Water and Nitrogen Balance in Natural and Agricultural Systems in the Wet Tropics of North Queensland: a Review

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Executive summary

- Most current Australian agricultural production systems are modified versions (albeit innovative and experience-based) of Northern Hemisphere practices, and evidence is mounting that they are not sustainable.
- Many of the sustainability problems occur because our agricultural systems are out of balance with the natural environment, so that they leak water and/or nutrients (vertically and/or horizontally). This ‘leakage’ can cause degradation of soil and water resources through soil salinisation, acidification, erosion, development of nutrient bulges below the root zone, rising watertables, and decreasing river and groundwater quality. Loss of soil organic matter and soil structural decline are further evidence that current agricultural systems are not sustainable.
- A major difference between natural and agricultural systems is the agriculturist’s ability to manipulate fluxes of nutrients into and out of the system
- The Redesign of Australian Plant Productions Systems (RAPPS) research and development program is a new national effort initiated by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Land and Water Resources Research and Development Corporation (LWRRDC) to help address these sustainability issues. The main aim of the RAPPS program is to enhance understanding of how natural and man-managed ecosystems function, especially in terms of the temporal and spatial distribution of water and nutrients, as a prelude to redesigning or reinventing plant production systems that are better aligned with the uniquely Australian environment.
- The wet tropics of northern Australia is a special, unique and environmentally sensitive ecosystem which will require site-specific solutions in developing more-productive and ecologically sustainable agricultural practices. It is one of the focus areas for the RAPPS effort.
- The wet tropics is characterised by high temperatures and high humidities, large amounts of rainfall with high intensities, the occurrence of major cyclonic events, soils with unique, variable charge characteristics, soils and landscapes that have evolved to cope with (and shed) large amounts of water, and unique native vegetation types (including rainforests). Water input in both natural and agricultural systems tends to be highly event-driven in this environment.
- Agricultural systems in the wet tropics are dominated by sugarcane, which is grown as a monoculture, and there is an increasingly important horticultural industry. Both sugarcane and horticulture use large quantities of fertilisers (especially nitrogen, phosphorus and potassium) and other agrochemicals as inputs.
- Data on water and nitrogen balances and the ‘leakiness’ of wet tropical systems are virtually non-existent, in either the natural or agricultural ecosystems. Only one study has attempted to address the complete water and nitrogen balance in wet tropics systems, although not all components were measured. There are some other short-term data on various components of the water and/or nitrogen balance in agricultural systems, but they have generally not been measured simultaneously. Thus, there is no complete ‘picture’ of the water or nitrogen balance, and it is difficult to determine the importance of the different aspects of these balances in the context of productivity and sustainability. However, the following generalisations can be made:
  - deep drainage rates, in both natural and agricultural systems, are higher in the wet tropics than in other ecosystems in Australia;
  - agriculture appears to increase deep drainage and run-off, as happens in other parts of Australia;
  - there are no long-term measurements of evapotranspiration from either natural or agricultural systems in the wet tropics;
  - nutrient cycling in natural systems is reported to be very efficient, with few nutrients escaping the rootzone;
  - nutrient inputs and outputs in agricultural systems are event-driven, being dominated by fertiliser applications and crop harvests which occur at specific times through the year. The event-driven nature of fertiliser applications tends to reduce the efficiency of nutrient recycling within agricultural systems;
  - in agricultural systems, nitrogen is applied in excess of plant needs, suggesting that there is room for considerable improvement in nitrogen management; and

  - this excess nitrogen application and its event-driven nature, together with the large, deep drainage fluxes in permeable soils, suggest that nitrogen loss below the rootzone will be considerable.
- A major challenge in trying to align agricultural systems with the natural environment is for agriculturists to better match the supply of water and nutrients to the actual needs of plant production systems. This will require:
  - a better understanding of plant needs as a function of crop growth stage;
  - development of practices where the type (organic, inorganic, slow-release sources etc.), timing of application, and spatial placement (most appropriate vertical and/or horizontal placement) of nutrients is better matched to meet actual plant needs; and
  - experimentation with novel vegetation patterns involving variations in space and time, or plant sequences that run in series or parallel, and which may or may not include trees.
- There is a need to improve understanding and quantification of water and nutrient balances in the wet tropics if the above ideal of more sustainable agricultural systems is to be achieved. Future research and development efforts will therefore need to include studies on:
  - the major water and nutrient flow pathways in the various soils and landscapes;
  - nitrate leaching and the development and amelioration of soil acidity, particularly at depth;
  - water and nutrient storage and movement in variable charge soils;
  - the potential for development and likely behaviour of deep nutrient bulges;
  - evapotranspiration;
  - water and nutrient uptake patterns by crops as a function of time, depth and crop growth stage; and
  - development of management strategies that match nutrient supply to actual plant needs.
- While any research and development work aimed at addressing the above issues will need to be focused at specific sites in the wet tropics, it will also be essential to develop predictive capabilities so that the experimental work that is undertaken can be extrapolated in space and time. The RAPPS research and development program is one initiative that can help facilitate this.

Introduction

Most rural production systems currently practised in Australia are modified versions (albeit innovative and experience-based) of Northern Hemisphere practices. While they have served Australia well, their longer-term sustainability is increasingly under question. Reasons for this are the ever-increasing signs of depletion and degradation of our natural resources, as evidenced by loss of soil organic matter, soil structural decline, salinisation, acidification, erosion, occurrence of nutrient bulges below the root zone, rising watertables, and decreasing river and groundwater quality. Many of these problems occur because current plant production systems are out of balance with the natural environment and they therefore leak water and nutrients. If it is possible to redesign plant production systems that make full use of the available water and nutrients so that leakage from the system is minimised, then the opportunity exists to create systems that may be both more productive and more ecologically sustainable.

This opportunity was recognised in the early 1990s and resulted in the establishment of the Redesign of Australian Plant Production Systems (RAPPS) initiative, brokered jointly by CSIRO and LWRRDC. The main aims of this initiative are to enhance the understanding of key characteristics of Australian agricultural environments, particularly the temporal and spatial distribution of water and nutrients, as a prelude to redesigning plant production systems that match the natural characteristics dictated by the uniquely Australian environment (see LWRRDC Occasional Papers RAPPS 01/98 and RAPPS 02/98).

The wet tropics of northern Australia is an especially unique and environmentally sensitive ecosystem within Australia, and therefore one which requires particular focus within the overall RAPPS program. High rainfall amounts and intensities have the potential to produce large water fluxes from the surface as run-off, and from the root zone as deep drainage in both natural and man-managed systems. The wet tropics is also characterised by unique soils, particularly in terms of their pH and charge characteristics, and landscapes which have deep groundwater systems in some places and shallow, highly responsive groundwaters in others. These wet tropical conditions are also conducive to high chemical fluxes across and through soils, with the potential for significant on- and off-site impacts if not managed appropriately. The wet tropics is therefore an important region to study, and a valuable region in which to validate and test modelling tools that may be applied to the nation-wide assessment and design of new plant production systems. Site-specific solutions will be required to meet the area's unique environmental characteristics, and its closeness to the Great Barrier Reef demands that these issues receive urgent attention.

This report provides a review of water and nitrogen balance in natural (rainforest) and agricultural (sugarcane and horticulture) systems in the tropics, with a special focus on the North Queensland wet tropics (see Appendix 1 for Terms of Reference). Information on which the review is based was obtained from:

1. a formal literature review (see Appendix 2 for search details and databases searched);
2. a survey of some 100 researchers who were known to have worked in, or who have had some contact with, the wet tropics [details of the survey questionnaire and results are summarised by Bristow et al. (1998) in a report to LWRRDC which is available at a cost of $5 from the Australia Agriculture, Fisheries and Forestry shopfront on 1800 020 157 (free call)]; and
3. a workshop involving key staff from several different research and development (R&D) organisations.

The aim of this review document is to provide an overview of the current state of knowledge of the water and nitrogen balance in wet tropics systems and a summary of key issues requiring future R&D.

The wet tropics

Location and climate

The term ‘tropics’ includes the geographical locations contained within the Tropics of Capricorn and Cancer, and various classifications are used to characterise particular features of these tropical regions. These include categories such as ‘humid tropical regions’ (World Meteorological Organisation 1983), ‘rainy tropics’, ‘monsoon tropics’, ‘wet–dry tropics’, ‘semi-arid tropics’ and ‘arid tropics’ (Critchfield 1966; Longman and Jenik 1974). These various descriptions or categories arise because there are differences within the tropics, with soils and vegetation types reflecting particular regional features such as parent material, rainfall, temperature, relief, wind and sea currents (Longman and Jenik 1974; Isbell and Edwards 1988).

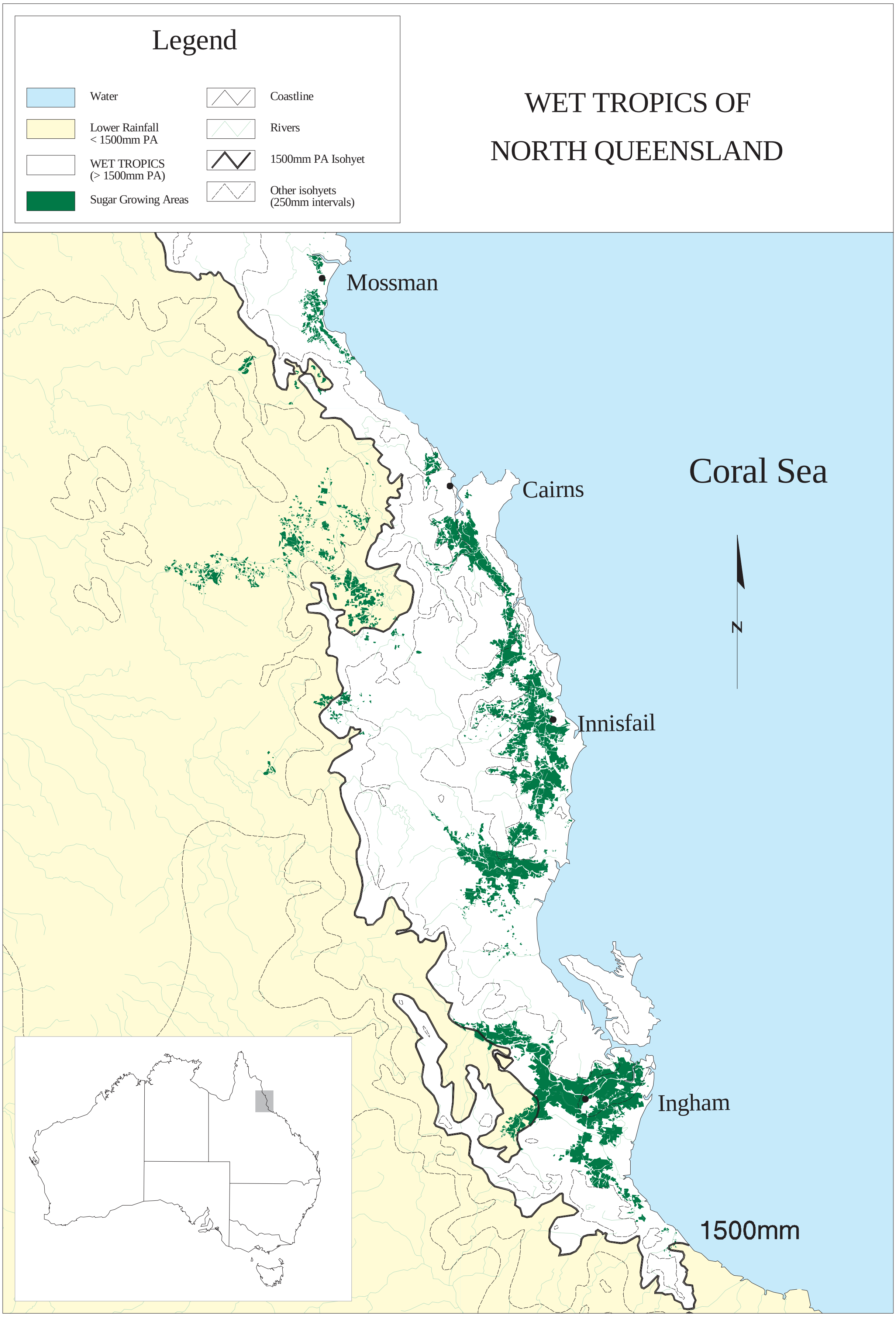
In this report we are mainly interested in a particular zone within the Australian tropics known as the ‘wet tropics’. This region lies largely within latitudes 15–19°South, and longitudes 145–146°30’East, and for convenience can be bounded by the 1,500 mm isohyet (Isbell and Edwards 1988; see Figure 1). This wet tropics region exhibits heavy periodic rain during summer leading to high humidity, with lower rainfall during winter months (Boughton 1994). Roughly 60% of the rain falls between December and March inclusive, and in some regions up to 90% can fall in the six-month period from November to April. Despite these high summer rainfalls, a feature of the region is the strong probability of receiving useful falls in any or all of the ‘dry season’ months. This seasonality in rainfall within the wet tropics (for example, see Table 1) is a key feature that distinguishes it from other humid tropical regions (Isbell and Edwards 1988).

Annual rainfall for the wet tropics is highest on the coastline at Tully (median annual rainfall of 4,400 mm), and decreases rapidly with distance from the coast (Tracey 1982; Boughton 1994). Much of the summer rain is associated with the monsoonal trough and cyclonic activity, and can result in extremely high 24-hour totals (Bonell 1993). This means that the hydrological pathways in the wet tropics may be quite different to those in other regions, and care is needed in trying to extrapolate hydrological findings from

Table 1 Rainfall data (mm) for Innisvale and Tully and showing differences between regions and differences in distribution through the year (QDPI 1995a,b).

Month	Rainfall (mm)					
	Innisfail (1881–1994)			Tully (1925–1993)		
	Max	Mean	Min	Max	Mean	Min
January	3,459	563	21	2,003	627	11
February	2,505	644	60	1,819	741	137
March	1,651	688	87	1,907	773	89
April	1,653	487	0	1,586	534	40
May	1,063	335	0	806	346	32
June	527	196	0	584	201	6
July	506	134	0	536	149	0
August	528	117	0	457	127	0
September	485	94	0	469	118	0
October	462	83	0	653	98	0
November	716	156	0	703	166	12
December	1,414	278	10	1,503	265	16
Annual	**7,730**	**3,769**	**1,775**	**7,898**	**4,160**	**2,339**

Figure 1 Map of North Queensland showing the wet tropics distribution (white area) as defined by the 1,500 mm isohyet.



one climatic zone to another. Another feature associated with tropical rainfall is that rain drop sizes tend to be bigger than in other regions (Calder et al. 1986), again cautioning against simple extrapolation of experience across regions.

In terms of temperature, a feature of the wet tropics is the relatively low minimum temperatures that can occur during the coldest months, with light frosts having been recorded on rare occasions on the coastal lowlands. This situation is in strong contrast to the more traditional humid tropical (equatorial) regions (Isbell and Edwards 1988).

Evaporative demand as given by pan data also varies through the year and is variable between regions within the wet tropics. Example data from two sites are given in Table 2. In most months of the year rainfall exceeds the evaporation, and it is only in the later part of the year from August–November that evaporation is likely to exceed rainfall.

Soils

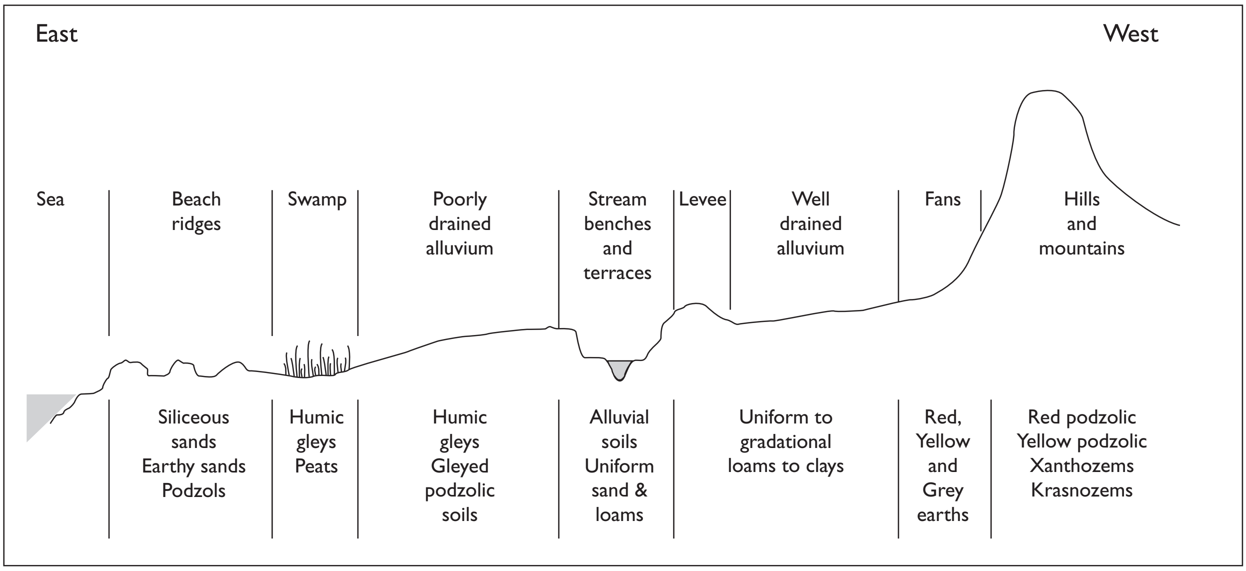
Soils within the wet tropics vary spatially and have properties that reflect their position in the landscape and the unique history and weathering cycle they have experienced (Isbell and Edwards 1988; Figure 2). The high rainfall combined with year-round high temperatures provides for high rates of leaching, weathering and humidification, and tropical soils tend therefore to be dominated by Oxisols, Ultisols and Alfisols (Lal 1986). These soils generally exhibit fairly stable micro-aggregation (although the degree of aggregation in Ultisols and Alfisols may be less stable than that in Oxisols), low cation exchange capacity (CEC), low available water holding capacity, low pH, and high (and sometimes toxic) levels of aluminium. Lal (1986) also indicates that the predominant form of clay is kaolinite, and that high levels of quartz are common. As the soil CEC is generally low, Lal (1986) argues that most of the nutrients held within tropical soils are bonded to the humus rather than the kaolinitic clays, which highlights the need to maintain organic matter levels in tropical soils. Soil organic matter levels as high as 4–6% have been measured in the Australian wet tropics under pasture and rainforest systems, and found to decrease rapidly to about 30–50% of these values when agricultural systems are introduced (Gillman and Abel 1987).

While soils of the Queensland wet tropics have been fairly well described and mapped (Table 3; Figure 3; Thompson and Beckman 1981; Hubble and Isbell 1983; Isbell and Edwards 1988; Murtha and Smith 1994), the most studied soils of the wet tropics are those occurring between Ingham and Mossman, and particularly between Tully and Innisfail. Murtha (1986) surveyed the latter area at 1:50,000 scale, and identified 43 soil series, characterising them in terms of morphology, and some chemical and physical properties. The soils from this region form distinctive patterns strongly related to position, site drainage and parent alluvium, as illustrated graphically in Figure 2 (Isbell and Edwards 1988).

Table 2 Evaporation data for South Johnstone and Koombooloomba showing differences between regions and differences in distribution through the year (QDPI 1995a,b).

Month	Evaporation (mm)					
	South Johnstone (1973–1988)			Koombooloomba (1973–1993)		
	Max	Mean	Min	Max	Mean	Min
January	246	174	82	145	125	88
February	180	136	84	132	95	66
March	178	149	109	143	107	89
April	141	120	76	88	71	51
May	15	106	84	75	59	45
June	121	103	79	68	50	38
July	120	106	93	61	48	40
August	142	123	86	82	67	52
September	171	149	115	118	97	67
October	213	176	146	146	124	96
November	224	188	144	158	136	109
December	229	197	137	168	135	96
Annual	**1,919**	**1,725**	**1,531**	**1,207**	**1,112**	**953**

Figure 2 Diagrammatic section of soils and landscapes in the Tully–Innisfail wet tropics area (taken from Isbell and Edwards 1988).



A sub-set of 18 soil series from the Tully–Innisfail region, which represents the principal soils from various parent materials, has also had its electrochemical properties characterised in detail (Gillman and Sumpter 1986; Gillman and Abel 1987; Gillman and Sinclair 1987). One important aspect of these activities was the description of how electrical charge, which greatly influences the movement of cations and anions in the profile, changes with soil pH, ionic strength, organic matter content, and clay mineralogical composition. On the basis of their electrochemistry, the soils fell into three distinct groups: high CEC (cation exchange capacity), low AEC (anion exchange capacity) (Group 1); low CEC, low AEC (Group 2); low CEC, high AEC (Group 3). The last-mentioned group was flagged as having the potential for nitrate retention at depth, and recently Prove et al. (1997) have shown the existence of a large nitrate accumulation deep in the profile of a Group 3 soil. It is not clear whether this nitrate represents a benefit that could be exploited agronomically, or a potential environmental threat.

Recent measurements on the poorly drained alluvial soil at the Sugar Yield Decline Joint Venture Rundown site near Tully have also shown that the

Table 3 Types and descriptions of soils found north of Rockhampton (taken from Thompson and Beckman 1981; Hubble and Isbell 1983).

Description	Parent rock	Classification (Northcote key)	Distribution
Red podzolic soils	Granitic rock	Gn 3.14	Common
Red or yellow pale loams: medium textured and red soils with uniform texture of silt loam to silt clay loam	Metamorphic rock	Um 4.41, Um 4.42, and Um 4.43	Common
Xanthozems and yellow podzolic soils	Acid to intermediate volcanic rock	Gn 3.71 and Gn 3.74	Common
Siliceous sands and yellow earths			Common on lower fans
Kraznozems	Basalts	Gn 3.11	Common on the Tablelands and wet coastal areas
Red earths	Acid rocks		Common on upper piedmont slopes and fans
Shallow stony soils and lithosols	Variety	Um 2.12 and Um 4.41	Infrequent
Gleyed podzolic soils, humic gleys and acid peats			Common on coastal plains
Brown earths	Andesite	Gn 3.24, 3.21	Common in Mackay–Proserpine area

AEC at depth (50–80 cm) is equivalent to, if not greater than, the CEC, suggesting the presence of variable charge characteristics in this soil as well. Just how widespread these features are and the implications for development of nutrient bulges at depth warrants further investigation because it is clear that soils with variable charge characteristics may behave differently to other soils with respect to the soil solution. It is thought that ions moving down through such soil profiles could be simultaneously adsorbed in the diffuse double layers of the opposite charge colloids, and that they could be immediately, and in some subsoils completely, depleted from the soil solution. While the full implications of this are still to be elucidated, it is clear that our water and chemical transport models cannot, at present, deal with these issues which, if not addressed, will place some doubt on the validity of modelling nutrient movement in these variable charge soils.

It is clear from the foregoing that improved understanding of the chemical/hydrological interactions in the soils of the wet tropics will be of critical importance in helping redesign innovative plant production systems to minimise leakage from agricultural systems.

Land use

Vegetation of the wet tropics has been described by Tracey (1982) and includes a diverse group of communities due largely to varying rainfall and soil hydrology (Cannon et al. 1992). Vegetation in the mountainous regions includes closed vine forest or rainforest in wetter parts, with open sclerophyll forests in the drier parts. Murtha (1986) noted that the diversity is in part a reflection of soil nutrient status but is largely a reflection of soil water status. Rainforest is confined almost entirely to well-drained soils. The non-rainforest communities may be very broadly grouped as follows (after Tracey 1982):

- tall open forests and woodlands—usually dominated by eucalypts;
- medium and low woodlands—dominated by eucalypts and acacias, *Casuarina* spp., *Melaleuca* spp. and *Tristania* spp.;
- seasonally inundated grasslands—*Ischaeumum* plains and *Cyprus* spp. swamps, in small areas only; and
- mangrove forests—which occur extensively along tidal inlets near mouths of rivers and sheltered bays.

Most of the broader alluvial plains have been cleared for agriculture. The major agricultural land use activities in the wet tropics include sugarcane, bananas, pastures for both dairying and beef production, and forestry (Table 4).

Figure 3 Map showing distribution of key soils within the wet tropics.

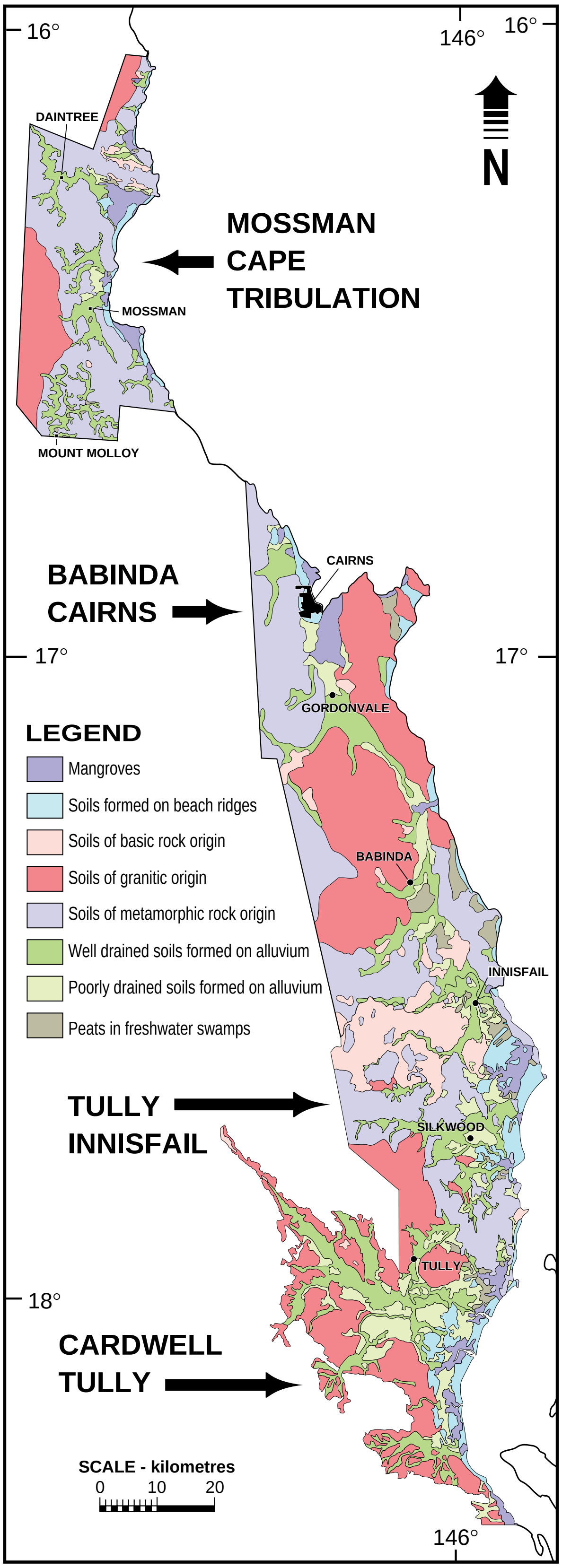


Table 4 Agriculture in the wet tropics of North-East Queensland (taken from QDPI 1995a).

Catchment	Land use	Land use size (ha)
Daintree catchment area	Agriculture and grazing	103,000
	Sugarcane	9,650 (99% of area cropped)
	Bananas and pawpaws	small areas
Cairns catchment area	Sugarcane	9,800 (90% of agricultural activities)
Barron catchment area	Agriculture: tobacco, pasture and fodder, rice and peanuts	17,800
Mulgrave River catchment	Sugarcane	16,000
Johnstone River catchment	Sugarcane	32,000
	Bananas	2,300

Fertiliser rates in these industries vary considerably from almost nothing in grass/legume pastures for low input beef production, to 160–180 kg nitrogen (N) ha^{-1} for sugarcane, to 400–500 kg N ha^{-1} for high input grass pastures for dairying (made up of 4–5 applications per year) and bananas (made up of 11–12 applications per year) (Prove et al. 1994).

Water and nitrogen balance—a general overview

Water balance

The water balance of both natural and agricultural systems defines the fluxes of water into and out of the system and the storage of water within the system. This is shown schematically in Figure 4. The water balance is an expression of the simple principle of conservation of mass, which states that water cannot be created or destroyed, but merely stored, transported from one site to another, or transformed from one state to another (such as liquid to gas). It is clear that it is the whole water balance that needs to be understood and managed, since focusing on and adjusting just one of the components will, by default, impact on at least one other component. Designing sustainable agricultural systems is therefore absolutely dependent on understanding how the whole water balance works and managing it in a way that is in harmony with the natural environment.

Water input into the system of interest to us here, namely the active root zone, is usually via precipitation (rainfall, irrigation, hail, fog, dew, cloud deposition, snow) and, in cases of upward movement of water, by capillary flow. Outputs include run-off, subsurface lateral flow, deep drainage, soil water evaporation and plant transpiration. Water storage within the system can take place in the plant canopy, surface litter and soil root zone. The water balance can therefore be expressed as:

$$P = R + E_s + E_v + T + L + D - C + \Delta S \qquad (1)$$

where

P = precipitation
R = run-off
I = infiltration = $P - E_v - R$
E_s = soil water evaporation
E_v = evaporation of water intercepted by vegetation
T = transpiration
L = subsurface lateral flow
D = deep drainage out of the system of interest
C = capillary flow up into the system of interest
ΔS = change in storage

Other simpler or more complex forms of the water balance can be derived from equation (1) depending on the particular application being addressed.

It is clear from the above that the soil water balance will be affected by several factors, including

- meteorological variables—rainfall amount, rainfall intensity, solar radiation, wind and atmospheric vapour;
- landscape features—topography, streams/rivers, soil type and subsurface geological features;
- plant physiological variables—vegetation type, quantity, structure, surface area, age, water stress and stomatal conductance; and
- soil properties—storage and transport properties.

While all terms of the water balance will operate within both natural and agricultural systems, the relative importance (magnitude) of individual components may differ because of basic differences between these systems, and this may change the net behaviour of the water balance for better or worse.

Changing from a rainforest to an agricultural system can cause a rapid loss of organic matter that can lead to degradation of soil surface features and soil structural decline, both of which usually lead to a decrease in infiltration and increased run-off.

Replacing rainforest with agricultural lands also impacts greatly on the surface albedo (the ratio between the reflected and incident radiant flux) which affects the amount of energy available for evapotranspiration. The albedo of typical rainforests is among the lowest of natural terrestrial systems, with measurements ranging from 0.10 to 0.14 (Pinker et al. 1980; Shuttleworth 1984; Turton and O'Sullivan 1995). Mean albedos of cultivated crops in the tropics are much higher, ranging from 0.17 to 0.25 (O'Brien 1996). The net result is that there is less energy available for heating and evapotranspiration from agricultural systems.

One major difference between natural (rainforest) systems and many man-managed agricultural systems is the ability to control inputs through irrigation, and yet it is often the use (or abuse) of irrigation that is pushing the water balance out of harmony with the natural environment and causing ongoing degradation of our agricultural systems (such as soil salinisation and acidification).

Rainforest canopies and root systems are, in general, characterised by diversity, while in agricultural systems they tend to be characterised by uniformity (see Figure 4). This implies that if not properly managed it is much easier for water to leak out of agricultural systems as run-off and/or deep drainage than it is from rainforest systems. Development of agricultural systems with more-distributed root systems that explore the root zone more fully may be one way of helping realign individual water balance components.

Interception of rainfall, canopy storage and loss to the atmosphere by rainforests can be large, but is seldom measured and accounted for in agricultural systems.

Spatial scales (plot, field, catchment, region) are of critical importance when addressing water balances which can be performed on a number of different time scales such as hourly or sub-hourly, daily, monthly, yearly or longer.

Other, more specific issues relating to the water balance of agricultural and rainforest systems are addressed in the sections below.

Nitrogen balance

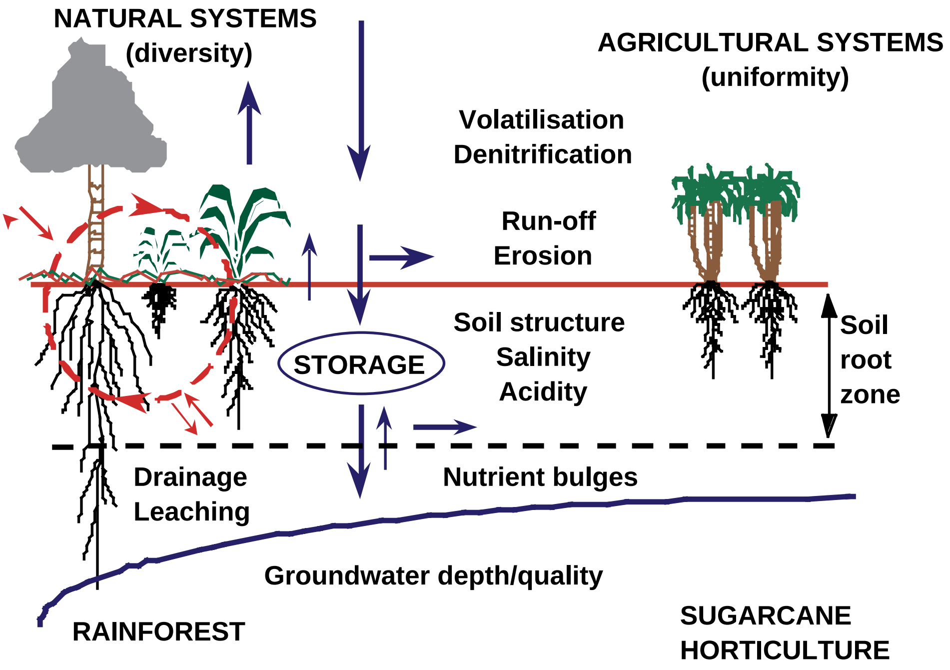
As with the water balance, the nitrogen (N) balance can be described in terms of inputs, outputs and changes in storage that occurs in various nitrogen pools. The N balance is shown schematically in Figure 5 and can be expressed mathematically as (see, for example, Moody et al. 1996):

$$N_f + N_{rain} + N_{fix} + N_{res} = N_{crop} + N_l + N_{ro} + N_v + N_{den} + \Delta N_i + \Delta N_m \quad (2)$$

where

N_f = fertiliser input
N_{rain} = rainfall input

Figure 4 Schematic diagram showing key components of the water balance, including major flow pathways (arrows) and key issues that need addressing in both natural and agricultural systems.



N_{fix} = nitrogen fixation
N_{res} = surface residue (mulch) input
N_{crop} = crop uptake
N_l = inorganic N leached
N_{ro} = N lost in run-off (total dissolved N + total particulate N + mineralisable N in bedload)
N_v = N volatilised
N_{den} = N denitrified
ΔN_i = change in profile inorganic N
ΔN_m = change in profile easily mineralisable N

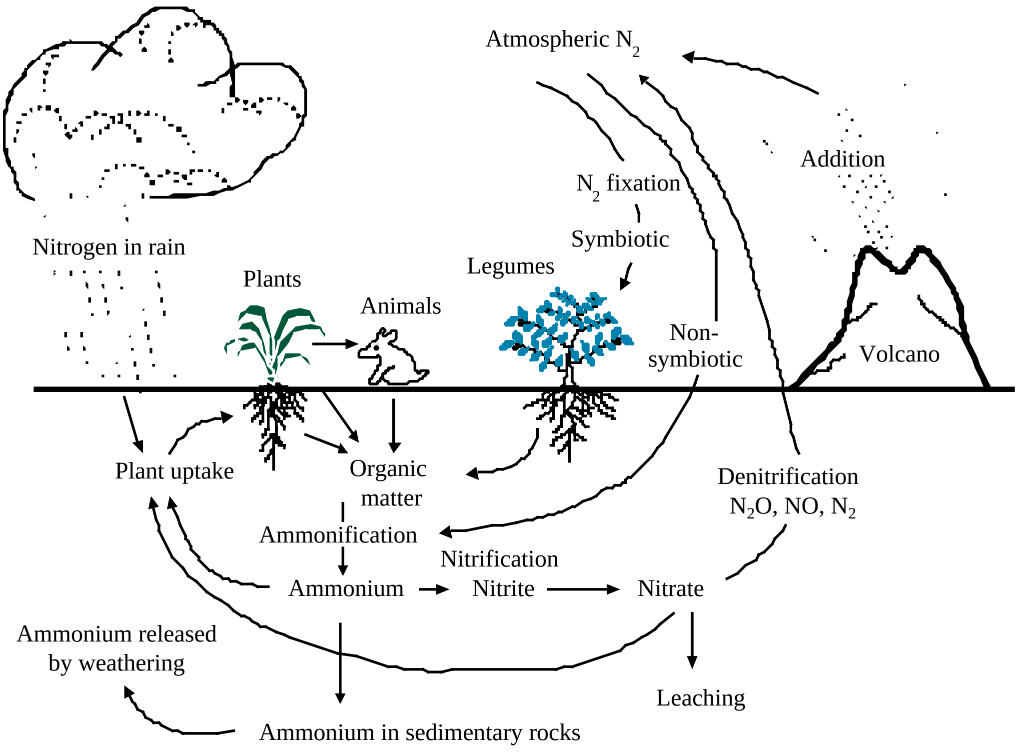
The main inputs for natural systems include biological fixation and rainfall. Amounts provided by rainfall are a function of the distance of the site from oceanic, industrial and agricultural areas (Attiwill and Adams 1993). Fertiliser input is the major input in agricultural systems. Outputs for both natural and agricultural systems include leaching, denitrification, volatilisation, and loss of nitrogen in run-off. Removal of biomass is usually the major output of nitrogen in agricultural systems. Components seldom quantified or considered in nitrogen-balance studies include nitrogen released into the soil via weathering of parent rock, losses via run-off and erosion, and gaseous losses.

In the humid tropics, the intensity of the N cycle is driven by constant high temperatures and rainfall which enable year-round biomass production together with high rates of decomposition, and hence nutrient release (Jordan 1985). The high rate of nutrient release increases the potential for leaching through tropical soils.

It has been shown that volatilisation occurs at high rates when the pH of the soil is high, and during fires. Since most humid tropical soils tend to be acidic, Attiwill and Leeper (1987) have suggested that volatilisation may not be of much importance in the humid tropics. This may be the case in natural systems, but significant losses of N through volatilisation have been documented in the wet tropics, particularly following surface application of urea in agricultural systems (Denmead et al. 1990). Also, Gigou et al. (1985) have shown that additions of large amounts of ammonium can lead to measurable volatilisation in tropical areas, despite the acidic soil conditions.

Ammonification is the process whereby organic N is converted to ammonium in the presence of heterotrophic bacteria (Attiwill and Leeper 1987). Although some of the ammonium released by the bacteria is immobilised through absorption by the bacteria for cell function, the major pathways for the positively charged ammonium ion include absorption by plants, attachment to the negative ions contained within the clay–humus complex, volatilisation, nitrification and leaching through the soil profile (Jordan 1985).

Figure 5 Schematic diagram showing key components of the nitrogen balance (after Jordan 1985).



The rate of ammonification is dependent upon the nature of organic matter present (C (carbon)/N (nitrogen)) and the rate of decomposition. When C/N ratios are high, large quantities of nitrogen are immobilised for microbial cell functions, and only small amounts of the N released by decomposition are available for plant uptake (Attiwill and Leeper 1987).

Nitrification is also a microbially controlled process in which ammonium is converted to nitrite and then to the essential nutrient, nitrate. Nitrification rates are generally high where there is a high amount of nitrogen within soil reserves, the cycling of nitrogen is rapid, and low C/N ratios exist (Attiwill and Adams 1993; Riley and Vitousek 1995). The major pathways for nitrate, which is positively charged and highly mobile, include absorption by plants, attachment to anion exchange sites within the soil, leaching and denitrification (Jordan 1985). Nitrification is limited by rates of decomposition, extreme temperatures, anaerobic conditions and low pH values (Attiwill and Leeper 1987). The limiting factor of low pH values has been disputed, with some studies showing considerable nitrification in soils with pH values lower than five, particularly when large amounts of N are added to the soil (Attiwill and Adams 1993). Indeed, nitrification rates appear to be greatest in tropical regions where soils are most likely acidic (Attiwill and Adams 1993).

Denitrification refers to the conversion of nitrate to gaseous N (nitrous oxide [N_2O], nitric oxide [NO], or nitrogen [N_2]) by denitrifying anaerobic bacteria (Jordan 1985; Magdoff et al. 1997). It is generally associated with saturated (waterlogged) conditions (Grimme and Juo 1985). This suggests that denitrification could be a major loss pathway in those wet tropic regions that experience frequent waterlogging.

Storage of N in the system occurs in various N pools, which are usually grouped to reflect plant N, soil N and N within leaf litter. The leaf litter pools are particularly relevant in forest systems. N cycling can occur within plant pools where N is moved from senescing leaves to sites of new activity (Attiwill and Leeper 1987). Plant N is taken up from the soil as either ammonium or nitrate. Where ammonium uptake is predominant, the soil solution becomes acidic, as hydrogen ions (H^+) are exchanged for ammonium ions (NH_4^+). Where nitrate uptake is dominant, the soil solution may become slightly alkaline (Attiwill and Leeper 1987). Attiwill and Leeper (1987) report the total N available in surface soils (0–20 cm) is in the range 0.8–10 tonnes ha^{-1}. In mature forests, most of this N is inaccessible to plants, with ionic forms rarely reported above 5% of the total N in surface soils (Attiwill and Leeper 1987).

As with the water balance, most components of the N balance operate in both natural and agricultural systems. Here again the relative importance (magnitude) of individual components may differ because of basic differences between natural and agricultural systems. Because this may change the net behaviour of the nitrogen balance for better or worse, it is crucial that the whole nitrogen balance be addressed and managed, not just one component in isolation from the others.

Other more specific issues relating to the nitrogen balance of agricultural and rainforest systems are addressed in the sections to follow.

Rainforests

In this section, the water and N balances of wet, tropical rainforests are examined. The approach taken is to present data on the different components of the N and water cycles. Wherever possible, an overview of knowledge of rainforests in general has been given, followed by information for those forests in Australia. Likely differences between rainforests in Australia and other parts of the world are highlighted. Finally, the likely changes that will occur to the N and water balances following deforestation are discussed.

Water balance

Complete water balance studies in rainforests have been rare, worldwide, with most studies focusing on a single aspect of the water cycle. Much of the research in tropical rainforests outside Australia has centred on estimating evapotranspiration (see Hutley 1995) while the greatest amount of research in Australian rainforests has been conducted on run-off generation processes (Bonell 1993; Elsenbeer et al. 1994). In this section, each of the terms in the water balance (Figure 6) will be examined to provide a summary of general information available and information specific to Australian wet, tropical rainforests.

Precipitation

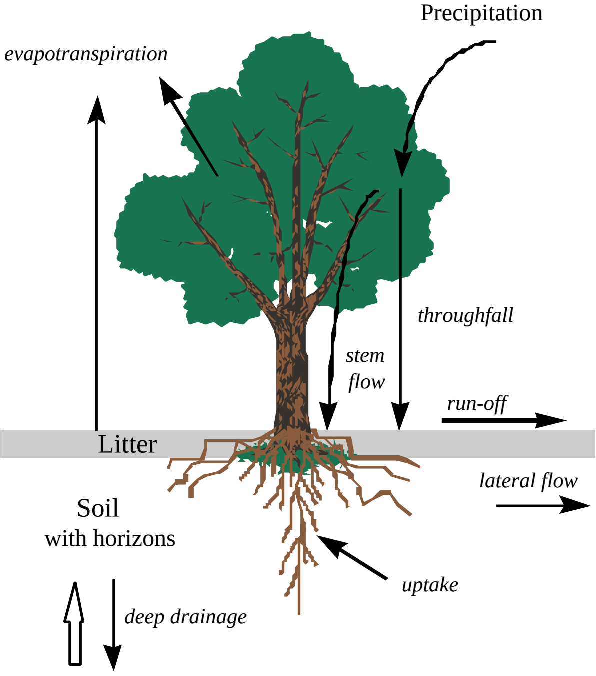
Rainfall, dew and fog

Rainforests occur in locations displaying a wide range in rainfall. In Australia alone they occur from the 800 mm isohyet (Webb and Tracey 1994) to locations with rainfall in excess of 4,000 mm yr^{-1} (Bonell and Gilmour 1978). In tropical areas, rainfall intensities can be high, which increases the likelihood of run-off (as discussed below).

A feature of precipitation in montane rainforests is that dew and cloud inputs can be significant. Apart from the contribution of dew to precipitation in rainforests, it has been suggested that fog and dew inputs may be essential for rainforest survival. Water is readily absorbed directly by leaves (Yates and Hutley 1995) and this may protect rainforest vegetation from water stress in otherwise climatically marginal sites (Hutley et al. 1997). The presence of dew on leaf surfaces can also reduce transpiration rates during the first few hours of the day (Longman and Jenik 1974).

Longman and Jenik (1974) estimate that between 0.1 and 0.3 mm of water can be contributed by dew following cloudless nights. In Australia, fog occurs at altitudes above 800–900 m for sites within the Great Dividing Range (Hutley et al. 1997). Yates and Hutley (1995) recorded large throughfall excesses that were attributed to fog and cloud deposition at a subtropical rainforest site at Gambubal, Queensland. In a subsequent study at the same site, Hutley et al. (1997) found that, of a total of 154 throughfall measurements, only 13 contained little or no fog deposition and that fog deposition was approximately 30% of total precipitation.

Figure 6 Schematic representation of the water balance of a rainforest. The processes considered are represented by the solid arrows.



Interception and canopy storage

Interception rates can be described as a function of the following: topography, rainfall characteristics such as intensity and duration, wind speed, canopy storage capacity and antecedent moisture, evaporation rate, foliage retention characteristics and bark storage capacity (Pook et al. 1991; Jetten 1996). Interception loss has been shown to be a significant component of the water balance equation within forests, with long-term values in the order of 11% (Leopoldo et al. 1995) to 21% (Calder et al. 1986) of annual rainfall.

On an individual rainfall event basis, canopy storage capacities of tropical rainforests can be as high as 1 mm (Table 5). Lower storage capacities are recorded for high rainfall intensity events where the kinetic energy of the raindrops is higher, as is the air turbulence (Jetten 1996).

Table 5 Canopy saturation storage capacities of various tropical rainforests (after Jetten 1996).

Study	Storage (mm)	Comments/location
Bruijnzeel and Van Wiersum (1987)	0.5–0.6	Java, Indonesia
Fritsch (1990)	1.05	ECEREX, French Guyana
Herwitz (1985)	0.03–0.49	turbulent air, Queensland
	0.26–0.99	still air, Queensland
Jackson (1975)	0.89	Tanzania
Lloyd et al. (1988)	0.74	Manaus, Brazil
Waterloo (1994)	0.8–1.4	pre-cyclone, Fiji
	0.3–0.6	post-cyclone, Fiji
Jetten (1996)	0.89	Mabura, Guyana

Throughfall

Throughfall within forests exhibits high spatial variability and it is common for measured throughfall to be greater than the gross rainfall in tropical rainforests. For example, Jetten (1996) reported 24–25% of throughfall measurements greater than gross rainfall for Guyanan rainforests. This spatial variability complicates the measurement of rainfall in rainforests. Brasell and Sinclair (1983) appear to be alone in their measurements of throughfall in Australian tropical rainforests with mean throughfall being 76–86% of rainfall over an 18-month period. Similar values were reported by Hutley (1995) in a subtropical forest in South-East Queensland.

Stemflow

Stemflow is a function of both rainfall intensity, and drainage characteristics of the canopy (Jetten 1996). In rainforests, stemflow can account for 1–2% of rainfall fluxes (Price 1982; Hutley 1995; Jetten 1996). In an Australian tropical rainforest, Herwitz (1986) recorded stemflows of 314 L m^{-2} of tree basal area per minute for a rainfall intensity of 2 mm min^{-1}. This local flux of water caused run-off to occur in an area over several metres from the base of the trees even though the soils infiltration capacity (~ 6 mm min^{-1}) was well above the rainfall rate. These results illustrate the impact of stem flow on rainforest hydrology.

Run-off and streamflow

In undisturbed forests, the surface soil often contains many macropores due to the presence of tree roots and burrowing animals. As a result, the transmissivity of the surface layers to water is often high relative to rainfall rates. Thus it is commonly considered that run-off is not a significant process in rainforest areas (Bonell 1993; Hutley 1995), being less than 5–10% of rainfall (Table 6).

The situation may be quite different for monsoonal areas where rainfall intensities may be ten times those recorded for temperate areas and exhibit temporal patterns distinct from equatorial regions (Bonell 1993). In addition, it has been suggested that the permeability of subsoils in some Australian rainforests (Bonell et al. 1982, 1983) is lower than those of many equatorial rainforests, and this impacts on run-off generation processes (Bonell 1993). Bonell et al. (1982, 1983) found that in tropical rainforests in North Queensland rainfall intensities (on a six-minute basis) of monsoonal and post-monsoonal rains were greater than the subsoil hydraulic conductivities. Thus, the soils had moisture contents at, or near, saturation during several months of the wet season and run-off was generated by the infiltration-excess process (Bonell et al. 1983, Bonell 1993). This run-off generation process has been found in rainforests in Africa (Dubreuil 1985) and Amazonia (Elsenbeer and Cassel 1990). At the latter site, rainfall intensities were lower than those in the North Queensland studies, but the hydraulic conductivity of the subsoil was also markedly lower (Bonell 1993).

The role that soil hydraulic properties play in the generation of run-off in Australian tropical rainforests can also be assessed from the chemical composition of stream water. Elsenbeer et al. (1994) found that overland flow in South Creek catchment in North Queensland was dominant enough in the hydrological cycle to have an effect on the streamflow chemistry. The contribution of ‘new’ water (that entering the catchment during a particular storm event) to streamflow was greater than the amount of ‘old’ water (that which existed in the soil storage before the rainfall event). Bonell (1993) suggested there is a difference between monsoonal regions and temperate regions with respect to run-off, in that the monsoonal hydrographs appear to be dominated by new water, whereas temperate hydrographs contain higher proportions of old water. This may have significant implications for streamflow sampling, particularly if calculations of nutrient losses are based on samples taken during events where overland flow has occurred.

Evapotranspiration

In equatorial rainforests, actual evapotranspiration is often greater than 90% of potential evaporation (Calder et al. 1986; Frank and Inouye 1994, Table 4.2). It would be surprising if the same conditions applied in monsoonal regions, such as North-East Queensland, where the dry season is rather pronounced. However, two studies in Queensland, one in the tropics (Gilmour 1975) and one in the subtropics (Hutley 1995), measured evapotranspiration rates close to 90% of potential. Overall, evapotranspiration rates are between 50 and 80% of rainfall (Table 6).

Deep drainage

Given that run-off and evapotranspiration combined are likely to total only 50 to 90% of rainfall (Table 6), deep drainage fluxes from wet, tropical rainforests could be considerable. Prove et al. (1997) found deep drainage from 0.6 m deep suction lysimeters to be approximately 40% of rainfall (up to 1,000 mm yr^{-1}) at a site in North Queensland. These amounts of deep drainage seem plausible even where subsoil hydraulic conductivities are low. For example, in the South Creek catchment in North Queensland, subsoil hydraulic conductivities were 3–4 mm h^{-1}, but the soils remained saturated for several months of the year (Bonell et al. 1983; Bonell 1991, 1993). Deep drainage fluxes of over 1,000 mm $year^{-1}$ would therefore be attainable.

Nitrogen balance

There have been many studies of nutrient cycling and N balances, including reviews by Vitousek and Sanford (1986) and Bruijnzeel (1991). There have also been studies on the impacts of forest disturbance on nutrient balance (eg. reviews by Lal 1986 and Bruijnzeel 1998) which provide relevant information. The general conclusion is that nutrient cycling in rainforests is very efficient, with input and output fluxes small in comparison to the nutrient storage within the forest (Bruijnzeel 1991). This efficiency has, in part, come about from the evolution of specific features that enable rainforest species to maximise nutrient uptake before the removal of nutrients from the ecosystem by processes such as leaching. These features include (Jordan 1985): the plant’s root distribution being concentrated at the soil surface, close to where nutrients are released from decomposing litter; high root-to-shoot ratios; aerial roots; and the efficient reabsorption of nutrients before leaf abscission. Some of these adaptive traits are influenced by soil fertility. For example, root/above ground biomass ratios are higher in less-fertile soils (Tables 7 and 8). Despite this wealth of knowledge, very little is known about nutrient cycling in Australian rainforests, either in the wet tropics or elsewhere (Congdon and Lamb 1990).

In this section, each of the terms in the N balance (Figure 7) will be examined to provide a summary of general information available and information specific to Australian wet, tropical rainforests.

Nitrogen inputs

Precipitation

Nitrogen (as nitrate [NO_3] and ammonium [NH_4]) inputs into rainforest systems from precipitation range from approximately 2 to 21 kg ha^{-1} yr^{-1} (Vitousek and Sanford 1986; Tables 7 and 8). The only published data for northern Australia are from Townsville, where inputs were 2 kg ha^{-1} yr^{-1} (Probert 1976). No data are available for rainforests or humid areas. There are difficulties in measuring these inputs due to spatial variability of rainfall across forests, and the collector vessels commonly used are not as efficient at trapping aerosols as forest canopies (Bruijnzeel 1991).

Table 6 Terms in the water balance of wet tropical rainforests (R = run-off, D = deep drainage, ET = evapotranspiration).

Study	Year	Rainfall (mm)	Water balance term as proportion of rainfall (%)			ET/potential ET (%)
			R	D	ET	
Prove et al. (1997)	1993	1,574	0	39		
	1994	2,898	7	39		
	1995	2,751	5	41		
Singh and Misra (1980)		1,264	13		75	54
Leopoldo et al. (1995)	1981	2,312	3		66	110
	1982	2,365	4		62	97
	1983	1,949	2		77	96

Table 7 Pool sizes and fluxes of the nitrogen cycle surveyed for rainforests around the world. The range in values represents site-to-site variation, but the individual sites do not necessarily correspond between the different processes.

Process	Level of soil fertility			Montane
	moderate	low	very low	
after Vitousek and Sanford (1986)				
Above ground biomass (kg ha^{-1})	1,980–1,685	2430–741	618–32	876–367
Total root system (kg ha^{-1})	1,896	2,834–1,570	1,170–222	1,114–508
Fine (< 6 mm) roots (kg ha^{-1})	68	146	364–170	157–21
Litter (kg ha^{-1})	224–110	170–61	55–42	90–28
Throughfall (kg ha^{-1} yr^{-1})	13	60–4	8	30–8
Hydrologic losses (kg ha^{-1} yr^{-1})	19	0.2	not given	5
after Sylvester-Bradley et al. (1980)				
Fixation (kg ha^{-1} yr^{-1})	245	20	2	not given
after Bruijnzeel (1991)				
Atmospheric inputs (kg ha^{-1} yr^{-1})	15–1	30–2	21	14–1
Hydrologic losses (kg ha^{-1} yr^{-1})	38–7	30–0.2	10	29–2
Difference (kg ha^{-1} yr^{-1})	+5 to –23	+24 to –8	+11	+8 to –15

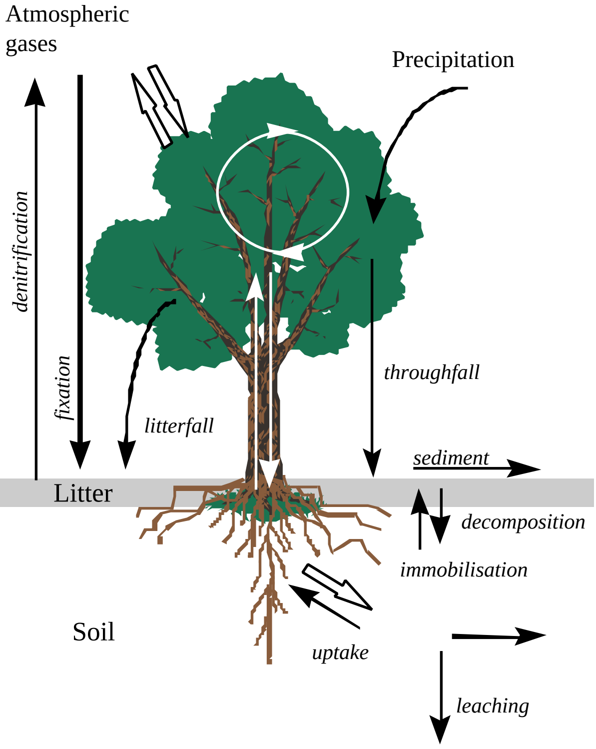
Table 8 Pool sizes and fluxes of the nitrogen cycle of two sites in the Amazonian rainforest.

	Level of soil fertility:	
	low (Jordan et al. 1982)	very low (Herrera and Jordan 1981)
Pools (kg ha^{-1})		
Above ground biomass	1,084	336
Roots	586	843
Litter	406	132
Soil	3,507	785
Total	5,583	2,096
Flux densities (kg ha^{-1} yr^{-1})		
Precipitation	12	21
Fixation	16	35
Leaching	14	9
Denitrification	3	not given
Leaffall	61.3	24
Throughfall	25.3	9

Fixation

An equally or more important input of N into forest systems is via biological fixation. This is particularly so for more mature forests, with mycorrhizal associations supplying most of the N required by the forest in the form of ammonia (Attiwill and Leeper 1987). Rates can be up to 200 kg ha^{-1} yr^{-1}, depending on the level of soil fertility (Tables 7 and 8). N may also be fixed by epiphytes in rainforests (Stewart et al. 1995), but the contribution of N from this source is likely to be less than 200 kg ha^{-1} yr^{-1} (Goosem and Lamb 1986).

Figure 7 Schematic representation of the nitrogen balance of a rainforest. The processes considered are represented by the solid arrows.



Nitrogen outputs

Denitrification

That rainforests are wet places suggests that denitrification may be an important pathway for nitrogen losses. This may be particularly so where watertables are shallow (eg. in riparian zones) or where perched watertables are common. Bowden et al. (1992) in a study of two watersheds in Luquillo experimental forest, Puerto Rico, found nitrous oxide (N_2O) production associated with anaerobic conditions and availability of nitrate, suggesting that denitrification was responsible. They suggest that high concentrations of N_2O in groundwater may be indicative of surface fluxes of N_2O. Owing to potentially high levels of denitrification taking place in riparian zones, Bowden et al. (1992) suggest that these zones may contribute a disproportionate amount of gaseous loss from a watershed and have important implications for N balances for watershed areas. This may be of particular importance where N concentrations in streamflow are used to estimate leaching losses from the catchment.

Hydrological outputs

While the humid tropics create ideal conditions for leaching, mature forests are highly efficient at conserving N, and very little is lost by leaching (Jordan 1985). N losses associated with run-off are rarely quantified. In general, rates of hydrologic losses of N from rainforests are similar to net input rates (Table 7).

In an Australian tropical rainforest, Walton and Hunter (1997) found < 10 kg ha^{-1} of N was lost from rainforested sub-catchments in the Johnston River catchment. In a more detailed study, Prove et al. (1997) found < 2 kg ha^{-1} yr^{-1} of N was lost in run-off from plots, but up to 13 kg ha^{-1} yr^{-1} of N was lost (below 60 cm depth) in deep drainage from suction lysimeters. These values are comparable with those from other countries (Tables 7 and 8).

Cycling between nitrogen pools

Storage in plant biomass and litter

Of all research pertaining to N balances in tropical rainforests, values of N contained within the soil, plant and litter are the most reported. The vegetation, including roots, has the highest nutrient capitals within tropical rainforest systems (Tables 7 and 8).

N stored in leaf litter is less than that stored within the vegetation. However, N in litter can be substantial when compared with above ground biomass. Between-study comparison of litterfall measures may be of little value, because of disparities between collection methods and definitions. What comprises litter can be quite different between studies, with some researchers including twigs, flowers, fruit, stems, branches, or a selection of these in their definition.

At two rainforest sites on the Atherton Tablelands in North Queensland, the flux of N falling in litter was 120–130 kg ha^{-1} yr^{-1} (Brasell and Sinclair 1983) with 120–140 kg ha^{-1} of N stored in the litter (Brasell et al. 1980). These litterfall rates are higher than those recorded in Amazonian rainforests (Table 8), although the storage is similar to that found in rainforests on soil of low fertility (Table 7).

N in leaf litter is often measured for assessing a forest's efficiency with respect to mineral cycling. Vitousek (1984) suggested that the ratio of litter dry mass to litter nutrient content is useful in determining the nutrient cycling efficiency of a stand in terms of biomass production per unit of nutrient acquired. This efficiency is different to that of the stand to absorb nutrients released from decomposing litter, although the two may be correlated. Vitousek (1984) found that forests exhibiting high N efficiency (high litter dry mass:N ratios) were associated with systems exhibiting low N fluxes in litterfall, and low efficiencies corresponded to high N fluxes in litterfall. The low efficiencies were particularly evident in lowland tropical forests.

Soil nitrogen and its availability

While total N levels in rainforest soils are high relative to other N pools, even in soils of low fertility (Table 8), there is little information on the availability of soil N. Given the high C/N ratios of rainforest litter (Attiwill and Leeper 1987) and substantial amounts of litter on the forest floor (10–20 t ha^{-1}; Brasell et al. 1980; Vitousek and Sanford 1986), it is likely that much of the available nitrogen will be immobilised as the litter breaks down. However, there is some evidence that soil mineralisation and nitrification rates in rainforests are higher than in pastures (Neill et al. 1995).

There have been many studies of N mineralisation rates in rainforest soils. These studies indicate that both mineralisation and nitrification rates generally increase as forests mature (Riley and Vitousek 1995). Research by Lamb (1980) of a succession of Australian subtropical rainforests found soil nitrate exhibited gradual increases during successional stages. This indicates that nitrate is not lacking in mature forests, and that ammonia becomes more accessible to microbes as forests age (Lamb 1980).

Rates of N mineralisation have been reported as being dependent upon altitude as well as latitude (Vitousek and Matson 1988). Montane forests are reported as having lower N transformation rates than lowland tropical forests, and lowland tropical forests exhibit higher net mineralisation and nitrification rates than temperate forests (Riley and Vitousek 1995; Vitousek and Matson 1988). The study of Vitousek and Matson (1988) revealed that not all tropical soils have rapid rates of mineralisation, particularly at upper montane sites.

Low soil nitrification rates are most likely to be associated with low soil fertility and availability of ammonia (Lamb 1980; Vitousek and Matson 1988). Vitousek and Matson (1988) recorded associations of low N mineralisation with low annual N circulation, based on measurements at 15 sites throughout Costa Rica, Panama, Brazil and Hawaii. These authors suggest that in N-limited sites (ie. where decomposition rates are low and C and N accumulate in the soil and litter), the adaptive features of the vegetation which have evolved to conserve nutrients actually help to perpetuate reduced nitrogen availability to plants. They describe a feedback cycle which occurs due to the system becoming more conservative in response to low levels of N, which in turn decreases N levels found in the litter and increases the immobilisation of N.

Studies of the soil N pool indicate that N accumulates over time, or as the forest ages. Most parent materials contain little N and, consequently, initial stages of soil development exhibit low soil N concentrations (Kawahara and Tsutsumi 1972; Riley and Vitousek 1995). In a study of five montane forests exhibiting similar environmental conditions throughout Hawaii, Riley and Vitousek (1995) found that N concentrations of mineral soil per mass basis increased with age. They also found that foliar and litter N concentrations increased to an intermediate age, 185,000 yrs, and decreased thereafter (sites studied ranged in age from 200 to 4,500,000 years). The ratio of (foliar – litter)/foliar N concentrations was lowest at the intermediate sites. Seasonal patterns in soil net mineralisation and nitrification rates were not obvious in a study conducted by Neill et al. (1995) of Brazilian forest over a period of a year and a half. Given the uniform climatic conditions that occur in equatorial zones, this may not be the case for monsoonal regions.

Impacts of deforestation

Changes to soil properties and the water balance

The magnitude of changes to soil physical properties following deforestation depends largely on the method used to clear the land (Table 9), with changes to structure more noticeable than textural changes (Lal 1986). General consequences of deforestation include an increase in soil bulk density, and decreases in infiltration rate, saturated hydraulic conductivity and porosity. These changes can be attributed to a higher degree of soil compaction, particularly when machinery is used, and have considerable impact upon the soil water retention characteristics (Lal 1986).

The potential effects of these changes in soil physical properties on the hydrological cycle are (Lal 1986):

- a decrease in transmission and retention characteristics of the soil;
- a decrease in water uptake from subsoil below 50 cm depth;
- an increase in evaporation;
- an increase in surface run-off; and
- an increase in interflow component.

The net result of the above is that more water is lost from the catchment via streamflow. The removal of deep-rooted trees increases the baseflow, and it is often reported that streams previously seasonal become perennial (Lal 1986). Kellman (1969) found increases in surface run-off (from 1.08% to 11.64% of

Table 9 Effect of various land clearing methods on soil properties illustrated by before clearing and after clearing measurements in the top 10 cm of an Alfisol (reproduced from Lal and Cummings 1979, as cited in Lal 1986).

Land clearing method	Bulk density (g cm^{-3})		Saturated hydraulic conductivity (cm min^{-1})	
	Preclearing	Postclearing	Postclearing	Postclearing
Mechanical	0.91	1.25	16.1	1.3
Slash and burn	0.86	1.12	15.2	5.0
Slash	0.89	1.13	9.8	4.6
LSD* ($P < 0.05$)	0.29		9.3	

* = least significant difference

rainfall) and soil erosion (from 1.45 g day^{-1} to 119.31 g day^{-1}) after 12 years cultivation following forest clearing in the Philippines. Malmer (1993, cited in Bonell 1993) recorded a change in flow paths from subsurface stormflow to infiltration–excess overland flow for an area where timber extraction was carried out using mechanical equipment at Sabah. The saturated hydraulic conductivity on tractor tracks declined from 154 mm h^{-1} to 0.28 mm h^{-1} for clays, and from 48.7 mm h^{-1} to 1.26 mm h^{-1} for sands. Bonell (1993) draws the conclusion that the tropical areas most likely to exhibit drastic changes in hydrological components upon land-use changes are those where soils of high permeability become compacted at or near the surface. The water balance study at the South Creek catchment, where a shallow impeding layer exists, showed that, following clearing, the streamflow recorded only slightly higher discharges than previously (Gilmour 1975, cited in Bonell 1993). In this area, overland flow is the dominant hydrological process in natural forests.

Changes to the nitrogen cycle

The major changes that occur to the nitrogen cycle upon deforestation are that the N losses increase while N inputs decrease. Perhaps the biggest change is the removal of above-ground biomass and the cessation of litterfall. The consequence of this is that soil microbial populations decrease, the C to N ratio falls, and nitrification rates increase (Jordan 1985; Attiwill and Leeper 1987). Neill et al. (1995) state that the elevated levels of N fluxes (increased nitrate, net nitrification and net mineralisation) can occur for periods up to two to three years following slash-and-burn clearing. Surface litter layer removal impacts on the system by increasing run-off, evaporation and surface salt content, as well as increasing the temperatures and aeration in the surface. The result of all these changes is an increased concentration of nitrate in the soil. As water is no longer lost via evapotranspiration, more water drains through the profile, and leaching of N increases (Attiwill and Leeper 1987). Vitousek (1980) indicates that it is not uncommon for the soil N pool to decrease by over 1,000 kg ha^{-1} in the top 30 cm of soil during the first few years following deforestation or burning.

Attiwill and Leeper (1987) describe the progression of nutrient cycling following clearing. They state that in the initial years after clearing there is little evidence of any nutrient cycling taking place. As time progresses, the pattern of nutrient conservation becomes established in the forest regrowth. Vitousek (1980) reports that for plantation forests as compared with natural ecosystems, N contents are lower although they increase at a much faster rate over time.

Summary

Rainforests of the wet tropics have evolved to successfully grow in areas of high annual rainfall on soils of low to moderate fertility. Fog and dew are important sources of water at higher altitudes, and may have particular ecological significance in the reduction of plant water stress in some hydrologically marginal environments. Rainforest plants suffer seasonal water stress in the monsoonal tropics, but less so in the continually moist humid tropics of the equatorial regions. Evapotranspiration can be as low as 50% of rainfall annually, so the fluxes of other terms of the water balance can be high. Run-off is primarily controlled by the hydraulic conductivity of subsurface soil horizons. Where these horizons are of low conductivity, run-off can be significant, being derived from saturation overland flow and base flow from perched watertables. This situation appears to be common in Australian tropical rainforests. Despite the low hydraulic conductivity of subsurface soil horizons, deep drainage can still be substantial due to the length of time (months) the profile remains saturated. There is no complete water balance of an Australian, wet tropical rainforest, although one study has been conducted in a subtropical forest.

Rainforests, worldwide, have very low (~1%) input and output fluxes of N compared with the amount stored within the above- and below-ground vegetation and litter layer. Nutrients are conserved by efficient translocation within the plants and efficient uptake of N reaching the ground, in precipitation (throughfall or stem flow) or litter, and by dense surface root mats. Inputs are from rainfall and dry deposition and fixation. Doubt exists over the magnitude of N fixed. Outputs are N carried in run-off and deep drainage water, with an Australian study suggesting most losses are via deep drainage. Apart from this latter study and some information of litterfall, there is no information to confirm that this general model of N cycling operates in Australian rainforests.

Agricultural systems

As already noted, agricultural plant production systems in the wet tropics are dominated by sugarcane with small, but important, areas of horticulture interspersed. In this section we focus on these systems. Literature on complete water and nutrient balances of these agriculture systems is almost non-existent. Most effort to date has been directed at 'improving' water and nutrient use efficiency, but usually by dealing with only a specific nutrient or component of the water or nutrient balance. There is only one study that has attempted to address the full water and nutrient balance (Prove et al. 1997).

The biggest difference between natural and agricultural systems is the agriculturist's ability to manipulate fluxes of nutrients, and to a lesser extent water, into and out of the system. Under rainfed conditions, control over water input is minimal, while under irrigated conditions the agriculturist has the ability to significantly alter the water input. In general, fluxes of nutrients into and out of agricultural systems are higher than those in natural systems because of fertiliser inputs and the regular removal of biomass during harvest. Nutrient losses to erosion, run-off and leaching are also higher in agricultural systems, usually because of increased availability of nutrients, occurrence of bare soil in the system and decreases in organic matter (Lal 1986; Magdoff et al. 1997). Removal of biomass from agricultural systems reduces the recycling of nutrients within the system.

Water inputs in both natural and agricultural systems tend to be event-driven, particularly in rainfed situations. While there is some continuity in the nutrient cycling in natural systems, nutrient inputs and outputs in agricultural systems tend to be event driven, being dominated by fertiliser applications and crop harvests which occur at specific times through the year. One of the biggest challenges therefore is for agriculturists to improve the matching of supply of water and nutrients to meet the needs of production systems.

Water balance

Research on water balance in the tropics has tended to focus on wateruse efficiency associated with irrigation (eg. Kingston and Ham 1975; Turner 1990). However, since irrigation in the wet tropics is usually only supplementary, little water balance work has been done is this region. The one wet tropics study that has attempted to address the complete water balance is that of Prove et al. (1997). The results of that study, together with other data addressing various components of the water balance, are considered in this section.

Precipitation

Agricultural plant production in the wet tropics takes place under very high rainfall (> 1,500 mm per year). Key features of this rain are its high intensity and marked seasonality, with up to 90% falling in the six-month November–April period. We are not aware of any studies in wet tropics agricultural systems that have addressed dew, fog, interception, canopy storage, throughfall or stemflow and their role in the overall water balance.

Run-off

Partitioning of precipitation between infiltration and run-off is controlled by soil surface and near surface properties. Although there tends to be more bare surface area and increased compaction in agricultural systems that will favour generation of run-off, few studies have quantified run-off from wet tropics systems. Prove (1991) reported run-off from individual storms that ranged from 35 to 65% of total rainfall for conventionally cultivated sugarcane lands. He reported similar values for run-off but noted that the peak run-off rates tended to be lower for zero-till systems. The data of Prove et al. (1997), when averaged over their three-year study period, indicate that run-off (expressed as a percentage of precipitation) was < 1% in pastures, roughly 7% in bananas and 12% in sugarcane, compared with about 5% in rainforest (see Table 10). The value for sugarcane is significantly lower than those reported earlier.

Evapotranspiration

In the wet tropics there are only a few months of the year (August–November) where rainfall is less than evaporative demand as quantified by pan evaporation. While this suggests that the soil profile should remain wet for large parts of the year and that evapotranspiration from agricultural systems will often be demand driven rather than supply limited, there are few data available to verify this. Reasons for this are that there are few lysimeters available for this type of work, most field experimental plots have been too small to employ standard meteorological measurement techniques (Bowen ratio, eddy correlation etc.), and water extraction data, while not commonly available, are difficult to interpret, especially from low-lying areas with shallow watertables.

Measurements that are available are those of Denmead et al. (1997) who measured evapotranspiration (ET) from sugarcane over an 18-day period in 1992. They reported ET values ranging from 1.9 to 3.75 mm day^{-1} at one site where the crop leaf area index (LAI) changed from 0.7 to 1.6 over the study period, and 2.24 to 5.0 mm day^{-1} at another site where LAI changed from 1.5 to 2.5 over the study period.

Prove et al. (1997) estimated ET using pan evaporation multiplied by a crop factor, with crop factors of 0.8 for sugarcane, 0.9 for bananas, 0.6 for pasture and 1.0 for rainforest. How these factors were derived is not clear.

Deep drainage

Given the high rainfall and finite storage capacity of soils, drainage from wet tropical soils could make up a large percentage of the water balance. Unfortunately, once again there are few measurements available to provide an accurate picture for wet tropical soils. Prove et al. (1997) attempted to measure drainage using suction lysimeters at 60 cm depth and their data averaged over the three-year study period indicated that drainage (expressed as a percentage of rainfall) was roughly 70% for pastures, 60% for bananas and 65% for sugarcane, compared with about 40% for rainforest (see Table 10).

Field water balance study

The only attempt to obtain a complete field water balance in the wet tropics that we are aware of is that of Prove et al. (1997). This study was carried out on a krasnozem soil in the South Johnstone catchment. A summary of the overall water balance (averaged over the three-year study period) is given in Table 10. Data for the individual years are given in Tables 11–13. Rainfall was measured using tipping bucket rain gauges. ET was estimated using pan evaporation and constant crop factors. The basis on which the crop factors were selected and their representativeness is not clear. Run-off was measured using measurements of water height in run-off flumes. Drainage was measured at 60 cm using barrel lysimeters with suction cups. It is not clear whether suctions within the lysimeters differed from those outside the lysimeters at the same depth. Drainage was also calculated using measured water gradients as a means of 'checking' the measurements. No change in profile storage was reported.

Table 10 Average hydrological data for sugarcane, banana, pasture and rainforest from 1992–1995. Values in brackets indicate percentage of rainfall (including irrigation for banana) (taken from Prove et al. 1997).

	Rainfall (mm)	Irrigation (mm)	ET (mm)*	Run-off (mm)	Drainage measured (mm)	Drainage calculated (mm)
Cane – Conventional	3,154 (100)	n/a	1,060 (34)	340 (11)	2,092 (66)	1,753 (55)
Cane – Best Bet	3,154 (100)	n/a	1,060 (34)	384 (12)	2,006 (64)	1,709 (54)
Banana – Overhead irrigation	2,732 (100)	112 (38)	1,095	199 (7)	1,799 (63)	1,551 (55)
Banana – Undertree irrigation	2,732 (100)	1,095	153 (38)	196 (7)	1,603 (56)	1,595 (55)
Pasture – High fertiliser input	2717 (100)	n/a	589 (22)	11 (0)	1,928 (71)	2,113 (78)
Pasture – Low fertiliser input	2,717 (100)	n/a	589 (22)	17 (1)	1,878 (69)	2,107 (77)
Rainforest	2,408 (100)	n/a	1,148 (48)	118 (5)	953 (40)	1,143 (47)

* ET = Evapotranspiration = pan evaporation multiplied by a crop factor where crop factors are 0.8 for cane, 0.9 for bananas, 0.6 for pasture, and 1.0 for rainforest.

Note: It is stated that rainforest drainage is not truly representative owing to non uniform distribution, ie. trees versus no trees.

The data given in Table 10 show that on these soils drainage dominated the water balance in both sugarcane and bananas. Drainage in these systems accounted for roughly 60% of precipitation while ET accounted for roughly 40%. Drainage in pastures accounted for roughly 70% and ET for 20% of rainfall, while drainage and ET were similar in the rainforest each accounting for roughly 40–50% of the rainfall.

Nitrogen balance

One of the biggest challenges facing researchers in tropical regions is to supply N at rates which meet the crop's needs without losing significant amounts via leaching, run-off and volatilisation. Minimising these losses to maintain surface and groundwater quality is of particular importance in the wet tropics given the proximity of the Great Barrier Reef to the intensively farmed coastal regions. For N there is the added challenge of coping with the generation of acidity so as to minimise degradation of the soil resource. At present, N use efficiency is generally less than 50%, and may be as low as 20–30% (Lal 1980; Smith et al. 1990; Prove et al. 1994). Separate ^{15}N balance studies have reported losses of 25 to 60% of the applied fertiliser N depending on soil characteristics and the way the N was applied (Weier 1994). Assuming the average fertiliser input of 160 kg N ha^{-1} in the Queensland sugar industry (of approximately 400,000 ha), this would mean about 10,000 to 35,000 tonnes of N leaving the sugarcane production systems annually, indicating that there is much room for improvement in how N is managed in these systems.

As reported by Keating et al. (1993), past research on N has tended to concentrate on only one or two components of the N balance at any one time, such as the recovery and losses of fertiliser N (Chapman and Haysom 1991; Chapman et al. 1991), volatilisation

Table 11 Summary of hydrological data for sugarcane, banana, pasture and rainforest from 1992–93 (taken from Prove et al. 1997).

	Rainfall (mm)	Irrigation (mm)	Run-off (mm)	Measured drainage (mm)	ET (mm)	*Calculated drainage (mm)
Cane Conventional	2,498.7	n/a	136	1,921.8	1,070.9	1,291.8
Cane – Best Bet	2,498.7	n/a	168	1,730.5	1,070.9	1,259.8
Banana – Overhead irrigation	2,548.3	0	98	2,018.3	1,020.7	1,429.6
Banana – Undertree irrigation	2,548.3	125	90	1,856.2	1,020.7	1,562.6
Pasture – High fertiliser input	2,865.8	n/a	0	1,840.4	6,18.7	2,247.1
Pasture – Low fertiliser input	2,865.8	n/a	0	1,948.4	6,18.7	2,247.1
Rainforest	1,574.2	n/a	6	610.0	927.3	640.9

* ET = Evapotranspiration = Pan evaporation times a crop factor. Crop factors – cane 0.8, bananas 0.9, pasture 0.6, rainforest 1.0.
Notes: Rainforest drainage not truly representative due to non uniform distribution, ie. trees versus no trees. Data collection: Rainforest—6 February 1993–31 October 1993, other sites—20 December 1992–31 October 1993

Table 12 Summary of hydrological data for sugarcane, banana, pasture and rainforest for 1993–94 (taken from Prove et al. 1997).

	Rainfall (mm)	Irrigation (mm)	Run-off (mm)	Measured Drainage (mm)	E_T (mm)*	Calculated Drainage (mm)
Cane – Conventional	3,767.9	n/a	463	2,161.8	997.1	2,307.8
Cane – Best Bet	3,767.9	n/a	482	2,408.2	997.1	2,288.8
Banana – Overhead irrigation	2,898.0	226.1	297	1,865.7	1149.2	2,025.7
Banana – Undertree irrigation	2,898.0	179.7	281	1,766.3	1149.2	1,995.3
Pasture – High fertiliser input	2,870.0	n/a	33	2,392.5	517.2	2,520.2
Pasture – Low fertiliser input	2,870.0	n/a	47	2,292.2	517.2	2,506.2
Rainforest	2,898.0	n/a	208	1,127.0	1276.9	1,760.9

*ET = Evapotranspiration = Pan evaporation times a crop factor. Crop factors – cane 0.8, bananas 0.9, pasture 0.6, rainforest 1.0.
Notes: Rainforest drainage not truly representative due to non uniform distribution, ie. trees versus no trees. Data collection: Cane—1 November 1993–11 October 1994, other sites—1 November 1993–13 September 1994.

losses (Denmead et al. 1990) and N fixation (Chapman et al. 1992). Since it is commonly agreed that the various components (eg. volatilisation, denitrification, run-off, leaching) are all important in different circumstances, the precise definition of their respective contributions to the N balance at any one place has been difficult. This has no doubt been exacerbated by lack of information on the water balance (especially run-off and/or deep drainage) which is needed to construct the complete N balance.

Nitrogen inputs

In agricultural systems, the main N inputs are fertiliser applications and contributions from biological fixation. N additions from atmospheric sources, usually in the range of 5–10 kg ha^{-1} yr^{-1}, are small compared with these, and often assumed to be negligible (Gigou et al. 1985). Data from Townsville, which is not in the wet tropics as such, are even lower at 2 kg ha^{-1} yr^{-1} (Probert 1976).

Fertiliser

The dominant form of N input to agricultural systems in the wet tropics is via fertiliser applications. Typical applications for sugarcane, bananas, papaws and pastures are given in Table 14. The 'standard' application rate in the sugarcane industry is 160 kg N ha^{-1} per year. In sugarcane the fertiliser is broadcast onto the surface or applied as a band within the plant row. In banana crops most of the fertiliser is applied as a broadcast every four to eight weeks (Daniells 1995).

While the amount of N required by crops for 'optimal' yields has been the focus of much research, little effort has gone into the N balance as a whole and in trying to match fertiliser applications with plant needs. The main reason for this has been the focus on production, rather than the efficiency of N applied, although this is changing given the current interest in off-site impacts and environmental sustainability.

To improve efficiency, fertiliser applications need to account for actual crop needs, the residual N available in the soil pool, the likely residence time of the applied fertiliser, the fertiliser's effect on the physical and chemical properties of the soil, and additions from biological fixation. Knowledge of these factors will help to more closely match fertiliser applications to plant needs, thereby reducing the leakage of N from agricultural systems.

Fixation

N fixation can provide considerable inputs into various cropping systems, particularly those involving legumes (> 100 kg N ha^{-1}; Magdoff 1977). Emtsev and Shelly (1987) have reported values up to 72 kg ha^{-1} over the three-month growing season in sugarcane and pineapple plantations.

Nitrogen outputs

The majority of N lost in the humid monsoonal tropics occurs during the growing season or wet season, predominantly from leaching and gaseous losses (Grimme and Juo 1985; Cogle et al. 1996). Other loss pathways include losses associated with harvesting, sediment transport during erosion processes, and run-off (Smith et al. 1990). Transport of sediments can occur via wind or water, but rates of wind erosion in agricultural lands in the humid tropics are probably negligible (McTainsh and Leys 1994).

In general, losses are greatest where there is a heavy reliance on soluble forms of N (Magdoff et al. 1997).

Table 13 Summary of hydrological data for sugarcane, banana, pasture and rainforest for 1994–95 (taken from Prove et al. 1997).

	Rainfall (mm)	Irrigation (mm)	Run-off (mm)	Measured drainage (mm)	ET (mm)*	Calculated drainage (mm)
Cane – Conventional	3,194.0	n/a	421	2,192.7	1,112.7	1,660.3
Cane – Best Bet	3,194.0	n/a	503	1,879.0	1,112.7	1,578.3
Banana – Overhead irrigation	2,750.9	109	201	1,517.0	1,114.5	1,544.4
Banana – Undertree irrigation	2,750.9	155	216	1,186.2	1,114.5	1,574.4
Pasture – High fertiliser input	2,406.1	n/a	1	1,550.0	632.0	1,773.1
Pasture – Low fertiliser input	2,406.1	n/a	5	1,394.7	632.0	1,769.1
Rainforest	2,750.9	n/a	139	1,121.0	1,238.3	1,373.6

* ET = Evapotranspiration = Pan evaporation times a crop factor. Crop factors – cane 0.8, bananas 0.9, pasture 0.6, rainforest 1.0.
Notes: Rainforest drainage not truly representative due to non uniform distribution, ie. trees versus no trees. Data collection: Cane—12 October 1994–24 October 1995, other sites—14 September 1994–4 August 1995.

Lowest loss rates are achieved from farming management practices which minimise erosion and run-off, and which discourage high amounts of readily leachable nutrients being available in the soil profile at any one time.

The major loss pathways for horticultural crops in North-East Queensland tropical regions have been determined as drainage and atmospheric returns (Prove et al. 1994, 1996a,b, 1997). N loss under bananas and papaya crops via run-off has not been identified as a significant pathway for agricultural crops grown on kraznozem soils (Prove et al. 1996b). N losses as measured in streamflow have been shown to be significant in North-East Queensland, exceeding ANZECC (1992) standards for freshwater ecosystem protection during peak wet season events (Cogle et al. 1996; Bramley and Johnson 1996), although the exact contribution from various land uses within the region is difficult to distinguish. Bramley and Johnson (1996) indicate that it is the intensiveness of the land use which determines downstream nutrient loss.

Harvest losses

The amount of N removed during harvest depends on the crop physiology, the portion of the plant removed, and the efficiency of N uptake (Magdoff et al. 1997). In the wet tropics recovery rates appear to be low (Table 15), indicating that either excess N is being applied or that there is significant room for improvement in terms of better synchronisation between nitrogen supply and uptake.

Leaching losses

Losses of N via leaching are largely determined by climatic factors and fertiliser release rate, efficiency of application, the quantity applied, the number of applications and soil physical properties, especially structure. In general, leaching losses increase with increasing use of soluble N, namely nitrate (Magdoff et al. 1997). Prove et al. (1994) have reported N leaching losses in the Johnstone River catchment under sugarcane, bananas, and pastures (Table 16),

Table 14 Fertiliser applications reported for agricultural industries in the humid tropics (kg N ha^{-1} year^{-1}).

Source	Location	Crop/land use	Fertiliser applied
Prove et al. (1994)	North Queensland	Sugarcane	160–180
		Bananas	400–500
		Pastures	400–500 for high input grass pastures; negligible for grass/legumes
Prove et al. (1996b)	Innisfail–Tully region	Papaya (papaw)	Farmer applications 100–1,300 kg N ha^{-1} every 2 years Most common range applied 300–900 Industry standard 550
Daniells (1995)	North Queensland	Bananas	Average application of nitrogen by farmers 519 Modal application of nitrogen applied by farmers 400–500 Range of nitrogen applied by farmers 0–1,100
Wood and Saffigna (1987)	North Queensland	Sugarcane	> 200
Gigou et al. (1985)	Tropical agrosystems	Sugarcane	< 15 Straw incorporation of 3–5 t/ha
Macleod (1994)	North Queensland	Sugarcane	Nitrogen applied by growers 300 Recommended leaf nitrogen levels 1.3–2.5%
Deuter (1994)	North Coast Australia	Sugarcane	QDPI* nitrogen recommendation for bean crops 150
Prove et al. (1997)	Johnstone River Catchment	Sugarcane	Input from banana residues: First ratoon broadcast 92 ± 3 fertigated 86 ± 6 Second ratoon broadcast 114 ± 27 fertigated 108 ± 12

* Queensland Department of Primary Industries

with up to 200 kg N ha^{-1} being lost under sugarcane. They also indicate that only 5% of the N was leached as ammonium; the bulk was leached as nitrate. Prove et al. (1997) have also reported large quantities of nitrate at depth (1,000 kg ha^{-1} between 5.5 and 7.5 m depth) on a krasnozem, which is further evidence of the large amounts of N that can be leached out of the root zone.

In the monsoonal tropics, rates of mineralisation are often highest at the beginning of the rainy season, particularly if residues high in N, such as green manures and legumes, have been incorporated into the soil (Gigou et al. 1985; Dart 1986). This often manifests itself as a flush or rapid pulse of nitrate with the initial rains, with subsequent rainfall events producing losses of smaller magnitude (Gigou et al. 1985; Prove et al. 1994). During the rainy season, soil N stocks may become low as a result of plant uptake, decreases in mineralisation rates and immobilisation (Gigou et al. 1985), thereby limiting leaching losses.

The slower the release of N into the soil profile, the less likelihood there is of large amounts of nitrate being leached. Leaching losses can be reduced by a greater dependence on N fixation associated with crop residues, or by slow-release fertilisers (Dart 1986; Magdoff et al. 1997). Nitrification inhibitors, such as nitrapyrin and DCD, can also be used in conjunction with ammonium applications to slow down the release rate for high-leaching regions (Hauck 1981; Smith et al. 1990). Nitrification of alkaline-hydrolysing ammonium compounds is higher than acid-hydrolysing ammonium compounds for soils of low pH (Hauck 1981).

Table 15 Nitrogen (N) removed from the system during harvest.

Source	Location	Nitrogen applied (kg N ha^{-1})	Description	Nitrogen removed (kg N ha^{-1})
Prove et al. (1997)	Johnstone River catchment	220 (N broadcast)	Banana plant crop	31 ± 8
		232 (N broadcast)	Banana 1st ratoon	66 ± 4
		402 (N broadcast)	Banana 2nd ratoon	60
		255 (N fertigated)	Banana plant crop	29 ± 5
		233 (N fertigated)	Banana 1st ratoon	79 ± 25
		336 (N fertigated)	Banana 2nd ratoon	70
		170	Sugarcane (plant)	83
		160	Sugarcane (1st ratoon)	68
Prove et al. (1994)	North Queensland wet tropics	Not given	Agricultural crops	20–30% of applied N
Lal (1980)	Humid tropics	Not given	Various crops	<50% of applied N

Table 16 Leaching losses in tropical agricultural systems (N = nitrogen).

Source	Location	N applied (kg N ha^{-1})	Crop	N leached (kg N ha^{-1})
Prove et al. (1997)	Johnstone River catchment	220 (N broadcast)	Banana plant crop	110
		232 (N broadcast)	Banana 1st ratoon	38 ± 22
		402 (N broadcast)	Banana 2nd ratoon	71 ± 45
		255 (N fertigated)	Banana plant crop	152
		233 (N fertigated)	Banana 1st ratoon	105 ± 44
		336 (N fertigated)	Banana 2nd ratoon	81 ± 44
Prove et al. (1996b)	Innisfail–Tully region	220	Papaya	0.2–26 mg N L^{-1} Monthly range of nitrate concentrations in lysimeter water
Prove et al. (1994)	North-East Queensland	Not specified, but in associated publication (McShane et al. 1993), experimental details indicate 170 kg N ha^{-1} was applied to plant crops	Sugarcane	Average: 62.4 Range: 9–209
			Bananas	Average: 109 Range: 10–221
			Grass pastures	Average: 0.33 Range: 0.26–0.42

By definition, higher efficiency of N fertiliser implies decreased loss. The type of irrigation used and the number of applications of fertiliser are factors which can be manipulated to produce higher degrees of efficiency. In the last decade, drip irrigation has been increasingly adopted by farmers in Queensland. One of its advantages includes the possibility of containing nutrients within the plant's root zone, increasing fertiliser efficiency and reducing losses to leaching (Smith et al. 1990). If broadcasting or applying fertiliser via surface fertigation, care must be taken that irrigation intended to water-in the applied fertiliser does not move it below the root zone, thereby increasing N loss via leaching (Prove et al. 1996a,b).

The use of split applications of nitrogen fertiliser has been identified as reducing leaching losses (Arora and Juo 1982). Nitrate losses for an Ultisol soil (calculated by the mean of both limed and unlimed plots) were 53%, 44% and 28% for one application, two splits and three splits, respectively (Arora and Juo 1982). Fertiliser was applied at 150 kg ha^{-1} for a maize crop and 90 kg ha^{-1} for a rice crop as calcium ammonium nitrate. These authors also showed that the amount of nitrate lost via leaching increased with lime applications (a method frequently used to combat acidification) due to the higher levels of nitrate with increasing pH.

Soil structure, in particular the presence of macropores, also plays a role in the leaching of nutrients, including nitrate. In situations where nutrients are contained in micropores, the presence of macropores can decrease leaching losses by enabling through-flowing water to bypass the micropores leaving most of the nutrients behind (Arora and Juo 1982; Magdoff et al. 1997; Cote et al. 1999). Just how important this is in limiting leaching losses is not clear, as Grimme and Juo (1985) indicate that in tropical areas of high rainfall, the pore volume of the A horizon typically contains a low proportion of storage pores (< 50 mm) relative to macropores (> 50 mm).

In general, leaching losses can be reduced by use of organic matter and practices which discourage a build-up of readily leachable nitrate, such as single fertiliser applications and soluble fertiliser additions.

Losses via run-off and erosion

Potential for nutrient loss via erosion and run-off is large in high rainfall wet tropical agricultural systems, particularly where fields are left bare, slopes are significant and machinery results in compaction of surface layers. The finer sediments, which contain the majority of soil N, are those most likely to be removed via erosion (Smith et al. 1990; Finlayson and Silburn 1996). There are few data available for erosion losses in North-East Queensland, let alone the accompanying loss of nutrients (Prove et al. 1997). What is known is that the majority of nutrient lost via these pathways in North-East Queensland occurs during the wet season (Mitchell et al. 1996). Data that are available are included in Table 17.

Nutrient concentrations in run-off can be higher under no tillage practices than conventional methods, although the overall loss is lower due to the smaller volume of run-off. While conventional systems integrate the nutrients throughout the surface soil, no tillage systems result in nutrient accumulation at the surface, giving higher concentrations more suitable for loss through run-off (Magdoff et al. 1997).

Reduction of nutrient loss via run-off and sediment transport can be achieved through reduced or no tillage practices, use of crop rotation during periods of bare fallow, grassed waterways, improvement of organic matter content and slow-release fertilisers (Hunter 1994; Prove et al. 1997).

Losses via volatilisation and denitrification

Gaseous nitrogen losses are site dependent (McShane et al. 1993), being influenced by precipitation, mineralisation, plant growth, and timing and depth of placement of the N fertiliser (Smith et al. 1990). In

Table 17 Reported nitrogen (N) losses via erosion and run-off.

Source	Location	Variable measured	Measure
Prove et al. (1997)	Johnstone River catchment	Particulate and dissolved N under banana crops—range for plant crop, first and second ratoon	< 1–7 kg ha^{-1}
Smith et al. (1990)	not given	Losses of nitrogen in run-off, both soluble and sediment-bound	10 mg L^{-1} nitrate 0.5 mg L^{-1} ammonium
Lal (1980)	not given	Nitrogen loss in run-off for a bare fallow Alfisol soil	9.6 kg ha^{-1} yr^{-1}
		Nitrogen loss in eroded soil for a bare fallow Alfisol soil	3.4 kg ha^{-1} yr^{-1}

general, N losses via volatilisation predominate after surface applications, whereas denitrification losses are predominant with subsurface applications. The occurrence of high temperatures, shallow watertables and extended wet periods in the wet tropics therefore suggests that gaseous losses of N may be an important loss pathway in this region. Typical values of N loss reported in the literature are summarised in Table 18.

Favourable conditions for denitrification are temperatures greater than 10°C, anaerobic conditions, and reasonable quantities of organic matter and nitrate (Grimme and Juo 1985). Denitrification losses are usually difficult to measure, since they often occur as infrequent, solitary events driven by a particular combination of environmental conditions (Grimme and Juo 1985). Nitrogen losses via volatilisation can also occur in acid soils where soil moisture is low but where chemical reactions raise the pH in the vicinity of urea granules (Gigou et al. 1985). Rates of N volatilisation have been found to be directly related to rates of evaporation (Smith et al. 1990; Hauck 1981). Freney et al. (1992, 1994) have reported N losses via ammonia volatilisation following surface application of urea to sugarcane of up to 40% of that applied. Weier et al. (1998) have reported N losses via denitrification of up to 9 kg N ha^{-1} over a 9-day period following surface application of 160 kg N ha^{-1} as potassium nitrate. In their study the soil was waterlogged using sprinkler irrigation.

Smith et al. (1990) recommended several management practices for reducing rates of atmospheric N loss. These included incorporation of N fertiliser rather than application to the surface, applying fertigation at night to facilitate deeper movement into the profile, avoiding N applications during periods of high temperatures and strong winds, and synchronising N applications with crop growth and demand. Given these recommendations, subsurface drip irrigation offers a fairly effective way of reducing gaseous losses of N from agricultural systems.

Field nitrogen balance study

The only attempt to obtain a complete field nitrogen balance in the wet tropics that we are aware of is that of Prove et al. (1997). This study was carried out on a krasnozem in the South Johnstone catchment. The nitrogen balance data reported for both sugarcane and bananas are reproduced in Tables 19–20. While it was not possible in this study to measure all components all of the time, the values do provide an indication of the range in magnitude that is likely to be encountered. When expressed in terms of the amount of fertiliser N applied, the sugarcane data showed that 30–55% of the N was found in the harvested millable cane, 5–30% was leached, and up to 70% was unaccounted for in one of the treatments. For bananas, 15–35% of the N was found in the harvested product and 15–60% was leached. At this site the amount of N lost via run-off was negligible for both sugarcane and bananas.

Vallis and Keating (1994) have also carried out a desktop study of the N balance of sugarcane which gives an approximate N-budget for a plant crop plus five ratoon crops (Table 21). Although the analyses used estimated inputs (based on assumptions taken from known values from the literature), the calculated total N-loss (leaching, denitrification, volatilisation) is well in the range of the values found experimentally, and has the advantage that it gives the partitioning of all

Table 18 Reported values for gaseous losses of nitrogen (N).

Source	Location	N applied (kg N ha^{-1})	Crop type	N loss (kg N ha^{-1})
Prove et al. (1997)	Johnstone River catchment	220 (N broadcast)	Banana plant crop	32
		232 (N broadcast)	Banana 1st ratoon	86
		402 (N broadcast)	Banana 2nd ratoon	199
		255 (N fertigated)	Banana plant crop	4
		233 (N fertigated)	Banana 1st ratoon	92
		336 (N fertigated)	Banana 2nd ratoon	7
Gliessman et al. (1982)	Tobasco, Mexico	Total of 320 kg ha^{-1} yr^{-1}	Rice	120
	Peru	Total of 250 kg ha^{-1} yr^{-1}	Three crops a year: rice, corn and soybean	20
Magdoff et al. (1997)	Not given	n/a	General range of gaseous nitrogen loss	5–10% of applied nitrogen
Smith et al. (1990)	Not given	n/a	Gaseous nitrogen loss for croplands	
			dinitrogen (N_2)	5–25 kg N ha^{-1} yr^{-1}
			nitrous oxide (N_2O)	0.1–3 kg N ha^{-1} yr^{-1}

components for a given set of conditions. These data show that the long-term potential N loss via denitrification and leaching can range from 50 kg N ha^{-1} for a trash burnt system to more than 100 kg N ha^{-1} for a trash blanketed system. This equates to 30–70% of the N when expressed in terms of the amount of fertiliser N applied.

It is clear from the data presented that the N use efficiency is general low, and that there is considerable scope for improving the management of N in wet tropical systems.

Summary

Agricultural systems in the wet tropics are dominated by sugarcane which is grown as a monoculture, and horticulture (especially bananas) which is increasing in importance in several areas. Data on water and nutrient balances of these agricultural systems are almost non-existent, with only one study having attempted to address the full water and nutrient balance (Prove et al. 1997). Most studies to date have tended to be short-term and focus on only a specific nutrient or component of the water or nutrient balance. This has made it difficult to develop a complete picture of the water and/or nutrient balance at any one place within the wet tropics.

Table 19 Nitrogen (N) balance (kg N ha^{-1}) for sugarcane (1992–1995) (taken from Prove et al. 1997).

Source	Plant crop 1992–93		1st Ratoon crop 1993–94		2nd Ratoon crop 1994–95	
	Flat profile, cultivated	Mounded profile, min tillage	Flat profile, surface urea	Mounded profile, split-row urea	Flat profile, surface urea	Mounded profile, surface nitram
Input (+)						
Fertiliser	+170	+170	+160	+160	+160	+107
Rainfall^{A}	+6	+6	+10	+10	+7	+7
Recycled > 60 cm^{B}	+8	+8	+3	+1	+1	+7
Sinks (±)						
Δ Profile mineral N^{C}	–1 ± 3	–2 ± 2	+5 ± 2	+1 ± 4	–3 ± 1	+7 ± 3
Δ Easily mineralised N^{C}	+54 ± 12	+52 ± 6	+19 ± 7	+20 ± 7	+20 ± 9	–2 ± 8
Δ Harvest Residues^{D}	–115 ± 18	–91 ± 9	+7 ± 5	+11 ± 8	+17 ± 5	–5 ± 17
Loss (–)						
N leached > 60 cm^{E}	–54 ± 25	–56 ± 7	–18 ± 8	–30 ± 14	–7 ± 3	–46 ± 9
Run-off	< –1	–3	–2	–6	–4	–6
Bedload	0	–1	0	0	0	0
Output (–)						
Millable cane	–79 ± 14	–96 ± 10	–63 ± 6	–73 ± 6	–53 ± 4	–75 ± 8
Estimated gaseous losses	0	0	–120	–39	–128	0
Voltatilisation^{G}	nm	nm	–60	–9	nm	nm
Denitrification^{H}	nm	nm	–7	–24	nm	nm
Unaccounted loss^{I} **(–) or input (+)**	+11	+21	–54	–6	–128	+6

A Estimated from rainfall and N concentration of 0.252 mg N L^{-1}, as measured for the plant crop.
B It was assumed that 15% of leached N was recycled by roots at depths greater than 60 cm.
C Delta profile values at harvest for 0–60 cm, on the basis of 1:3 (row:inter-row) with the exception of the first ratoon split-row treatment which was based on 1:4. Bulk density of 1g cm^{-3} assumed.
D Delta values after harvest for tops, trash and cane left on the surface and stool with roots below ground.
E Spatial representation of row:inter-row samples as for (c) above except for the second ratoon mounded, nitram treatment for which 1:1 was used.
F Includes both particulate and dissolved total N.
G Determined using a micro-meteorological technique.
H Estimated by ^{15}N balance for 11-month period.
I Obtained by difference. This term includes 10 kg N ha^{-1} lost by the crop during the 5.5 to 11 month period as determined by the ^{15}N mass balance.
nm = not measured.

Table 20 Nitrogen (N) balance (kg ha^{-1}) for plant and two ratoon banana crops (1992–95) (taken from Prove et al. 1997).

	Plant 1992–93		First Ratoon 1993–94		Second Ratoon 1994–95	
	Overhead	Undertree	Overhead	Undertree	Overhead	Undertree
Input (+)						
Fertiliser	+220	+255	+232	+233	+402	+336
Rainfall[A]	+6	+6	+7	+7	+7	+2
Recycled from > 60 cm[B]	+9	+12	+3	+8	+6	+12
Residues from previous crop[C]	n/a	n/a	+92 ± 3	+86 ± 6	+114 ± 27	+108 ± 12
Sinks (+/–)						
Δ Profile mineral N[D]	+29 ± 27	+37 ± 27	+48 ± 11	+36 ± 19	–29 ± 9	–49 ± 15
Δ Easily mineralisable N[D]	+60 ± 13	+28 ± 17	10 ± 22	+78 ± 28	–63 ± 33	–120 ± 44
Δ in corm + roots + 3/4 stem + 1/4 suckers[E]	–57 ± 4	–73 ± 13	–60 ± 10	–56 ± 17	–13	–50
Residues from current crop[C]	–92 ± 3	–86 ± 6	–114 ± 27	–108 ± 12	–79	–89
Loss (–)						
N leached > 60 cm[F]	–110	–152	–38 ± 22	–105 ± 44	–71 ± 45	–81 ± 44
Run-off[G]	< –1	< –1	–7	–7	< –5	< –5
Bedload	< –1	< –1	< –1	< –1	< –1	< –1
Output (–)						
Harvested product	–31 ± 8	–29 ± 5	–66 ± 4	–79 ± 25	–69	–70
Estimated gaseous losses	–32	–4	–86	–92	–199	–7
Volatilisation	nm	nm	–58[H]	nm	nm	nm
Denitrification	nm	nm	negligible	nm	nm	nm
Unaccounted	nm	nm	–28	nm	nm	nm

[A] Estimated from rainfall and N concentration of 0.252 µg N L^{-1}, as measured for the plant crop.
[B] It was assumed that 8% of leached N was recycled by roots at depths greater than 60 cm.
[C] Compromises leaves, 1/4 stem, 3/4 suckers and trash.
[D] Delta values pre-emergence and post harvest for 0–60 cm, on the basis of 1:1 (row:inter-row). Bulk density of 1 g cm^{-3} assumed.
[E] Change in N content of these partitions.
[F] Spatial representation of row:inter-row as 1:1.
[G] Includes both particulate and dissolved total N.
[H] Assumes 24.8% (measured in field experiment) of applied fertiliser is volatilised, and denitrification is negligible.
nm = not measured

Table 21 An approximate sugarcane nitrogen (N) budget for a plant crop plus four ratoon crops (taken from Vallis and Keating 1994).

Inputs	kg N ha^{-1} yr^{-1}	Outputs	kg N ha^{-1} yr^{-1}
Fertiliser*	152	Harvested cane	60
Symbiotic N_2 fixation	0	Burning of trash	0/55**
Irrigation	20	NH_3 loss (fertiliser)	10
Precipitation	5	Erosion	4
Dry deposition	5	Run-off	1
Planting material	2	NH_3 loss (leaf senescence)	10
Non-symbiotic N_2 fixation	10		
Total inputs	194	**Total outputs**	85/140**

Long-term potential N loss (leaching plus denitrification):
Trash retained systen: 94 – 85 = 109 kh N ha^{-1} yr^{-1}
Trash burnt system: 194 – 140 = 54 kg N ha^{-1} yr^{-1}

* 120 kg ha^{-1} on plant crop, plus 160 kg N ha^{-1} yr^{-1} on four ratoon crops.
** Not burnt/burnt.

The lack of data on the fate of water and nutrients is of particular concern given the high chemical and fertiliser inputs (especially N/phosphorus/potassium) which are used in both sugarcane and horticulture and the very high rainfall that occurs in the wet tropics. The data that are available indicate that, in general, very little of the applied N is removed in the harvested product (< 55% for sugarcane and < 35% for bananas), and that drainage and leaching can be dominant loss pathways for water and nutrients, at least for the landscapes and soils studied. For other landscapes and soils, run-off and/or subsurface lateral flow could play a more dominant role. The main message from the available data, however, is that N is usually applied in excess of plant requirements and there is considerable room for improvement in N management. The need for improvement in quantifying plant needs and matching N supply to meet these needs is especially apparent when attempting to address sustainability of soil and water resources rather than just trying to maximise production.

Summary and conclusions

The wet tropics of North Queensland is unique in terms of its soils, vegetation and climate (with rainfall in excess of 1,500 mm annually), and its proximity to the environmentally sensitive Great Barrier Reef. Natural systems in the wet tropics are dominated by rainforest in the uplands and a mosaic of different vegetation types in the lowlands. Agricultural systems are dominated by sugarcane and increasing areas of horticulture, and like other man-managed systems around Australia, their long term sustainability and impact on the environment are being questioned. Most of the sustainability problems can be linked in one way or another to ‘leakage’ of water and/or nutrients from agricultural systems. There is therefore a need to improve understanding of the water and nutrient fluxes in both natural and agricultural systems, so that new and better design principles can be employed to align agricultural systems more closely with the unique wet tropics environment.

Natural systems such as rainforests tend to be characterised by diversity, whereas agricultural systems tend to be characterised by uniformity (see Figure 4). The neat rows and uniform vegetation height are classic agricultural features, but raise questions about how efficient they are at exploiting the available water and nutrients. There have been suggestions that modern agricultural systems need a greater diversity, and agroforestry systems are one area where we are seeing this. Invariably, when these issues are raised, the need for trees to be incorporated into the system is highlighted. Reasons for this are that trees tend to be deep rooted so that they can capture water and nitrogen that is missed by agricultural crops. While there would no doubt be advantages to incorporating high-value, fast-growing, deep-rooted trees into agricultural systems so that they can ‘mop up’ excess water and nitrogen, the absolute need for this requires careful analysis. It may be that design and management principles based on better understanding of water and nutrient processes will open a range of options that may or may not include trees. Having more than one option available for agriculturists to consider will, in the long run, provide greater chances for successful adoption of new, more sustainable practices.

There are currently very few data on water and nitrogen fluxes in the wet tropics, and even fewer data on complete water and nitrogen balances. Those data that are available tend to focus on one or two site-specific components of the water and/or nitrogen balance, and tend to be short-term. Only one study has attempted to address the complete water and N balance of sugarcane, bananas, and rainforest, and even then not all components were measured. The data that are available clearly show that in agricultural systems N is applied in excess of plant needs, suggesting that there is room for considerable improvement in N management.

The biggest difference between natural and agricultural systems is the agriculturist’s ability to manipulate fluxes of nutrients, and to a lesser extent water, into and out of the system. Under rainfed conditions, control over water input is minimal, while under irrigated conditions the agriculturist has the ability to significantly alter the water input. In general, fluxes of nutrients into and out of agricultural systems are higher than those in natural systems because of fertiliser inputs and the regular removal of biomass during harvest. It has been suggested that nutrient losses to erosion, run-off and leaching are also higher in agricultural systems, usually because of increased availability of nutrients, occurrence of bare soil in the system, and decreases in organic matter (Lal 1986; Magdoff et al. 1997). There are, however, very few water and nutrient data available for wet tropics systems that can be used to help verify or refute this. It is clear though that addition of large amounts of particular nutrients (eg. N, phosphorus, potassium) and removal of biomass from agricultural systems reduces the recycling of nutrients within those systems.

Water input in both natural and agricultural systems tends to be event driven, particularly in rainfed situations. While it is felt that there is some continuity in the nutrient cycling in natural systems, nutrient inputs and outputs in agricultural systems are event driven, being dominated by fertiliser applications and crop harvests which occur at specific times through the year. Therefore, one of the biggest challenges in trying to align agricultural systems with the natural environment is for agriculturists to improve the matching of supply of water and nutrients to meet the actual needs of plant production systems.

This will require:

- a better understanding of plant needs as a function of crop growth stage;
- development of practices where the type (organic, inorganic, slow-release sources etc.), timing of application, and spatial placement (most appropriate vertical and/or horizontal placement) of nutrients are better matched to meet actual plant needs; and
- most probably, new vegetation patterns involving variations in space and time and/or plant sequences that run in series or parallel, and which may or may not include trees.

While none of the issues raised above is trivial, there is a need to improve understanding and quantification of water and nutrient balances in the wet tropics if the ideal of more sustainable agricultural systems than those currently employed is to be achieved. Future research and development efforts will therefore need to include studies on:

- the major water and nutrient flow pathways in the various soils and landscapes;
- nitrate leaching and the development and amelioration of soil acidity, particularly at depth;
- water and nutrient storage and movement in variable charge soils;
- the potential for development and likely behaviour of deep nutrient bulges;
- evapotranspiration;
- water and nutrient uptake patterns by crops as a function of time, depth and crop growth stage; and
- development of management strategies that match nutrient supply to actual plant needs.

In addressing the above issues it will be important to recognise that:

- the wet tropics consists of a diverse range of soils, landscapes and vegetation types;
- the soils and landscapes of the wet tropics have evolved to cope with and shed large amounts of water, and that any new plant system designs will need to accommodate this feature; and
- while any R&D work that is undertaken will need to be focused, it will also be essential to develop predictive capabilities so that the experimental work that is undertaken can be extrapolated in space and time.

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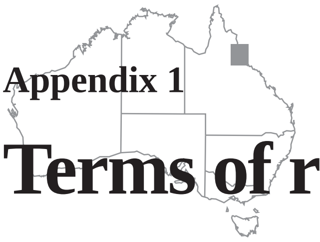


Appendix 1

Terms of reference

The purpose of this study is to review existing information and data sets concerning water and nitrogen (N) use by natural plant communities and agricultural plant production systems in northern Australia (primarily the wet tropics). The purpose of the review is to provide a sound starting base for R&D projects within the CSIRO/LWRRDC Redesign of Australian Plant Production Systems R&D Program.

The major components of the review will be as follows:

1. Review and summarise from published literature, work that quantifies the availability, uptake and loss of water and N (especially via deep drainage) from within natural vegetation ecosystems and from the agricultural plant production systems (primarily sugar and horticulture) that have largely replaced them in the wet tropics of Australia
2. Identify, as far as possible, similar work available in the ‘grey’ literature or as unpublished technical reports etc.
3. Summarise the information available in those reports, including a brief description of the location and natural or agricultural vegetation type, the representativeness of the climatic conditions during data collection, trends in water use efficiency, together with a collation and summary of the quantitative data collected.
4. Provide wherever possible, contact details on the location of those data sets for use by others
5. Draw out any general conclusions arising from the reviewed results
6. Arrange and hold a workshop at a suitable location to review the results of the project so far, including discussion of the sites and plant systems, the measurement techniques, and the data obtained
7. Prepare a written summary of the project, to include the review of past work and data sets, general conclusions drawn, and results of the workshop.

Appendix 2

Details of library searches

The search strategy and databases searched for this review are summarised below. We recovered 4,134 references, which are available in electronic form on request. It goes without saying that only a small percentage of these were directly relevant to the aims of this review.

The search strategy used was based on the following:

Search 1: ((water and B) or C) and A

Search 2: (nitrogen or nitrate) and B and A

Search 3: (salinity or acidification or sustain* or D) and A

where

A (tropic* or Queensland or rainforest or sugarcane or sugarcane or banana or mango or Atherton or tea)
B (balance or cycle* or flux* or leaching or drainage)
C (evapotranspiration or transpiration or run-off or surface flow or infiltration or seepage)
D (groundwater or ground water or recharge or baseflow or stream water or discharge)

DATABASES:

The following information concerning the databases that were searched was reproduced from the University of Queensland's database information page located at the Internet address:

http://www.library.uq.edu.au/database/catalog.html

CAB ABSTRACTS (1969+)

The database contains more than 3 million records from over 10,000 journals, books, conferences, reports, and other kinds of literature published internationally. Subjects covered: Agriculture, Agronomy, Animal Science, Biology, Botany, Crop Management, Dairy Science, Environment, Fertilisers, Food & Agriculture, Forestry, Horticulture, Natural Resources, Pesticides, Plant, Genetics, Soils, Veterinary Science, Water.

CURRENT CONTENTS (1994–PRESENT)

Current Contents Search provides access to tables of contents and bibliographic data from current issues of the world's leading scholarly research journals in the sciences, social sciences, and arts and humanities. Cover-to-cover indexing of articles, reviews, meeting abstracts, and editorials, is provided for over 7,000 journals. Subjects covered: Agriculture, Art, Biology, Chemistry, Computer, Earth Sciences, Engineering, Environment, Humanities, Life Sciences, Medicine, Science and Technology, Social Sciences.

STREAMLINE (1982+)

Subjects covered include: soil degradation, sustainable primary production systems, conservation, land use, vegetation rehabilitation, ecological processes, river health, management of nutrients and eutrophication, wetlands, aquatic ecosystems, urban water utilities, wastewater management and irrigation systems. Journal articles, published and unpublished reports, research in progress, books, book chapters and conference papers are all included. Material is taken from both Australian and international sources, but all relates to the Australian situation. Contains over 30,000 records, from 1982 onwards.

Appendix 3

Workshop report

A workshop entitled

> ‘REDESIGN OF AUSTRALIAN PLANT PRODUCTION SYSTEMS IN THE WET TROPICS: IDENTIFICATION OF RESEARCH AND DEVELOPMENT PRIORITIES’

was held in Brisbane on 16 March 1998 as part of the wet tropics review. The aim of the workshop was to present results of the review to a broader audience from a range of organisations, and to discuss the scope of future R&D priorities for RAPPS work to be carried out in the wet tropics. The workshop participants are listed in Table A1.

The workshop was divided into several sessions:

1. Introduction (Bristow)
2. Background to the RAPPS effort (Williams/Price)
3. The wet tropics review (Bristow/Thorburn)
4. Scoping research and development priorities (workshop groups)
5. Conclusion (Williams/Price)

Discussion and debate was encouraged during and after each session. Key points addressed during the discussions are summarised in Table A2. Workshop participants were divided into three smaller groups during session four to address three key questions, namely

- What do we know?
- What do we need to know to meet RAPPS design criteria?
- What R&D strategy do we need to adopt?

A summary of the issues raised by each group is given in Table A3. The slides used by Drs K.L. Bristow and P.J. Thorburn to facilitate presentation of the wet tropics review and guide the workshop progress are given in an annex to this appendix.

Summary of the main points highlighted during workshop discussions

The wet tropics of North Queensland is characterised by diversity in soils, landscapes and vegetation.

There are deep, well-drained soils in some upland regions and poorly drained soils with shallow fluctuating watertables in some lowland areas. These differences need to be acknowledged and addressed, with particular emphasis given to the differences in movement of water and nutrients in these two contrasting systems. The role of interflow (lateral flow) in the low lying, poorly drained soils as a flow pathway, especially for nutrients, needs attention.

The unique features of variable charge soils was highlighted together with the need to improve understanding of water and nutrient movement in these soils, especially as it relates to the development and fate of deep nutrient bulges.

While rainforests are important and occupy fairly large areas in the upland regions, the point was made that in the coastal lowlands there is a mosaic of different native vegetation types that are dominated by the local water regime. The point was also made that the current vegetation in these areas probably reflects the impact of drainage and changed water regimes more so than the impact of clearing. Improved understanding of natural vegetation function was suggested as one way of teaching design principles needed in the RAPPS effort.

The role of roots in water and nutrient dynamics was raised and the need to differentiate between distribution and function highlighted. The presence of mycorrhiza as a means of enhancing nutrient uptake by native vegetation and the general inefficiency of use of nutrients by crops was also highlighted.

It was felt that run-off was often overlooked as a major flow pathway in the wet tropics, and that a few massive events associated with cyclonic activity could cause large losses of surface litter from natural systems. With this in mind it was suggested that nutrient cycling within native systems might not always be as tight or as efficient as thought, or as reported in the literature.

The scarcity of water and nutrient balance data from the wet tropics was highlighted with particular mention made of the fact that there were no ET measurements of any reasonably useful time duration.

In addressing what knowledge gaps existed and what was needed to address the RAPPS R&D priorities the following points were highlighted:

- recognition that the wet tropics consisted of a diverse range of soils, landscapes and vegetation types, but a focused experimental effort was needed (requiring careful choice of field sites);
- the need for a balance between experimental and modelling work, with development of appropriate predictive capability to facilitate extrapolation of experimental results;
- better understanding of rainfall partitioning and the major flow pathways in the various soils and landscapes, recognising that the soils had evolved to cope with large amounts of water and the landscapes designed to shed water;
- more complete water and nutrient balance data, and especially ET data over long time periods;
- better understanding of water and nutrient storage and movement in variable charge soils;
- better understanding of nitrate leaching, soil acidification and amelioration of soil acidity;
- better knowledge of water and nutrient uptake patterns by crops as a function of time, depth and growth stage; and
- better management of nutrient supply to meet actual plant needs.

The effect of shallow, fluctuating watertables on rootzone nutrient dynamics and their potential impact on soil acidification received little attention.

Table A1 Workshop participants

Presenters	Keith Bristow	CSIRO Land and Water (LW)
	Peter Thorburn	CSIRO Tropical Agriculture (TAG)
Sponsors	Phil Price	LWRRDC
	John Williams	CSIRO LW
External participants	Jennifer Marohasy	CANEGROWERS
	Christian Roth	CSIRO LW
	Keith Weier	CSIRO TAG
	Mike Hopkins	CSIRO Wildlife and Ecology/CRC for Tropical Rainforest Ecology and Management (TREM)
	Paul Reddell	CSIRO LW/TREM
	Graham Kingston	Bureau of Sugar Experiment Stations
	Heather Hunter	Department of Natural Resources (DNR)
	Robin Bruce	DNR
	Phil Moody	DNR
	Steve Turton	TREM/James Cook University (JCU)
	Gavin Gillman	Consultant/JCU
	Viki Cramer	University of Queensland (UQ) Botany Department
	Tina Langi	UQ Botany Department
RAPPS participants	Brian Keating	CSIRO TAG
	Kirsten Verburg	CSIRO LW
	Merv Probert	CSIRO TAG
	Neil Huth	CSIRO TAG
	Jeff Baldock	CSIRO LW
	Chris Smith	CSIRO LW
	Warren Bond	CSIRO LW
	Frank Dunin	CSIRO Plant Industry
	Murray Unkovich	University of Western Australia

Table A2 Key points addressed during workshop discussions

Introduction/Overview	
Frank Dunin	Reminder of the work of Downes (1959) advocating the reinstating of perennials in agricultural systems to prevent hydrologic imbalances, and his predictions of the consequences of not doing so. Reminder also of the example catchment he set up in Victoria which included perennials and which has not developed problems.
Merv Probert	The key difference between natural and agricultural systems is that the latter involves removal of product, so that there is a need to replace it. A potential problem is that the replacement occurs as large events.
Jennifer Moharassy	Need to consider not only rainforest as a natural system, but also what may have preceded it. Also need to consider that they may not have been in equilibrium.
John Williams	Stressed that we needed to know how natural systems work.
Keith Bristow	Need to keep the time scale in mind when considering sustainability.
Christian Roth	Economic viability was mentioned, but it is not clear how it is built into the program.
John Williams	Both current projects will have economic outputs, ie. will predict yields, from which production can be estimated.
Christian Roth	Need to also consider environmental benefits in dollar terms.
Phil Price	This will not be done yet. Need to keep in mind that this is the first step in a 20–30 year program.
Wet Tropics Review	
Introduction	
Mike Hopkins	There seems to be undue concentration on the use of rainforest as a benchmark for natural systems. In the lowlands there is a mosaic of many different native vegetation systems of which rainforest is only one.
Paul Reddell	That mosaic is strongly controlled by the water regime. Note, however, that with trend of sugar to move to upland, rainforest will be more important.
Jennifer Moharassy	As an example, there is evidence that the Herbert was open burnt woodland before European settlement.
Mike Hopkins	The Ingham area was sedge grassland. The important step in changed land management may have been draining rather than clearing.
Steve Turton	It is important to remember that it was a cultural landscape before the Europeans
Climate, Soils, Vegetation	
Paul Reddell	There are large differences in root distribution (and strategy) between different communities.
Merv Probert	It would be expected that mixed vegetation systems must have niches with something evolved to exploit them.
Viki Cramer	Mycorrhizal systems associated with native root systems enhance nutrient capture.
Merv Probert	Time scales, for example of nutrient bulges, are important. Given enough time they can occur in natural systems, eg. sulfur bulge.
Phil Moody	N cycling is very important.
Rainforest Systems	
Mike Hopkins	Re-emphasised that there are five to six different types of coastal lowland forest systems, about which we know even less than for the rainforest ones.
Paul Reddell	It is important to remember that the rainforest work cannot be generalised because of the site specificity of some results, owing to the geological setting.
Frank Dunin	Work suggests that there is an upper bound of ET for a dry canopy, which is about 75% of Penman–Monteith potential. Interception processes etc. can enhance this.
Mike Hopkins	Run-off is often in massive single events, which may result in large losses of litter once or twice a year. Therefore forest nutrient systems are not necessarily as tight as sometimes believed.
Heather Hunter	A study of mineral N carried out at CSIRO Atherton may be relevant.
Phil Moody	There is perhaps a gap in knowledge of run-off losses in lowland systems.
Brian Keating	Was there any primary production information found? [Peter: Yes, but not reviewed.] Was the N cycle in equilibrium in the studies cited? [Peter: The expectation is 'yes' at the sub-catchment scale.]
John Williams	It is surprising that the effect of fertility on the hydrologic losses of nutrients was not greater.
Merv Probert	Do they include sediment?
Warren Bond	Given the difficulty of monitoring large events, they may underestimate hydrologic losses of nutrients.

Table A2 (cont'd) Key points addressed during workshop discussions

Agricultural Systems	
Phil Moody	Banana industry has improved its N use efficiency since being shown the results of the South Johnstone study, by fertigation, under-tree irrigation, and using less N.
Heather Hunter	Potential for associative N fixation.
Implications for RAPPS	
Phil Moody	Is interflow caused by compaction likely to be significant? [On some soils yes]
Jennifer Moharassy	How can growers be convinced of the need to prevent run-off losses of nutrients? [John Williams/Phil Price: stream impact (algae), acidification, fertiliser cost lost, groundwater impact, impact on future landuse]
Viki Cramer	There is some work on root function in systems other than rainforest systems that may be generic enough to be applied in this program.
Paul Reddell	There has been some recent work on root distribution and extent to which the soil is being explored, and this shows that rainforest and sclerophyll forests are very different. The former is much coarser, the latter much finer. Therefore it is difficult to extrapolate from measurements in other systems. Examples of data: rainforest—130,000 km/ha at soil surface; Melaleuca—700,000 km/ha.
John Williams	What about depth? [Paul Reddel: There is a difference between metamorphic parent material and granites/basalt, the former being shallow, the latter deeper.]
Viki Cramer	A reminder that distribution cannot be equated to function.
Robin Bruce	Concerned that run-off appears to have been downplayed. Run-off occurs in big events and is often not captured. There is also a difference between upland and lowland; in the latter it is much greater.
Christian Roth	In the lower Herbert in poorly drained soils run-off is 30–40% of the water balance. The wet tropics are not uniform; there is a diversity of soils, hydrology, vegetation etc. but there is a need to focus the study.
Scoping R&D Priorities	
Session 1	
Jennifer Moharrasy	Work has been done on old systems. The sugar industry is changing and making more use of trash blankets. It is necessary to repeat the measurements under the new systems. The comparison of natural versus agricultural systems is less useful from the point of view of knowing the magnitude of losses from natural systems than knowing how the natural systems work.
Steve Turton	There is a need to judge what is a significant change.
Christian Roth	Yes, however, it is hard to get resource managers to define what is a significant downstream effect.
Gavin Gillman	The value of studies of natural systems is that they may teach us the design principles so that we can emulate their function.
Session 2	
Kirsten Verburg	If the dominant part of the study is to be experimenation in primary catchments, surely the project needs to be quite long to ensure that events of any give magnitude are included. [Response: need to run long enough] Should modelling be included? [Response: modelling only works if the same processes operate for events of different magnitudes.]
Brian Keating	The focus has been on N. What about other ions and, eg. acidity development? [Response: Only needs, not strategies.]
John Williams	How have the sugar rotations of Alan Garside been performing? [Graham Kingston: If the rotation crop is not a cash crop, it is necessary to show the farmer that the benefit outweighs the income forgone by including it. It is also necessary to build leguminous crops in such a way that they don't add too much N.]
Conclusion	
Phil Price	RAPPS work in the wet tropics must show linkages with other Queensland projects (eg. Keating, Weier, Prove et al.) as well as the other RAPPS projects.

Table A3 Summary of the workshop working groups tasked to address the questions

GROUP A:

What do we need to know to meet RAPPS design criteria?

- Differentiate 'wet tropics'
  - land systems
  - hydrologic units
  - physico-chemical behaviour
- Understand relationships between units ('catchment dimensions')
- What is 'unsustainable'?
  Do we attempt to match water and nutrient fluxes from natural systems or define thresholds to N inputs accepted by society?
- Need to develop predictive capabilities

What R&D strategy do we need to adopt ?

- Throw all resources at a site, calibrate system model, run scenarios, derive strategies for redesign, test
- Criteria for site selection
  - accessibility
  - sensitivity of response
  - uniqueness for wet tropics
- Link into additional (existing) sites to test extrapolative capability
- Ensure current modeling frameworks capable of reproducing variable charge soils

GROUP B:

What do we know?

- Water has to go somewhere
- Systems are complex
- Sparseness/non-representativeness of existing data—why ? Curiosity driven work, few 'scientists'?
- Current cultural practice leads to unsustainable systems
  - Sugar—perennial
  - Bananas—multi-canopy
- Soils acidify—at minimum pH ultimate limitation is calcium (or aluminium or magnesium?)

What do we need to know to meet RAPPS design criteria?

- ET of natural systems and crops
- Partitioning of water into run-off and drainage
- To what extent we can use models to extrapolate
- How groundwater systems impact locally and downstream
- More about root distribution and function
- More about variable charge soils and nutrient fluxes
- More about soil biology and nutrient cycling
- Impacts of riparian zone and remnant wetlands on nutrient cycling
- Up-scaling

What R&D strategy do we need to adopt?

To improve sugarcane production we need to

1. Identify leaks
2. Can then (i) Exploit/Trap nutrients or (ii) Reduce leaks eg.—by controlled input, associative N fixation

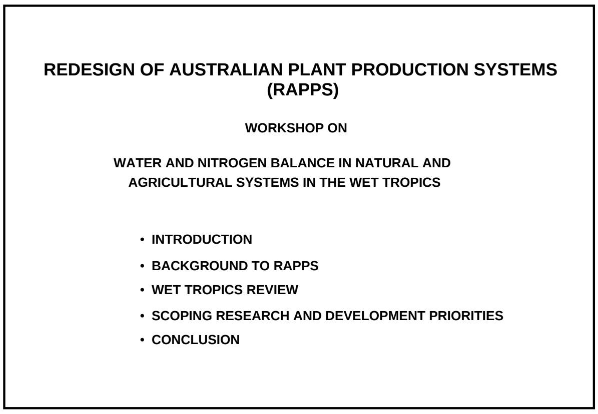
- Experimentation
  - Contrasting sites (a) free draining soil, (b) poorly drained, shallow watertable

Table A3(cont'd) Summary of the workshop working groups tasked to address the questions

GROUP C:
What do we know?
• Need to improve current agricultural systems—nutrients, sediments, fertility • Inefficient use of nutrients by current crops
What do we need to know to meet RAPPS design criteria?
• Degree of change in leakiness following development • Effect of heterogeneity of soils and vegetation • Is the issue the deep drainage or the nutrients/contaminants ? • Damping effects of system on episodic events • Nature of nutrients in the system and susceptibility to movement • Nutrient movement in two systems (deep versus shallow watertables) different • Benchmarking of present systems under best practices • Alternatives to monoculture • Water/nutrient uptake by cane and other crops; time, depth, growth stage. Also need for natural systems
What R&D strategy do we need to adopt?
Scale: 1. Primary catchment level with well characterised properties (soil, vegetation, slope, flow etc). Land use—natural and agricultural paired catchments 2. River basin Balance between experiment/modelling? • Data collection/experiment dominant • Scale up 1 to river basin via modelling Where would we do the work ? • Identify potential areas with significant problems • Define where we are at with the study area using existing literature and current research (unpublished) Assess potential of possible sites 1. Will implementation of best management practices improve current situation? – modeling – experimentation 2. Explore options with data we have to ensure a potential benefit 3. Release information along the way—don't hold back data or findings Sustainability involves defining a time scale—are we at equilibrium or still changing?

Annex

Workshop presentation slides



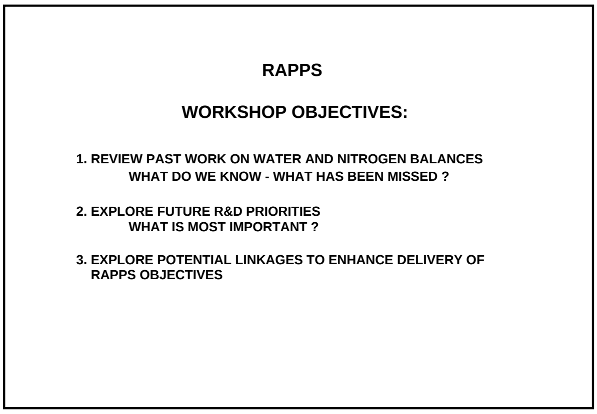
REDESIGN OF AUSTRALIAN PLANT PRODUCTION SYSTEMS (RAPPS)

WORKSHOP ON

WATER AND NITROGEN BALANCE IN NATURAL AND AGRICULTURAL SYSTEMS IN THE WET TROPICS

- **INTRODUCTION**
- **BACKGROUND TO RAPPS**
- **WET TROPICS REVIEW**
- **SCOPING RESEARCH AND DEVELOPMENT PRIORITIES**
- **CONCLUSION**

Slide 1

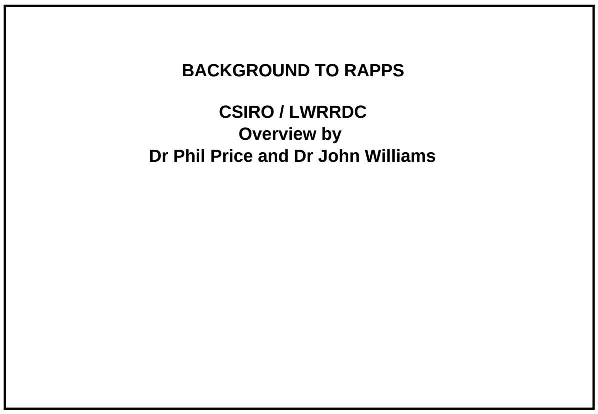


RAPPS

WORKSHOP OBJECTIVES:

1. **REVIEW PAST WORK ON WATER AND NITROGEN BALANCES**
   WHAT DO WE KNOW - WHAT HAS BEEN MISSED ?
2. **EXPLORE FUTURE R&D PRIORITIES**
   WHAT IS MOST IMPORTANT ?
3. **EXPLORE POTENTIAL LINKAGES TO ENHANCE DELIVERY OF RAPPS OBJECTIVES**

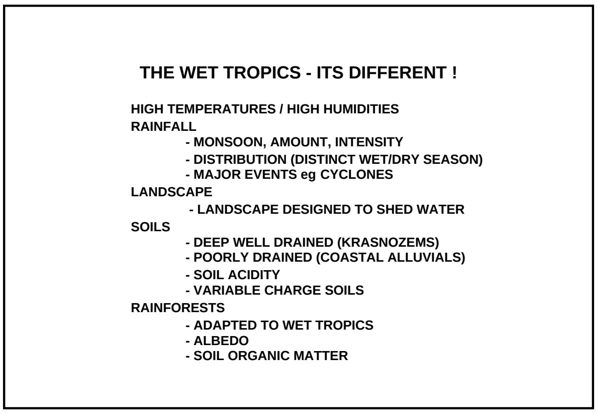
Slide 2



BACKGROUND TO RAPPS

CSIRO / LWRRDC
Overview by
Dr Phil Price and Dr John Williams

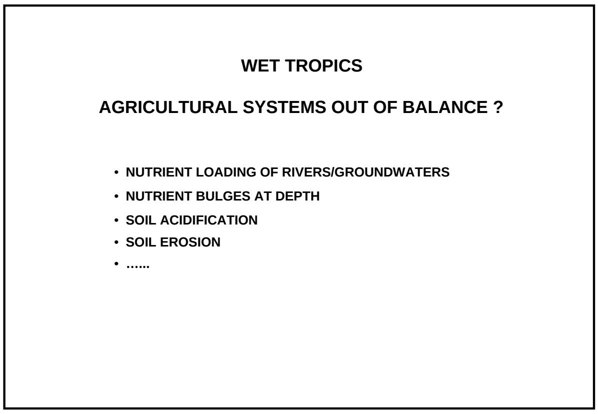
Slide 3



THE WET TROPICS - ITS DIFFERENT !

HIGH TEMPERATURES / HIGH HUMIDITIES
RAINFALL
  - MONSOON, AMOUNT, INTENSITY
  - DISTRIBUTION (DISTINCT WET/DRY SEASON)
  - MAJOR EVENTS eg CYCLONES
LANDSCAPE
  - LANDSCAPE DESIGNED TO SHED WATER
SOILS
  - DEEP WELL DRAINED (KRASNOZEMS)
  - POORLY DRAINED (COASTAL ALLUVIALS)
  - SOIL ACIDITY
  - VARIABLE CHARGE SOILS
RAINFORESTS
  - ADAPTED TO WET TROPICS
  - ALBEDO
  - SOIL ORGANIC MATTER

Slide 4

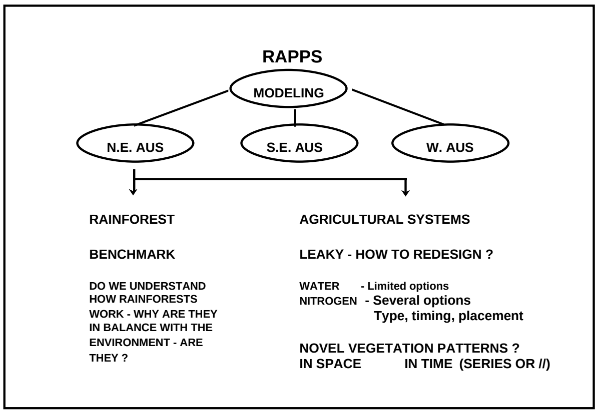


WET TROPICS

AGRICULTURAL SYSTEMS OUT OF BALANCE ?

- **NUTRIENT LOADING OF RIVERS/GROUNDWATERS**
- **NUTRIENT BULGES AT DEPTH**
- **SOIL ACIDIFICATION**
- **SOIL EROSION**
- **……**

Slide 5



RAPPS

RAINFOREST

BENCHMARK

DO WE UNDERSTAND HOW RAINFORESTS WORK - WHY ARE THEY IN BALANCE WITH THE ENVIRONMENT - ARE THEY ?

AGRICULTURAL SYSTEMS

LEAKY - HOW TO REDESIGN ?

WATER - Limited options
NITROGEN - Several options
Type, timing, placement

NOVEL VEGETATION PATTERNS ?
IN SPACE IN TIME (SERIES OR //)

Slide 6

WET TROPICS REVIEW

- SURVEY QUESTIONNAIRE
- LITERATURE SEARCH
- PERSONAL CONTACT / WORKSHOP

Slide 7

WET TROPICS REVIEW - SURVEY

INFORMATION SOUGHT USING QUESTIONNAIRE

1. Project/Experiment Title and Funding Agencies:
2. Principal Supervisor(s):
3. Address/Contact details:
4. Key Project Objectives:
5. Site Location and Key Experimental Measurements:
6. Reports/Publications emanating from the project/experimental work:
7. Summary of project outcomes/major findings:
8. Current state of project/experiment
   (early establishment/ongoing/terminated):

Slide 8

WET TROPICS REVIEW - SURVEY

- 102 questionnaires sent out
  40 returned
- Information obtained of variable value
- Only a few new leads resulted from survey

Slide 9

WET TROPICS REVIEW - LITERATURE SEARCH

- WET TROPICS CHARACTERISTICS
  - LOCATION
  - CLIMATE
  - SOILS
  - LAND USE
  - WATER AND NITROGEN BALANCE
- RAINFORESTS
  - WATER AND NITROGEN BALANCE
- AGRICULTURAL SYSTEMS
  - WATER AND NITROGEN BALANCE
- IMPLICATIONS TO RAPPS

Slide 10

WET TROPICS

RAINFALL
(mm)

INNISFAIL (1881 -1994)

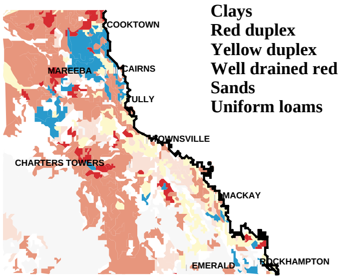
Month	Max	Mean	Min
Jan	3459	563	21
Feb	2505	644	60
Mar	1651	688	87
Apr	1653	487	0
May	1063	335	0
Jun	527	196	0
Jul	506	134	0
Aug	528	117	0 *
Sep	485	94	0 *
Oct	462	83	0 *
Nov	716	156	0 *
Dec	1414	278	10
Annual	7730	3769	1775

EVAPORATION
(mm)

SOUTH JOHNSTONE (1973-1988)

Month	Max	Mean	Min
Jan	246	174	82
Feb	180	136	84
Mar	178	149	109
Apr	141	120	76
May	15	106	84
Jun	121	103	79
Jul	120	106	93
Aug	142	123	86
Sep	171	149	115
Oct	213	176	146
Nov	224	188	144
Dec	229	197	137
Annual	1919	1725	1531

Slide 11

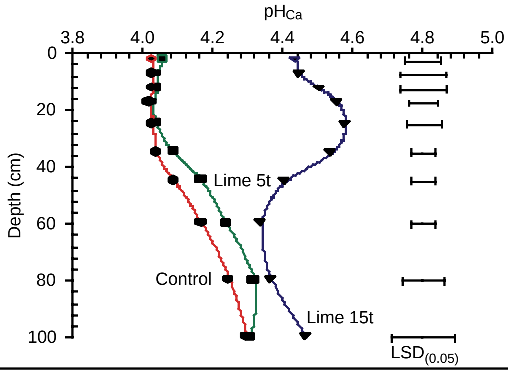


Soils(adapted from CSIRO 1:5 M)

Clays
Red duplex
Yellow duplex
Well drained red-yellow soils
Sands
Uniform loams

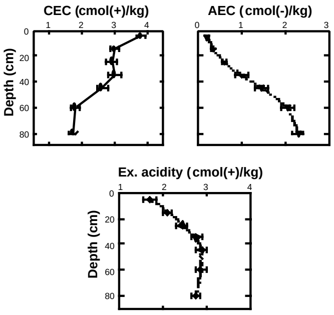
Slide 12

Changes in soil pH under a long-term lime trial: Tully

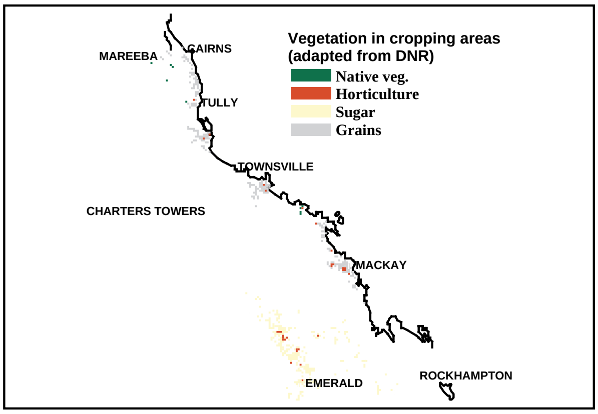


Slide 13

Wet Tropics - variable charge soils



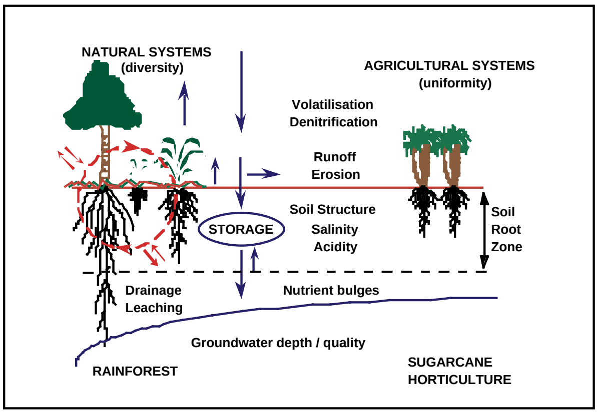
Slide 14



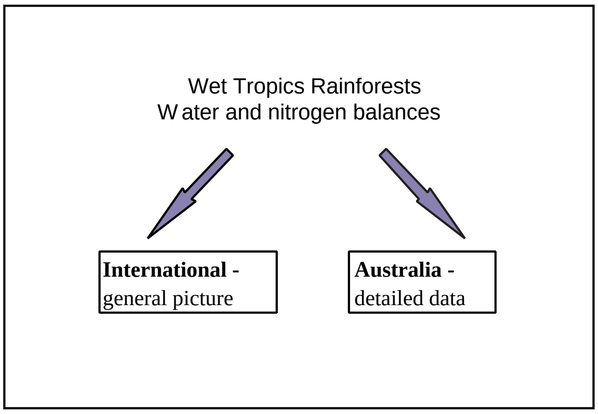
Vegetation in cropping areas (adapted from DNR)

🟩 Native veg.
🟥 Horticulture
🟨 Sugar
▨ Grains

Slide 15



Slide 16

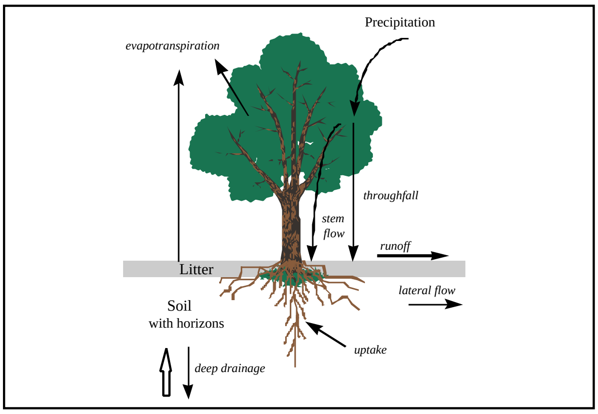


Wet Tropics Rainforests
Water and nitrogen balances

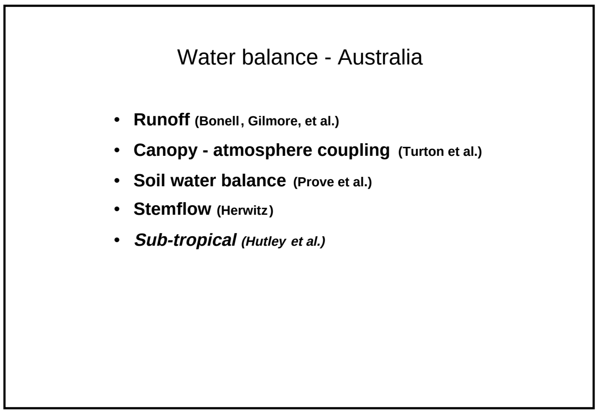
International -
general picture

Australia -
detailed data

Slide 17



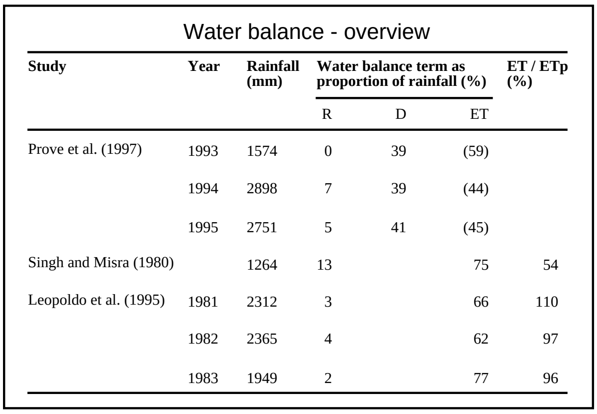
Slide 18



Water balance - Australia

- **Runoff** (Bonell, Gilmore, et al.)
- **Canopy - atmosphere coupling** (Turton et al.)
- **Soil water balance** (Prove et al.)
- **Stemflow** (Herwitz)
- ***Sub-tropical*** *(Hutley et al.)*

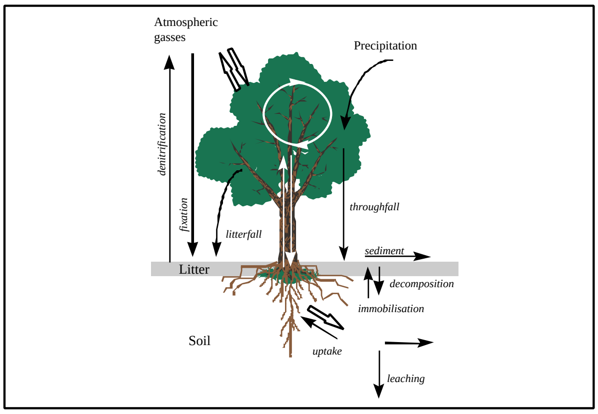
Slide 19



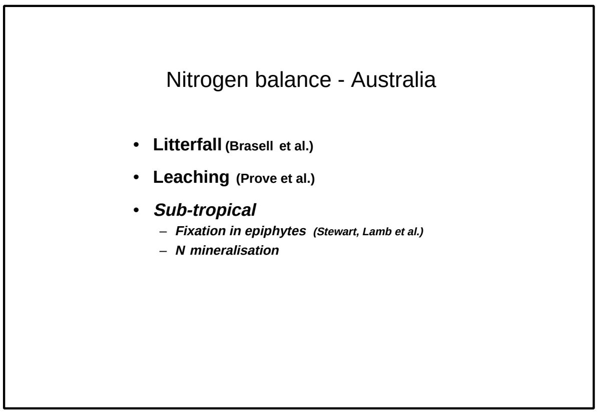
Water balance - overview

Study	Year	Rainfall (mm)	Water balance term as proportion of rainfall (%)			ET / ETp (%)
			R	D	ET	
Prove et al. (1997)	1993	1574	0	39	(59)	
	1994	2898	7	39	(44)	
	1995	2751	5	41	(45)	
Singh and Misra (1980)		1264	13		75	54
Leopoldo et al. (1995)	1981	2312	3		66	110
	1982	2365	4		62	97
	1983	1949	2		77	96

Slide 20



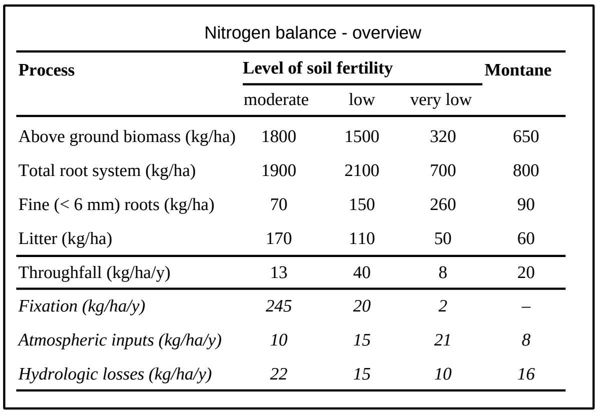
Slide 21



Nitrogen balance - Australia

- **Litterfall** (Brasell et al.)
- **Leaching** (Prove et al.)
- ***Sub-tropical***
  - ***Fixation in epiphytes*** *(Stewart, Lamb et al.)*
  - ***N mineralisation***

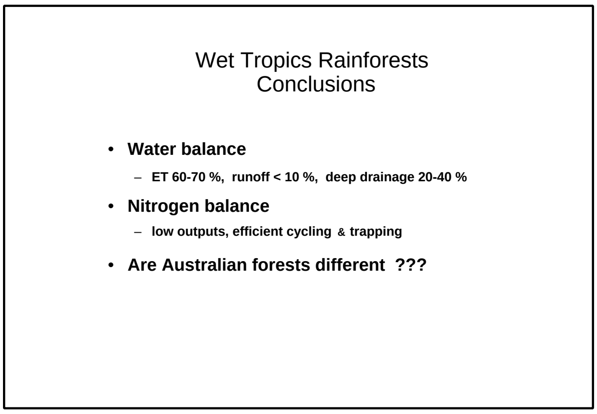
Slide 22



Nitrogen balance - overview

Process	**Level of soil fertility**			**Montane**
	moderate	low	very low	
Above ground biomass (kg/ha)	1800	1500	320	650
Total root system (kg/ha)	1900	2100	700	800
Fine (< 6 mm) roots (kg/ha)	70	150	260	90
Litter (kg/ha)	170	110	50	60
Throughfall (kg/ha/y)	13	40	8	20
Fixation (kg/ha/y)	*245*	*20*	*2*	*–*
Atmospheric inputs (kg/ha/y)	*10*	*15*	*21*	*8*
Hydrologic losses (kg/ha/y)	*22*	*15*	*10*	*16*

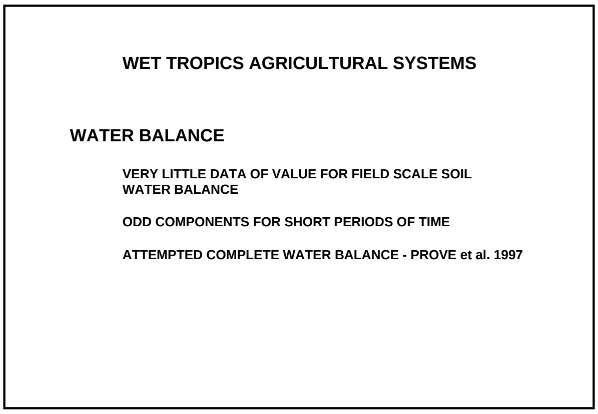
Slide 23



Wet Tropics Rainforests
Conclusions

- **Water balance**
  - **ET 60-70 %, runoff < 10 %, deep drainage 20-40 %**
- **Nitrogen balance**
  - **low outputs, efficient cycling & trapping**
- **Are Australian forests different ???**

Slide 24



WET TROPICS AGRICULTURAL SYSTEMS

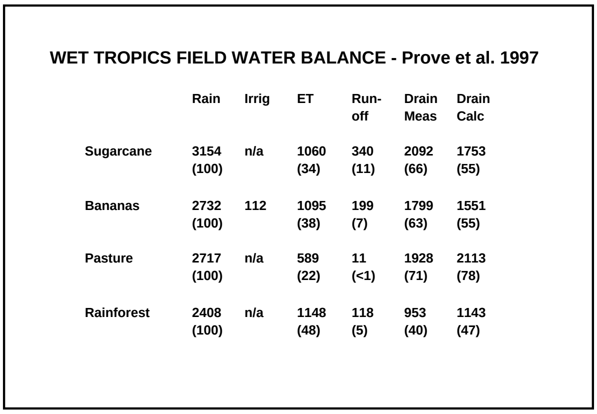
WATER BALANCE

VERY LITTLE DATA OF VALUE FOR FIELD SCALE SOIL WATER BALANCE

ODD COMPONENTS FOR SHORT PERIODS OF TIME

ATTEMPTED COMPLETE WATER BALANCE - PROVE et al. 1997

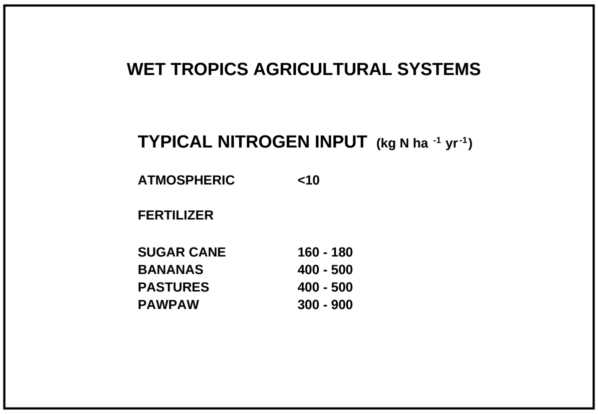
Slide 25



WET TROPICS FIELD WATER BALANCE - Prove et al. 1997

	Rain	Irrig	ET	Run-off	Drain Meas	Drain Calc
Sugarcane	3154 (100)	n/a	1060 (34)	340 (11)	2092 (66)	1753 (55)
Bananas	2732 (100)	112	1095 (38)	199 (7)	1799 (63)	1551 (55)
Pasture	2717 (100)	n/a	589 (22)	11 (<1)	1928 (71)	2113 (78)
Rainforest	2408 (100)	n/a	1148 (48)	118 (5)	953 (40)	1143 (47)

Slide 26

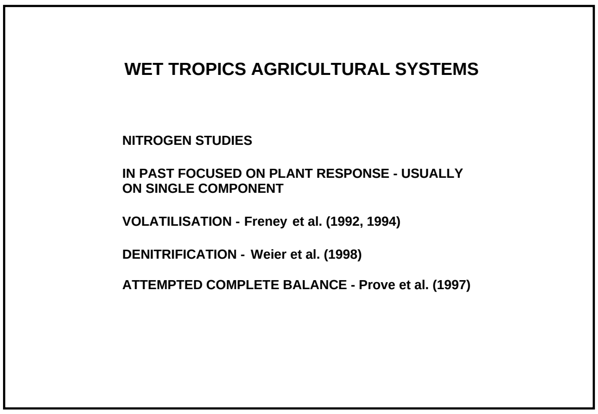


WET TROPICS AGRICULTURAL SYSTEMS

TYPICAL NITROGEN INPUT (kg N ha $^{-1}$ yr^{-1})

ATMOSPHERIC	<10
FERTILIZER	
SUGAR CANE	160 - 180
BANANAS	400 - 500
PASTURES	400 - 500
PAWPAW	300 - 900

Slide 27



WET TROPICS AGRICULTURAL SYSTEMS

NITROGEN STUDIES

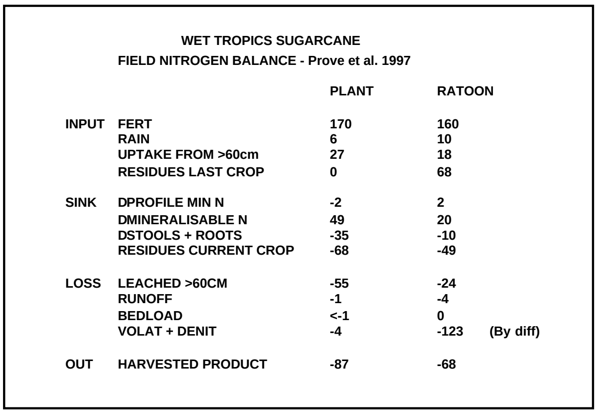
IN PAST FOCUSED ON PLANT RESPONSE - USUALLY ON SINGLE COMPONENT

VOLATILISATION - Freney et al. (1992, 1994)

DENITRIFICATION - Weier et al. (1998)

ATTEMPTED COMPLETE BALANCE - Prove et al. (1997)

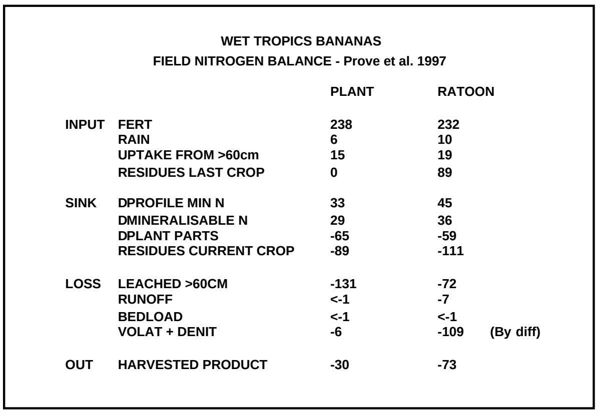
Slide 28



WET TROPICS SUGARCANE
FIELD NITROGEN BALANCE - Prove et al. 1997

		PLANT	RATOON	
INPUT	FERT	170	160	
	RAIN	6	10	
	UPTAKE FROM >60cm	27	18	
	RESIDUES LAST CROP	0	68	
SINK	DPROFILE MIN N	-2	2	
	DMINERALISABLE N	49	20	
	DSTOOLS + ROOTS	-35	-10	
	RESIDUES CURRENT CROP	-68	-49	
LOSS	LEACHED >60CM	-55	-24	
	RUNOFF	-1	-4	
	BEDLOAD	<-1	0	
	VOLAT + DENIT	-4	-123	(By diff)
OUT	HARVESTED PRODUCT	-87	-68	

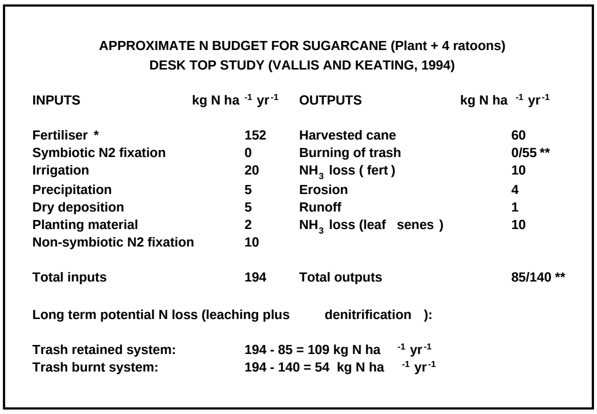
Slide 29



WET TROPICS BANANAS
FIELD NITROGEN BALANCE - Prove et al. 1997

		PLANT	RATOON	
INPUT	FERT	238	232	
	RAIN	6	10	
	UPTAKE FROM >60cm	15	19	
	RESIDUES LAST CROP	0	89	
SINK	DPROFILE MIN N	33	45	
	DMINERALISABLE N	29	36	
	DPLANT PARTS	-65	-59	
	RESIDUES CURRENT CROP	-89	-111	
LOSS	LEACHED >60CM	-131	-72	
	RUNOFF	<-1	-7	
	BEDLOAD	<-1	<-1	
	VOLAT + DENIT	-6	-109	(By diff)
OUT	HARVESTED PRODUCT	-30	-73	

Slide 30



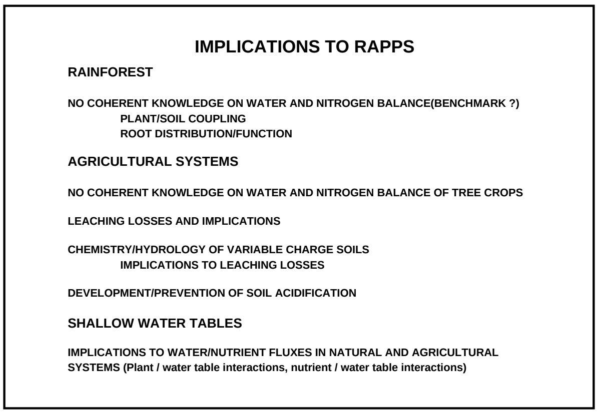
APPROXIMATE N BUDGET FOR SUGARCANE (Plant + 4 ratoons)
DESK TOP STUDY (VALLIS AND KEATING, 1994)

INPUTS	kg N ha^{-1} yr^{-1}	OUTPUTS	kg N ha^{-1} yr^{-1}
Fertiliser *	152	Harvested cane	60
Symbiotic N2 fixation	0	Burning of trash	0/55 **
Irrigation	20	NH_3 loss (fert)	10
Precipitation	5	Erosion	4
Dry deposition	5	Runoff	1
Planting material	2	NH_3 loss (leaf senes)	10
Non-symbiotic N2 fixation	10		
Total inputs	194	Total outputs	85/140 **

Long term potential N loss (leaching plus denitrification):

Trash retained system:	194 - 85 = 109 kg N ha^{-1} yr^{-1}
Trash burnt system:	194 - 140 = 54 kg N ha^{-1} yr^{-1}

Slide 31



IMPLICATIONS TO RAPPS

RAINFOREST

NO COHERENT KNOWLEDGE ON WATER AND NITROGEN BALANCE(BENCHMARK ?)
- PLANT/SOIL COUPLING
- ROOT DISTRIBUTION/FUNCTION

AGRICULTURAL SYSTEMS

NO COHERENT KNOWLEDGE ON WATER AND NITROGEN BALANCE OF TREE CROPS

LEACHING LOSSES AND IMPLICATIONS

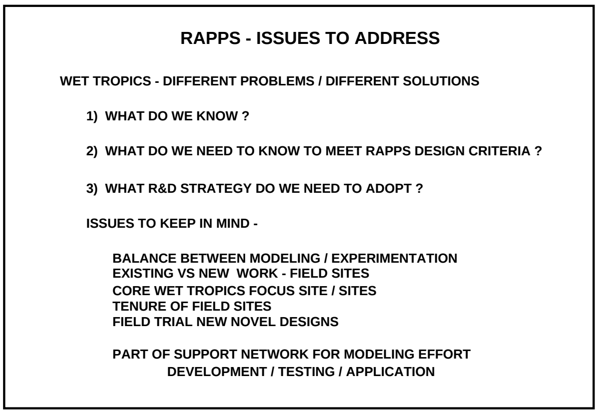
CHEMISTRY/HYDROLOGY OF VARIABLE CHARGE SOILS
- IMPLICATIONS TO LEACHING LOSSES

DEVELOPMENT/PREVENTION OF SOIL ACIDIFICATION

SHALLOW WATER TABLES

IMPLICATIONS TO WATER/NUTRIENT FLUXES IN NATURAL AND AGRICULTURAL SYSTEMS (Plant / water table interactions, nutrient / water table interactions)

Slide 32



RAPPS - ISSUES TO ADDRESS

WET TROPICS - DIFFERENT PROBLEMS / DIFFERENT SOLUTIONS

1) WHAT DO WE KNOW ?

2) WHAT DO WE NEED TO KNOW TO MEET RAPPS DESIGN CRITERIA ?

3) WHAT R&D STRATEGY DO WE NEED TO ADOPT ?

ISSUES TO KEEP IN MIND -

- BALANCE BETWEEN MODELING / EXPERIMENTATION
- EXISTING VS NEW WORK - FIELD SITES
- CORE WET TROPICS FOCUS SITE / SITES
- TENURE OF FIELD SITES
- FIELD TRIAL NEW NOVEL DESIGNS

PART OF SUPPORT NETWORK FOR MODELING EFFORT
DEVELOPMENT / TESTING / APPLICATION

Slide 33