan van een vuur-resistente grasland begroeiing in west Viti Levu, Fiji (Twyford en Wright, 1965), waar de neerslag een sterke seizoenale verdeling vertoont met een jaartotaal van ongeveer 1800 mm. Om te voldoen aan de toenemende vraag op de wereldmarkt naar houtpulp voor papierproduktie, aan de lokale vraag naar hout voor constructiewerkzaamheden, en om werkgelegenheid te scheppen voor de landeigenaren, zijn sinds 1960 door de Fiji Pine Commission *Pinus caribaea* plantages aangeplant op deze *Pennisetum polystachyon* graslanden. Echter, binnen zes jaar na de aanplant van dennen op graslanden in het noorden van Viti Levu, werden sterk verlaagde debieten geobserveerd in stroomgebieden gebruikt voor de waterwinning (Kammer en Raj, 1979). Dit had ondermeer tot gevolg dat tekorten voor de stedelijke watervoorziening ontstonden tijdens droge perioden. Het kappen van deze bossen in de jaren tachtig veroorzaakte nieuwe problemen voor de waterwinning, met name in de vorm van een vermindering in de kwaliteit van het rivierwater door de hoge sedimentconcentraties tijdens regenbuien (erosie). In de jaren tachtig na het kappen van de eerste bosrotatie gevolgd door het branden van de strooisellaag nutriëntentekorten geconstateerd (ontwikkeling van scheuten zonder naalden) in de tweede rotatie. Dit riep vragen op over de duurzaamheid van de huidige wijze van houtproduktie in Fiji (dat wil zeggen, zonder toevoeging van kunstmest). Om meer inzicht te krijgen in deze problemen is

Table 20.1: *Eigenschappen van de vegetatie op de verschillende onderzoekslokaties. Biomassa en bijbehorende produktie gegevens (CAIs) verzameld in de periode voor november 1990 (cycloon Sina).*

Lokatie	Leeftijd [jr]	Dichtheid [ha-1]	Dbhob [m]	h [m]	BO [m2 ha-1]	Groene biomassa [t ha-1]	CAI(1990) [t ha-1 jr-1]
Nabou grasland	0	nvt	nvt	nvt	nvt	8	nvt
Tulasewa bos	6	825	0.16	11.6	18.1	70	22.5
Korokula bos	11	822	0.20	14.7	27.5	111	7.6
Koromani bos	15	621	0.25	17.5	31.6	148	9.6
Oleolega bos	15	459	0.25	18.3	15.8	109*	-

Dbhob: Diameter op 1.35 m; h: Boomhoogte; BO: Basale oppervlakte; CAI: Groei in 1990
nvt: Niet van toepassing; *: Biomassa van loofbos niet meegerekend

in 1989 een studie begonnen in een samenwerking van de Vrije Universiteit van Amsterdam en de Fiji Pine Commission (tegenwoordig Fiji Pine Ltd.) met financiering door de stichting voor wetenschappelijk onderzoek van de tropen (WOTRO, projectnr. W84-295). De studie had de volgende doelstellingen:

- Kwantifikatie van eventuele veranderingen in de hydrologische kringloop ten gevolge van herbebossing van *Pennisetum polystachyon* graslanden in zuidwest Viti Levu met *Pinus caribaea*
- Bestudering van de nutriënten kringlopen in graslanden en plantagebossen ter evaluatie van de duurzaamheid van de huidige manier van houtproduktie
- Bestudering van de effekten van kappen gevolgd door het afbranden van de strooisellaag zowel op de hoeveelheid en kwaliteit van rivierwater, als op de fysische en chemische eigenschappen van de bodem

Omdat het niet mogelijk was om een enkele plantage te bestuderen vanaf het planten tot aan de kap van het volwassen bos na 16–20 jaar, werd een serie bossen van verschillende ouderdom geselecteerd om de kringlopen van water- en nutriënten te bestuderen tijdens verschillende fasen in de ontwikkeling van de plantage (Hase en Fölster, 1982; Bruijnzeel, 1983a; Gholz *et al.*, 1985). Hydrologisch, hydrochemisch, micro-meteorologisch en ecologisch onderzoek werd verricht in een grasland bij Nabou, in de zes jaar oude Tulasewa plantage, in de elf jaar oude Korokula plantage en in de vijftien jaar oude Koromani plantage gedurende de periode november 1989 tot oktober 1991, en in het Oleolega stroomgebied tussen 4 januari 1990 en 5 april 1991. Het Oleolega stroomgebied was in 1975 aangeplant met *Pinus caribaea* en werd in 1991 gekapt en verbrand nadat het bos grote schade had ondervonden van cycloon Sina in november 1990. Deze cycloon bleek een grote invloed te hebben op de hydrologie en op de nutriëntenkringlopen van alle bestudeerde bossen. De onderzoekslokaties lagen allemaal in het Nabou plantage gebied (herbebossing vanaf 1975) in zuidwest Viti Levu (Figuur 2.2). De resultaten, verkregen voor de verschillende onderzoekslokaties, zullen hierna in het kort besproken worden. Relevante informatie over de eigenschappen van de vegetatie op de verschillende lokaties ten tijde van de studie is gegeven in Tabel 20.1

De *Pennisetum polystachyon* graslandvegetatie heeft een sterk seizoenaal karakter met een hoge produktie in het natte seizoen (november – april) waarna het bovengrondse deel van het gras grotendeels afsterft tijdens het droge seizoen. Omdat watertekorten ten gevolge van herbebossing van dit soort graslanden juist tijdens droge perioden voorkomen, werden metingen in het grasland voornamelijk tijdens het droge seizoen van 1991 verricht. In tegenstelling tot de graslandvegetatie is de groei van de dennebossen slechts in zeer geringe mate seizoensgebonden en deze bossen vertonen gewoonlijk een hoge biomassaproduktie vanaf het planten tot aan het eind van de rotatie na 16–20 jaar.

Fysische en Chemische Eigenschappen van de Bodems

De bestudeerde bodems onder gras en dennenbos verschilden aanmerkelijk in hun fysische en chemische eigenschappen, wat voornamelijk te wijten was aan verschillen in het onderliggende gesteente (daciet, andesiet en basalt–diabaas) en verschillen in de mate van verwering en erosie. Op basis van de verzamelde gegevens konden de bodems geklassificeerd worden als Mollisols (Nabou grasland, Tulasewa en Korokula plantagebossen) en Oxisols (Koromani plantage), met een redelijke (Koromani) tot goede vruchtbaarheid (Tulasewa). De bodemeigenschappen vertoonden een grote ruimtelijke verscheidenheid in het Oleolega stroomgebied, maar op basis van textuur, diepte en kleur konden twee groepen worden onderscheiden, die gerelateerd waren aan verschillen in het onderliggende gesteente (daciet–trachiet of basalt–diabaas). De bodem in de Korokula plantage was dun (verweerd moedergesteente op 30–80 cm diepte) en bevatte grote hoeveelheden sterk verweerde gesteentemineralen wat erop duidde dat de bodem relatief jong was. De bodem van de Tulasewa plantage was wat verder verweerd en wat dieper (moedergesteente op 80–150 cm diepte), terwijl die van de Koromani plantage het meest verweerd was en weinig gesteentemineralen bevatte. De bodems in het Oleolega stroomgebied vertoonden een grote ruimtelijke variatie. De bodems op de ruggen in het noorden van het stroomgebied (op dacietgesteente) waren vergelijkbaar met die beschreven voor het plantagebos bij Korokula, terwijl die op de hellingen in het zuiden (op basalt–diabaas gesteente) vergelijkbaar waren met de bodems onder de bossen bij Tulasewa en Koromani.

De bestudeerde bodems waren goed gedraineerd, met relatief hoge verzadigde doorlatendheden in de toplaag, en lage tot zeer lage waarden dieper in de bodem. De bulkdichtheden varieerden van 0.97 tot 1.16 g cm^{-3} in de toplaag, en namen toe met de diepte tot 1.1–1.5 g cm^{-3}. Alle bodems hadden hoge porositeiten, zowel in de toplaag (46–51%), als dieper in de bodem (39–64%). De verschillen in fysische eigenschappen, met name in de bulkdichtheden en verzadigde doorlatendheden, tussen de bosbodems onderling waren even groot waren als die tussen de bodems onder gras en bos. Dit wees erop dat er geen grote veranderingen waren opgetreden ten gevolge van herbebossing. Er waren wel aanwijzingen dat de hogere wortelactiviteit van de dennen een verandering in de structuur van de bodem onder de worteldiepte van gras ($\pm$80 cm) tot gevolg had. Dit in tegenstelling tot de bevindingen van Latham (1983) en Bayliss-Smith (1983), die wel verbeteringen in de fysische eigenschappen van de toplaag van de bodem vonden na herbebossing van graslanden met *Pinus caribaea* op het eiland Lakemba in Fiji. De grote ruimtelijke variatie in de eigenschappen van bodems in zuidwest Viti Levu maakt het echter moeilijk om veranderingen ten gevolge van herbebossing te evalueren door een vergelijking van gras en bosbodems.

De beschikbare hoeveelheid water voor planten (59–123 mm) in de dunne bodem (30–80 cm) van de Korokula plantage was niet voldoende om transpiratie door de dennen in stand te houden gedurende een droge periode in mei en juni 1990, zoals bleek uit een verhoogde strooiselproduktie in deze periode. Zulke watertekorten ontstonden niet op de andere lokaties, waar de bossen aangeplant waren op dikkere bodems met inherent grotere hoeveelheden beschikbaar water (>150 mm) voor transpiratie. Dit onderstreept het belang van de bodemdikte als een bepalende factor (naast de neerslaghoeveelheid) of een bos al dan niet onderhevig zal zijn aan periodieke watertekorten. Periodieke watertekorten kunnen verwacht worden in bossen aangeplant op bodems dunner dan 50 cm en het mag gevoeglijk aangenomen worden, dat de produktiviteit van deze bossen in zuidwest Viti Levu laag zal zijn ongeacht de vruchtbaarheid van de bodem.

De fysische eigenschappen van de bodem in het Oleolega stroomgebied veranderden signifikant na het kappen van het bos en het branden van het stooisel. De gemiddelde bulkdichtheid van de toplaag van de bodem steeg van 1.07 g cm^{-3} onder ongestoord bos naar 1.13–1.17 g cm^{-3} na kappen en branden. Deze stijging was echter niet zo groot dat de waarden na kap hoger waren dan die gemeten in de andere ongestoorde plantagebossen (0.97–1.16 g cm^{-3}). De stijging in de bulkdichtheid na kappen en branden viel samen met een sterke daling in de verzadigde doorlatendheid, vooral op nieuw aangelegde wegen, uitsleepsporen en houtverzamelplaatsen. De fysische veranderingen in bodems in gebieden, die niet machinaal verstoord waren, waren niet zodanig dat regenwater afgevoerd werd over het oppervlak (overland flow) tijdens grotere regenbuien, of dat deze veranderingen gevolgen zouden kunnen hebben voor de produktiviteit van de tweede rotatie. Oppervlakkige afvoer van water (en de daarmee geassocieerde erosie) werd echter wel waargenomen op de machinaal verstoorde en sterk gecompakteerde oppervlakken van houtoverslagplaatsen, wegen en uitsleeppaden. Het verdwijnen van de toplaag van de bodem in deze sterk verstoorde gebieden verminderde de bodemdiepte in vele gevallen zo, dat de C-horizont of het verweerde moedergesteente aan het oppervlak kwam. Op deze sterk verstoorde bodems kan derhalve een lage productiviteit van tweede-rotatie plantagebossen verwacht worden om de volgende redenen:

- De bodemdikte, en derhalve ook de beschikbare hoeveelheid water voor transpiratie door planten, was sterk verminderd. Bomen geplant op deze bodems zullen daardoor regelmatig watergebrek ondervinden tijdens droge perioden wat, de groei sterkkan beïnvloeden
- De massieve structuur van de bodem kan een remmende invloed hebben op de ontwikkeling van het wortelstelsel van de aangeplante bomen, en daarmee ook op de bovengrondse biomassa produktie (Van der Weert, 1974)

De vruchtbaarheid van de bodems in de onderzoeksgebieden was redelijk (Koromani plantage) tot goed met de grootste hoeveelheid beschikbare nutriënten in de relatief jonge bodem onder de Korokula plantage. De Bray-II (Bray en Kurtz, 1945) en de Ca-lactaat extractiemethoden voor de bepaling van voor planten beschikbaar fosfor gaven sterk verschillende resultaten. De resultaten van de laatstgenoemde methode (3.5–5.0 kg ha^{-1}) waren onwaarschijnlijk laag mede gelet op de hoeveelheden fosfor die reeds opgenomen waren in de bovengrondse biomassa en in de strooisellaag. De resultaten verkregen met de Bray-II methode waren realistischer (24–164 kg ha^{-1}).

Watergebruik van Graslandvegetatie en Dennebossen

Schattingen voor de evapotranspiratie (ET) door grasland in geselecteerde droge perioden (n= 59 dagen) tijdens het droge seizoen van 1991 werden verkregen door het bepalen van de vochtverliezen in de bodem met behulp van een Didcot capacitievebodemvochtsonde. Deze ET_{sm}-fluxen en gelijkertijd boven het gras verzamelde micrometeorologische gegevens, werden gebruikt om de oppervlakte weerstand (surface resistance, r_s) te berekenen met behulp van de geïnverteerde Penman-Monteith vergelijking. Op zijn beurt werd r_s gerelateerd aan veranderingingen in de bladoppervlakte-index (LAI) van gras en de gevonden regressievergelijking werd vervolgens gebruikt om een gemiddelde dagelijkse verdamping van 1.0($\pm$0.3) mm dag^{-1} uit te rekenen voor een 131 dagen lange periode, gedurende welke het meeste gras dood was. De Penman-open-water verdamping (E_0) voor dezelfde periode was gemiddeld 3.7 mm dag^{-1} wat resulteerde in een erg laag quotiënt van 0.26 voor ET/E_0. Dezelfde aanpak voor de bepaling van r_s kon niet toegepast worden in de bestudeerde bossen aangezien te lage waarden voor ET_{sm} werden verkregen omdat het niet mogelijk was om bodemvochtsmetingen te maken tot op een diepte onder die van de dennewortels.

Halfuurlijkse waarden voor de ET van de Tulasewa en Koromani plantagebossen werden daarom bepaald door een combinatie van verschillende micro-meteorologische methoden te gebruiken, met name de Bowen ratio en temperatuurfluctuatie – energiebalans methoden en de Penman-Monteith methode. Tevens werd de stroomgebied–waterbalans methode gebruikt om schattingen te verkrijgen van de verdamping tijdens het natte zowel als het droge seizoen voor het Oleolega stroomgebied. Zoals eerder vermeld, passeerde cycloon Sina Fiji in November 1990. Dit had als gevolg dat de bladmassa van alle bossen aanzienlijk verminderde door ontbladering, zowel als de totale bovengrondse biomassa van het bos bij Tulasewa waar de bosdichtheid van 835 bomen ha^{-1} naar 489 bomen ha^{-1} daalde. Het zal duidelijk zijn dat dit het watergebruik van het bos beïnvloedde.

De voor het droge seizoen van 1990 (dat wil zeggen in de periode voor cycloon Sina) berekende ET waarden varieerden van 3.3 mm dag^{-1} voor het vijftien jaar oude bos in het Oleolega stroomgebied tot 4.0 mm dag^{-1} voor het zes jaar oude Tulasewa bos. De bijbehorende Penman-open-water verdampingen waren respectievelijk 3.8 en 3.5 mm dag^{-1}, zodat waarden van 0.9 en 1.1 werden verkregen voor de quotiënten van ET/E_0. Hoewel E_0 gemiddeld hoger was tijdens het droge seizoen van 1991 (4.2 mm dag^{-1}), werd er toch een relatief lage ET-waarde van 3.0 mm dag^{-1} berekend voor de Koromani plantage. Dit was zeer waarschijnlijk te wijten aan een verminderde transpiratie ten gevolge van de ontbladering teweeggebracht door cycloon Sina in november 1990. Een relatief lage waarde van 0.7 werd berekend voor het quotiënt van ET/E_0 tijdens het droge seizoen in 1991. De lagere transpiratie van het bos bij Tulasewa, waar 40% van de bomen waren omgewaaid, resulteerde in aanmerkelijk hogere vochtgehalten in de bodem tijdens het droge seizoen van 1991, vergeleken met die gemeten in dezelfde periode in 1990.

Kortgolvige stralingsmetingen gemaakt boven de twee vegetatietypen toonden aan dat de reflectiecoëfficient daalde van 0.18 voor gras naar 0.10–0.13 voor de dennebossen, wat resulteerde in hogere netto stralingswaarden voor de bossen. De bodemwarmteflux was reeds laag onder de dichte grasvegetatie bij het Oleolega stroomgebied, maar nog lagere waarden werden gemeten in de dennebossen. De opslag van energie binnen het bos was laag. Uit deze waarnemingen bleek dat de hoeveelheid beschikbare energie voor verdeling over de voelbare en latente warmtefluxen hoger was boven bos dan boven gras. Herbebossing had tevens tot gevolg dat de aerodynamische weerstand daalde van 31 s m^{-1} voor het gras naar ongeveer 14 s m^{-1} voor de bossen. De veranderingen in deze factoren geven aan dat de verdamping door de bosvegetatie tijdens het natte seizoen hoger zal zijn dan die van het gras. Herbebossing van de graslanden verkleinde de dagelijkse gang van de temperatuur en luchtvochtigheid.

Verliezen van water door interceptie van neerslag in het kronendak en in de strooisellaag in de plantagebossen van verschillende ouderdom werden bepaald door het meten van de hoeveelheden water die het respectievelijk het kronendak (neerslag), de bosvloer (doorval en stamafvoer), en de bodem (strooiselpercolaat) bereikten tijdens regenbuien. De relatieve interceptieverliezen waren ongeveer even groot in de verschillende plantagebossen en varieerden tussen 26% van de neerslag in de vijftien jaar oude Koromani plantage en 29% van die in de elf jaar oude Korokula plantage. In alle plantages bedroegen de interceptieverliezen in de strooisellaag rond de 10% van de neerslag. De gemodelleerde interceptieverliezen in de vegetatie en strooisellaag (Analytisch model van Gash en strooisellaag interceptiemodel ontwikkeld in deze studie, Paragraaf 5.5) van het Nabou grasland bedroegen om en nabij de 10% van de neerslag. Het interceptieverlies in het zes jaar oude Tulasewa bos bedroeg 27%. Dit wijst erop dat een stijging in de totale interceptieverliezen in het kronendak en in de strooisellaag verwacht kunnen worden van rond de 15% van de neerslag in de periode tussen aanplant van het bos en de bijna afgeronde ontwikkeling van het kronendak ongeveer zes jaar later. De ontbladering ten gevolge van cycloon Sina had als resultaat, dat de verliezen door interceptie tijdelijk (mogelijk gedurende 1 à 2 jaar) enige procenten kleiner werden in de bossen waarin het aantal bomen niet drastisch afgenomen was. Een permanente daling van de interceptieverliezen mag verwacht worden in de Tulasewa plantage, door de daling van de bosdichtheid met 40%.

Een vergelijking van de verliezen van water door verdamping gevonden voor *Pennisetum polystachyon* grasland en *Pinus caribaea* plantages toonde aan dat de verliezen met 300 tot 400 mm stegen binnen zes jaar na de aanplant van de plantagebossen, en dat de verdampings verliezen daarna min of meer constant bleven. Dit zal ongetwijfeld leiden tot reducties van vergelijkbare grootte in de oppervlaktewaterhoeveelheden na herbebossing van deze graslanden. Het verschil in waterverbruik was voornamelijk te wijten aan verschillen in de verliezen door transpiratie tussen het dode gras en de actief groeiende dennen. Verschillen in neerslaginterceptie karakteristieken van de twee vegetatietypen zijn minder belangrijk in het droge seizoen, maar kunnen een wel grote rol spelen in het waterverbruik tijdens het natte seizoen.

Hydrologische metingen in het Oleolega stroomgebied wezen uit dat het waterverbruik met 7–14% daalde gedurende een vrij droge periode na het kappen van het volwassen bos en het verbranden van de strooisellaag ten opzichte van de beboste situatie. Toch was deze geringe reductie genoeg om een stijging van 51% in de waterafvoer te bewerkstelligen ten opzichte van de gemodelleerde afvoer voor het beboste stroomgebied voor dezelfde periode. (Hoofdstuk 15). Zowel de minimum afvoeren, die 20–80% hoger waren dan de gemeten minimum afvoeren in de beboste situatie, en de piekafvoeren waren aanmerkelijk hoger na het kappen van het bos en het verbranden van de strooisellaag. Omdat de periode na kappen en branden aanmerkelijk droger was dan gewoonlijk (totale neerslag was 887 mm i.p.v. 1418 mm) kunnen grotere reducties in de verdamping, en grotere stijgingen in de debieten verwacht worden in jaren met neerslaghoeveelheden dichter bij het lange termijn gemiddelde.

Concluderend kunnen we stellen, dat de huidige studie aantoont, dat het aanplanten van *Pinus caribaea* plantages op seizoenale graslanden in zuidwest Viti Levu zal leiden tot een vermindering in de waterafvoer, en daardoor tot watertekorten, tijdens het droge seizoen door verhoging van de verliezen door transpiratie, en waarschijnlijk ook tijdens het natte seizoen door de verschillen in interceptie tussen de vegetatie typen. Op zijn beurt zal het kappen van het bos aan het eind van de rotatie gevolgd door het verbranden van de strooisellaag leiden to verhoogde afvoeren. Omdat de graslandvegetatie binnen een paar maanden na het branden teruggekeerd was en de verstoring van de bodem ten gevolge van de kap niet leidde tot oppervlakkige afvoer van regenwater op grote schaal, kan verwacht worden dat het watergebruik na het kappen/branden ongeveer gelijk zal zijn aan dat van voor de herbebossing.

Nutriënten Kringloop

De produktiviteit van de bestudeerde plantagebossen was hoog in de periode voor de destruktie en ontbladering van de bossen door cycloon Sina, zoals blijkt uit de hoge CAI waarden gegeven in Tabel 20.1. De totale bovengrondse biomassa van bos en ondergroei steeg van 8 t ha^{-1} in Nabou grasland tot 150 t ha^{-1} in het vijftien jaar oude Koromani bos. De opname van nutriënten uit de bodem voor de produktie van biomassa was het hoogst tijdens de snelle ontwikkeling van het nutriëntenrijke kronendak, ongeveer zes jaar na het aanplanten, en daalde scherp nadat het kronendak zich sloot, mede door het vrijkomen van nutriënten (vooral kalium) vanuit de ondergroei, waarvan de bovengrondse biomassa daalde tot ongeveer 3 t ha^{-1}. De vegetatie in het Nabou grasland bevatte ongeveer 35 kg ha^{-1} stikstof, 3 kg ha^{-1} fosfor, 95 kg ha^{-1} kalium, 16 kg ha^{-1} calcium, 29 kg ha^{-1} magnesium en 2 kg ha^{-1} mangaan. Bijbehorende waarden voor het vijftien jaar oude Koromani bos, bepaald in de periode voordat cycloon Sina schade aan het bos toebracht, waren respectievelijk 235, 23, 133, 165, 53, en 14 kg ha^{-1}. Geen van de bestudeerde bossen toonde tekenen van nutriëntentekorten. Ten gevolge van de toegebrachte schade door cycloon Sina waren de bovengrondse biomassa en nutrientenopslag in de bomen in september 1991 30% lager in de Tulasewa plantage en 10% lager in de Koromani plantage ten opzichte van die in januari 1990. De cycloon had derhalve een grote invloed op de biomassa en de nutriëntenoplag in de bossen.

De strooiselproduktie door de dennen (voornamelijk naalden) vertoonde een stijging met de ouderdom van het bos, maar was ook afhankelijk van de dichtheid van het bos en van bodemeigenschappen (met name beschikbare hoeveelheid water). De jaarlijkse strooiselproduktie in de periode voor cycloon Sina varieerde tussen 5 t ha^{-1} in de Tulasewa en Koromani plantages en 9 t ha^{-1} in de Korokula plantage. De nutriëntentoevoer naar de bodem in strooisel vormde een aanzienlijk deel van de netto jaarlijkse opname door de bossen, met name voor Ca, Mg, Mn en B. Echter, het grootste gedeelte van kalium keerde terug naar de bosvloer in doorval en stamafvoer, en niet in het strooisel. De stooiselproduktie tijdens de passage van cycloon Sina was meer dan twee (Korokula) tot vier (Tulasewa) keer de normale jaarlijkse produktie (d.w.z. in jaren zonder cyclonen). De nutriëntenconcentraties in het relatief verse strooisel, gedeponeerd tijdens de cycloon, waren hoger dan die in de normale strooiselval. Dit resulteerde in 3–4 keer hogere deposities van N, P en K (Korokula) en 4 (N) tot 10–11 (P, K) keer hogere deposities (Tulasewa) in strooisel gedeponeerd tijdens de cycloon, dan in die gedeponeerd tidens de gehele voorafgaande periode. De strooiselproduktie bleef laag na de ontbladering van de bossen door cycloon Sina.

De afbraak van het strooisel op de bosvloer was relatief snel, met gemeten gewichtsverliezen voor naalden (in stooiselzakjes) van ongeveer 70% over een periode van 18–20 maanden. Omzettingssnelheden, berekend als het quotiënt van de jaarlijkse naaldval en de hoeveelheid naalden op de bosgrond (K_L, in $jaar^{-1}$), in de periode voor de ontbladering door cycloon Sina varieerden tussen 0.4 (Korokula) en 0.6 $jaar^{-1}$ (Koromani). De afbraak van hout was veel minder snel, aangezien verrot hout van een in 1983 vernielde plantage nog steeds op de bosvloer aanwezig was in het bos bij Tulasewa. De omzettingssnelheden waren verschillend voor de verschillende voedingsstoffen. Meer dan 60% van het oorspronkelijk in de naalden aanwezige kalium was uitgespoeld binnen drie maanden na het plaatsen van de strooiselzakjes op de bosvloer. De omzettingssnelheden voor N en Ca, en in mindere mate voor Mg en P, waren veel lager en minder dan de helft van de oorspronkelijke inhoud van deze elementen was omgezet binnen een jaar na de plaatsing van de strooiselzakjes op de bosvloer in de Koromani plantage. Door de onderlinge verschillen tussen de bossen konden geen trends in de decompositiesnelheden met de bosleeftijd bepaald worden, al leek het erop dat de afbraak het langzaamst was in het oudste bos.

Gegevens over het gewicht van de strooisellaag in de Tulasewa, Korokula en Koromani plantages verzameld in de periode voor ontbladering suggereerde een lichte stijging in de massa van de strooisellaag met de ouderdom van het bos (van 10.5 t ha tot 13.5 t ha^{-1}). Tegelijkertijd veranderde de compositie van de strooisellaag die voornamelijk bestond uit gras resten in de jonge Tulasewa plantage in een strooisellaag voornamelijk bestaande uit dennenaalden in het volwassen Koromani bos. De grote hoeveelheid strooisel gedeponeerd door cycloon Sina ruim verdubbelde de massa en nutriënteninhoud van de strooisellaag in alle bestudeerde plantagebossen. Omdat zulke cyclonen regelmatig voorkomen in de Fiji eilanden zijn grote fluctuaties in de massa en nutriënteninhoud van de strooisellaag mogelijk binnen een rotatieperiode.

Onder normale weersomstandigheden (d.w.z. geen cyclonen) valt de atmosferische nutriënteninvoer in zuidwest Viti Levu in het lagere bereik van die gemeten boven tropische bossen op andere plaatsen (Bruijnzeel, 1989a, 1991). Echter, tijdens cyclonen kunnen oceanische elementen (zoals Na, Cl, Mg, en SO_4) gedeponeerd worden in de kustgebieden (en waarschijnlijk ook verder landinwaarts) in hoeveelheden die veel groter zijn dan de normale jaarlijkse droge en natte depositie. De verliezen van voedingsstoffen in drainage van de onderzoekslokaties waren relatief laag, met uitzondering van die elementen, die vrijkomen bij verwering van het gesteente (Na, Mg, Ca, Si en SO_4). Vergelijking van de atmosferische nutriënteninvoer met de verliezen in drainage suggereerde, dat N, P, K en Mn accumuleerden in de bossen, terwijl neutrale budgetten of kleine verliezen werden geconstateerd voor Ca en Mg. Verhoogde ionenconcentraties werden waargenomen in het bodemvocht in de plantages na de depositie van oceanische elementen en grote hoeveelheden vers strooisel door cycloon Sina en dit, in combinatie met verhoogde drainagesnelheden door verminderde neerslaginterceptie en transpiratie, resulteerde in belangrijk grotere verliezen van nutriënten met percolerend bodemwater in de periode na de cycloon.

De atmosferische nutriëntendepositie was niet voldoende om de opname van voedingsstoffen door de snelgroeiende bossen, de immobilisatie van deze stoffen in de strooisellaag, en de verliezen in percolerend water te compenseren. Dit leidde ertoe, dat de bodem een groot gedeelte van de benodigde voedingstoffen voor de produktie van biomassa moest leveren, zowel vanuit de bodemreserves als door verwering van bodem- en gesteentemineralen. Zoals reeds vermeld was de opname van voedingsstoffen het hoogst tijdens de ontwikkeling van het kronendak ongeveer zes jaar na het planten en werden er in deze periode aanzienlijke hoeveelheden nutriënten aan de bodem onttrokken. Na het sluiten van het bladerdak, echter, kwamen nutriënten (vooral kalium) vrij uit de ondergroei, en de onttrekking vanuit de bodem was daardoor laag in de periode van zes tot elf jaar na planten. De vraag naar nutriënten vanuit de bodem steeg weer wat in ouder plantagebos, maar bleef laag ondanks een relatief hoge produktie omdat een groot deel van de voedingsstoffen opgenomen werd voor de produktie van nutriënten-arm hout. Berekende efficiëntie-indexcijfers voor het gebruik van voedingsstoffen (Vitousek, 1984) door de bossen toonden aan, dat de bossen zeer efficiënt met stikstof en fosfor omgingen, en minder efficiënt met calcium, magnesium en kalium. De efficiëntie-indexcijfers gingen sterk omlaag, nadat de bossen beschadigd waren door cycloon Sina, wat te wijten viel aan de geringe translokatie van voedingsstoffen voor het afstoten van de relatief jonge naalden.

Het voorgaande laat zien, dat de effekten van cycloonschade op de kringloop van voedingsstoffen groot zijn, en dat de hoeveelheden tijdens de cycloon gedeponeerde voedingsstoffen voldoende zijn om voor enkele jaren in de opname van het herstellende bos te voorzien via afbraak van het verse strooisel. Het feit, dat het aantal cyclonen in een rotatieperiode, en de eventuele schade die ze toe brengen aan de plantages, onvoorspelbaar zijn, bemoeilijkt het opstellen van een nutriëntenbudget over een rotatie voor de plantagebossen in Fiji.

De bodems in zuidwest Viti Levu zijn relatief dun, en het wortelstelsel van de dennen reikt over het algemeen tot in de zone waar actieve verwering plaatsvindt, zoals in spleten en scheuren in het verweerde moedergesteente. Dit wijst erop dat verwering een belangrijk aandeel kan leveren van de nutriënten, die nodig zijn voor de groei van de bossen, waarbij fosfor een mogelijke uitzondering vormt omdat dit element snel geïmmobiliseerd wordt in de bodem (Clayton, 1979).

Effekten van Kappen en Branden op de Nutriëntenhuishouding

Het bos in het Oleolega stroomgebied werd gekapt tussen december 1990 en juli 1991 als een soort reddingsoperatie, nadat het bos zwaar beschadigd was door cycloon Sina. Er werden in totaal ongeveer 55 ton ha^{-1} hout weggehaald uit het stroomgebied, en dit leidde tot de uitvoer van 45 kg ha^{-1} stikstof, 5 kg ha^{-1} fosfor, 29 kg ha^{-1} kalium, 23 kg ha^{-1} calcium, 11 kg ha^{-1} magnesium, 0.6 kg ha^{-1} zink, 3.1 kg ha^{-1} mangaan en 0.1 kg ha^{-1} boor. Al voor het kappen begon, was de massa van de strooisellaag flink gestegen van ongeveer 14 naar 29 ton ha^{-1} door de cycloonschade aan het bos, en de strooiselmassa steeg verder tijdens het kappen naar 37 ton ha^{-1}. De concentraties van voedingsstoffen in het rivierwater vanuit het beboste stroomgebied waren laag. Echter, na de depositie van oceanische elementen en vers strooisel door cycloon Sina gingen de EC, pH en de concentraties van de meeste elementen omhoog, met uitzondering van die van nitraat, ammonia, fosfaat en totaal fosfor die niet signifikant veranderden, en die van sulfaat en mangaan, die signifikant lager waren na de gebeurtenis. Tijdens het kappen in het natte seizoen van 1991 leken de ionenconcentraties in de basisafvoer langzaam terug te keren naar de niveaus van voor de cycloon, met uitzondering van die van nitraat, die leken te stijgen (hoewel niet signifikant). Veranderingen in de chemische samenstelling van de stormafvoer na de cycloon en het kappen van het bos waren niet dusdanig, dat dit grote gevolgen had voor de export van nutriënten in het rivierwater, ten opzichte van die vanuit het ongestoorde stroomgebied. Echter, hoewel de geëxporteerde hoeveelheden laag bleven in absolute zin, waren de geëxporteerde hoeveelheden van kalium, nitraat, totaal stikstof, fosfaat en totaal fosfor 1.5 (PO_4) tot 2.2 (K) keer zo hoog als de hoeveelheden geëxporteerd vanuit het ongestoorde stroomgebied.

Het verbranden van de strooisellaag in augustus 1991 reduceerde de strooiselmassa van 37 naar 6 ton ha^{-1} en de nutriënteninhoud met 245 (N), 10 (P), 72 (K), 95 (Ca), 37 (Mg), 0.8 (Zn), 19.1 (Mn) en 0.3 kg ha^{-1} (B). Een vergelijking tussen de beschikbare voedingsstoffen in de bodem voor het kappen en die aanwezig na het branden toonde aan dat de meeste voedingsstoffen die door decompositie en branden vrijgekomen waren, terecht waren gekomen in de bodemreserves. Na het branden veranderden de nutriëntconcentraties in de basisafvoer signifikant, maar niet voordat de bodem voldoende vochtig was geworden aan het begin van het natte seizoen in december 1991. Hierna werden signifikante stijgingen geobserveerd in de EC en de concentraties van Na, Mg, Ca, NH_4, Cl, HCO_3, NO_3, PO_4, Mn, totaal N en totaal P. De concentraties van kalium en sulfaat waren relatief hoog in de afvoer tijdens de eerste regenbui na het branden, maar niet in die van de daaropvolgende regenbuien. Dit wees erop, dat deze elementen snel uitspoelden vanuit de aslaag. De sulfaatconcentraties in de basisafvoer waren lager in de periode na het branden dan in de periode daarvoor, wat mogelijk te wijten is aan biologische activiteit in het rivierwater (algen). De geëxporteerde hoeveelheden Na, Ca, Mg, NH_4, SO_4, Si, Mn en Fe in rivierwater in de periode na het branden waren hoger dan die verkregen via een modelsimulatie voor de beboste situatie over dezelfde periode. De extra uitvoer was bijna geheel te wijten aan de verhoging van de waterafvoer na het kappen/branden. Echter, de geëxporteerde hoeveelheden totaal P, PO_4, NO_3, en K waren hoger dan verwacht zou mogen worden op basis van de verhoogde debieten. De verliezen aan voedingsstoffen in rivierwater na het kappen en branden bleven echter laag vergeleken bij de hoeveelheden, die vrijkwamen vanuit de strooisellaag na het branden. De grootste verliezen tijdens het kappen en branden waren daarom die in het geëxporteerde hout.

Duurzaamheid van de Plantage Bosbouw in Fiji

Nutriëntenbudgetten over een volledige rotatieperiode (januari 1975 – april 1992) werden opgesteld voor het Oleolega stroomgebied, waarbij rekening werd gehouden met verschillende intensiteiten van kap en met twee scenarios voor de nutriëntenbijdragen van verwering. De atmosferische nutriëntendepositie werd berekend door de neerslaggegevens verzameld in het Oleolega stroomgebied (hoeveelheden en concentraties) te combineren met dagelijkse neerslagtotalen verzameld op de luchthaven van Nadi (1975–1979) en bij het Nabou hoofdkwartier (1980–1989). De bijbehorende export van voedingsstoffen in rivierwater uit het stroomgebied over de rotatieperiode werd verkregen door de gemiddelde ionenconcentraties in rivierwater vanuit het beboste stroomgebied te kombineren met gesimuleerde dagelijkse debieten. Door de verschillen in de bodems van de verschillende bossen kon de bijdrage van verwering aan de nutriëntenopname van het bos niet worden bepaald. Daarom werden 'pessimistische' (geen bijdrage van verwering, nutriënt opname volledig uit bodemreserves) en 'optimistische' (geen opname uit bodemreserves, alle voedingsstoffen geleverd door verwering) budgetten opgesteld. Door de voor de groei benodigde hoeveelheden nutriënten te combineren met de beschikbare hoeveelheden voedingsstoffen in de bodem konden schattingen worden gemaakt voor het aantal mogelijke rotaties. Het pessimistische budget suggereerde, dat het onwaarschijnlijk was dat nutriëntentekorten voor zouden komen binnen de volgende vijf (Ca) tot 19 (K) rotaties, onder de voorwaarden dat alleen de stammen (inclusief bast) zouden worden weggehaald en dat erosie, en de daarmee geassocieerde nutriëntverliezen, tot een minimum beperkt zou worden. Het weghalen van de bomen in zijn geheel verminderde het mogelijke aantal rotaties naar 2–3 voordat er tekorten in stikstof en fosfor zouden ontstaan. Omdat de verwering, die in dit budget buiten beschouwing bleef, toch een belangrijk aandeel in de voedingsstoffenvoorziening kan vormen, en omdat de invoer van stikstof onderschat was, is het waarschijnlijk, dat de huidige bosbouw in zuidwest Viti Levu duurzaam is vanuit het oogpunt van de bodemvruchtbaarheid. Daarom moet beschadiging van de plantages door cyclonen beschouwd worden als de belangrijkste bedreiging voor de houtproduktie. Echter, om de huidige snelheid van houtproduktie vast te houden moet al het mogelijke gedaan worden om de fysische achteruitgang van de dunne bodems door verstoring tijdens kappen, en de daarmee geassocieerde erosie, te voorkomen.

Chapter 21

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