Invasion of *Piper aduncum* in the shifting cultivation systems of Papua New Guinea

Alfred E. Hartemink

ISRIC World Soil Information

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PO Box 353
6700 AJ Wageningen
The Netherlands

CIP-Gegevens Koninklijke Bibliotheek, Den Haag

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"When the war finally came to an end, I was at a loss as to what to do. I took stock of my qualifications. A not-very-good degree, redeemed somewhat by my achievements at the Admiralty. A knowledge of certain restricted parts of magnetism and hydrodynamics, neither of them subjects for which I felt the least bit of enthusiasm. No published papers at all. Only gradually did I realize that this lack of qualification could be an advantage. By the time most scientists have reached age thirty they are trapped by their own expertise. They have invested so much effort in one particular field that it is often extremely difficult, at that time in their careers, to make a radical change. I, on the other hand, knew nothing, except for a basic training in somewhat old-fashioned physics and mathematics and an ability to turn my hand to new things... Since I essentially knew nothing, I had an almost completely free choice... "

Francis Crick
What Mad Pursuit
Basic Books, New York, (1988)

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Foreword

The invasion of the shrub, *Piper aduncum* or bamboo piper, is having major ecological, economic, sociological, nutrient, and botanical impacts in Papua New Guinea. The author, Alfred Hartemink, is an outstanding soil scientist and ecologist and who has spent 10 years investigating the impact of this invasive plant on the natural environment and economy of Papua New Guinea.

Piper aduncum was introduced many years ago onto the island from South America as well as many other regions of the world, including Florida. It is a related bamboo species and has some value as a traditional medicine and other agroforestry benefits, like biomass fuel. The shrub or small tree grows rapidly under favorable conditions. For example, in the humid lowlands of Papua New Guinea, the shrub produced an average of 24 tons of biomass in nearly one year.

After New Guinea farmers remove the primary forest growth, plant their crops for two or three years, and then abandon the land, *Piper aduncum*, invades the land, completely dominates all the vegetation, and becomes a thicket. As Hartemink reports, the growing bamboo piper rapidly removes fertilizer nutrients, including nitrogen, phosphorus, and potassium from the soil. This invasive bamboo piper does provide fuel biomass for the rural people, as well as rapid cover over the land to protect it from soil erosion. Although *Piper aduncum* has some value in agroforesty, it is generally considered an invasive weedy shrub or tree.

In general, invasive species of plants, animals, and microbes are second only to the environmental impacts of human populations on earth, and generally considered more serious than the problem of global warming. Invasive plants, such as bamboo piper, cause major ecological and economic impacts in the U.S. and elsewhere in the world. Invasive plants may displace native plants by various means, including competition. After major reductions in numbers of native plants, all the animal and microbe species associated with the displaced or lost native plant species are also lost or severely reduced in number.

In the United States, an estimated 50,000 species of plants, animals, and microbes have been introduced and are causing an estimated $137 billion in damage and control costs per year. There the invasive species are causing the extinction of about 40% of the native plants, animals, and microbes. This extinction impact is second only to human population impacts.

Hartemink conveys a detailed evaluation of the diverse effects of the invasion of bamboo piper and makes clear how such invasions alter both agriculture and the natural environment. In particular, the island ecosystem provides a unique area in which to investigate the diverse impacts of invasives.

Prof. David Pimentel
Cornell University, USA
April 2006

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Preface

In 1995, I arrived in Papua New Guinea to take up the position of lecturer in soil science at the University of Technology in Lae in the Morobe Province. The position embraced a teaching and research component and the university encouraged interaction with other scientific disciplines like forestry, entomology and ecology. Being new in a country where there were only a handful of soil scientists and keen to see the country-side, I took the first opportunity to get to the field. That came soon.

Within a week after my arrival, I was taken to the experimental sites of a Dutch forest ecologist at about one hour drive from the university. He showed me soil erosion measurement plots in an area where shifting cultivation was common. Soils were young and rich, and with more than 4,000 mm rain per year you could almost watch plants growing. Despite the heavy rainfall and the fairly steep sloping land, there was relatively little soil erosion in the vegetated plots. At that first day in the field I was not particularly taken by those findings but was absorbed by the surrounding rainforest – that massive cathedral of all colour greens, those giant broccolis.

In several places, the rainforest was cleared and smallholder farmers had planted plots with taro, sugar cane and sweet potato. As in many shifting cultivation areas in the humid tropic, the landscape was a mosaic of untouched forest, cultivated plots and secondary regrowth. The secondary fallow vegetation was dominated by a single species, a few metres high, lush green and in massive dense stands: *Piper aduncum*. It was the first time I saw such stands of this shrub; its peculiar smell was everywhere.

When we drove back to the university, I saw stands of *Piper aduncum* on all fallow land but also on road-cuts and it was also the first plant revegetating fresh landslides. The Dutch forester told me that *Piper aduncum* is indigenous in South America and that little was known about it. Whilst driving through the patchwork of forest, crops and fallow land we wondered how it got there, why it was so successful, and how it affected the cropping phase. Those questions formed the start of an intriguing research journey.

Later on that week, a group of foresters and ecologists told me that the spread of *Piper aduncum* was closely linked to selective logging of the rainforest. Some farmers around the university told me it has always been there, whereas others remembered that their relatives brought it in from other parts of the country. Many farmers claimed that *Piper aduncum* fallows affected their cultivation systems: some liked it, some didn't, some said it dries out the soil, whereas other mentioned that *Piper aduncum* fallows give the soil a lot of "grease" – that is a high soil fertility and high yielding crops once the fallows are cleared and crops are planted. Some of my colleagues viewed *Piper aduncum* as an insignificant weed that sooner or later would be taken over by natural fallow vegetation, whilst others hadn't noticed its presence. It seemed that little research was being conducted on *Piper aduncum* in the shifting cultivation systems.

It took several months of thinking, discussions and research fund applications before serious field experiments could be started. Coming from Western Kenya, where we had worked on natural and improved fallows in on-farm experiments, I looked for a site in which experiments could be conducted in between farmers' fields, but in which all operations (harvesting, planting, weighing of produce etc.) were researchers-managed. With the help of various people and Drs Mark Johnston and Mike Bourke we found such site: near the primary school and health post in Hobu.

In Hobu, *Piper aduncum* was overwhelmingly present, farmers were keen to cooperate, and it was close to the university. From then on, I spend at least a day per week at Hobu – mostly for the research but also as part of field practicals for the soil science and ecology courses that I was teaching. Farmers in Hobu agreed to clear about half a hectare and plots were laid out to investigate the effects of different fallows on sweet potato, which is the main staple crop in the area. Other plots were laid out to investigate biomass and nutrient accumulation of *Piper aduncum* and other fallow vegetation types. A weather station was installed near the health post. The school was involved in managing the plots and various farmers assumed responsibility for parts of the experiments.

We also started a series of nutrient management experiments at Hobu as well as the university experimental farm with sweet potato, taro and maize. The experiments included various rates and types of inorganic fertilisers and poultry litter with the idea to compare the results with the fallow trials and in order to intensify the predominant shifting cultivation systems. Although about two-third of the area was under primary forest, sooner or later farmers had shift to more permanent farming systems including the use of inorganic fertilisers and other amendments.

Although the running of all these experiments and data analysis took most of my research time, investigations on the invasion of *Piper aduncum* continued. Some were more successful than others. We looked into ecological aspects of the invasion and started a seed bank trial using soils from different areas. Spectacular differences were found. A greenhouse trial was started using soils in trays covered with *Piper aduncum* litter and in which lettuce and other vegetables were sown. The idea was that the litter contained substances that were toxic to seedlings of other plan species – the so-called allelopathic effect. All vegetable seeds germinated and grew perfectly, although chemically analysis and the literature suggest showed that *Piper aduncum* leaves could have such effect.

We continued to look on the questions of its invasion: how could an exotic species be so successful and when was it actually imported or had it be brought in by accident? Our research was started when the internet emerged in Papua New Guinea and I thank many contacts and information sharing through that electronic network. Contact with botanists and ecologist in different parts of the world increased the knowledge on the origin and spreading. At the time of the experiments, awareness on the spread of *Piper aduncum* grew from other disciplines (e.g. pharmacology, entomology, quarantine experts, taxonomy). It was exciting to follow the research from people with different disciplines focussing on the same plant and issue: the invasion of *Piper aduncum*.

Through the years we quantified some basic characteristics on *Piper aduncum* and published a series of papers. This book brings the major research papers together supplemented with an introduction and a set of conclusions. The papers have been loosely grouped in four parts. In the first part, the origin and spreading of *Piper aduncum* is described, including a general introduction on bioinvasion and *Piper aduncum* in different parts of the world. In the second section, biomass and nutrient characteristics are summarised and much of this information was unknown whereas it largely affects the management of nutrient the in shifting cultivation systems. The third part brings together the papers on nutrient management of sweet potato in Papua New Guinea; there are papers on nutrient deficiencies, nutrient use efficiency and the effects of different fallows on sweet potato. The last section focuses on some of the socio-economic effects of the *Piper aduncum* invasion - a research area which has received little attention, both nationally and internationally. The book ends with some conclusions including ideas for future research, followed by colour plates of *Piper aduncum*.

During the past 10 years, I have been in contact with many people discussing the issue of plant invasion and especially that of *Piper aduncum*. The discussions influenced the research, the writing of our papers but also increased my knowledge on bioinvasion and shifting cultivation. I was in contact with botanists, herbarium directors and sociologists and for an ordinary soil scientist such interaction was enlightening. During fieldwork I was in close contact with villagers in the Hobu area where the on-farm trials were conducted between 1996 and 1998. I would like to thank the people in the Hobu area for their great support and interaction. There was no difficulty in explaining the use and meanings of the on-farm experiments as farmers in the area had lived with the *Piper aduncum* dominance in the fallow vegetation for many years and farmers' opinions steered the research.

Several students from the University of Technology were involved in the on-farm experiments at Hobu. I wish to thank Mr Wesley Julius, Mr Anthony Kerru, Mr Rauke Buimeng, Mr Otto Ngere, Mr Philip Vovola, and Mr Awepsta Seka for all their help and great time in the field. Technical assistance of Mr Spencer Poloma, Mr Gelang Gwaidong, Mr Maquin Maino, Mr Joshua Yauwo, Mr David Arapi, Mr Vui Kila and Mr Hendry Gindo of the University of Technology in Lae is greatly acknowledged.

I am very grateful to Drs Bryant Allen, Mike Bourke and Robin Hide of the Australian National University (ANU) in Canberra with whom I have had many stimulating discussions. They were always keen to share their vast knowledge about Papua New Guinea and I thank them for the hospitality and the months spent as Visiting Fellow at ANU in 1999, 2003 and 2004. Dr Jan Veldkamp and Prof. Pieter Baas of the National Herbarium are thanked for the help in searching through their specimens database. Thanks to my co-authors Dr Rogers, Dr Jane O'Sullivan, Mr Spencer Poloma, Mr Maquin Maino, Dr Powell, Mr Joe Eganae, Dr Robin Hide, Dr Mark Johnston, Dr Mike Bourke, Mr Chris Walo, Mr Thomas Siges, Dr Paul Hebinck and Dr Bryant Allen for our joint papers. I furthermore wish to thank Mr Tine Ningal for his help in putting this book together, Dr David Dent is for his overall support and Drs Hans van Baren for commenting on the manuscript.

The research described in this book was funded through grants from the Research Committee of the University of Technology in Lae, and through ACIAR Project 9101 on 'Mineral Nutrition of Root Crops in the Pacific' and its successor LWR2/96/162 ('Correction of nutritional disorders of sweet potato in Papua New Guinea and North Queensland'). The research would not have been possible without those grants

All in all, it has been an exciting 10-years research journey, a bit wobbly at times, but highly enjoyable. Joy may be enough to stimulate research and advance a publication record, but for any academic sensitive to real-world issues that is insufficient. It is therefore my hope that the research described in this book will encourage more detailed and more spatial investigations and that the results will help to alleviate the constraints of the poor smallholder farmers in areas where *Piper aduncum* dominates the fallow vegetation. Moreover, I hope that this book will contribute to the difficult discussion on the use and need of biodiversity in areas of plant invasion and increasing agricultural activity.

Alfred E. Hartemink
Amsterdam-Wageningen
April 2006

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Part I
Invasion of *Piper aduncum* in Papua New Guinea

Chapter 1
Hartemink, A.E. and Hide, R. Bioinvasion and *Piper aduncum* (unpublished)

Chapter 2
Rogers, H.R. and A.E. Hartemink, 2000. Soil seed banks and growth rates of an invasive species, *Piper aduncum*, in the lowlands of Papua New Guinea. Journal of Tropical Ecology, 16: 243-251.

1. Bioinvasion and *Piper aduncum*

1.1. Bioinvasion

A major component of human-induced global change is the deliberate or accidental translocation of plants and animals from their native ranges to alien environments, where they may cause substantial environmental and economic damage (Blackburn and Duncan, 2001). This book focuses on plant invasion, which has been defined by Cronk and Fuller (2001): an alien plant spreading naturally (without the direct assistance of people) in natural or semi natural habitats to produce a significant change in terms of composition, structure or ecosystem process. Plant invasion is recognised as an important component of the global biodiversity crisis which contains, amongst others, a loss of species and habitats. Some have argued that it is a threat more ominous than the greenhouse effect, industrial pollution or ozone depletion (Mack *et al.*, 2001).

Successful invasions tend to be concentrated in certain regions, especially islands and the temperate zone, suggesting that species-rich mainland and tropical locations are harder to invade because of greater biotic resistance – the so-called biotic resistance hypothesis (Blackburn and Duncan, 2001). Some plants are highly successful in new territories whereas other never make it outside their own specific habitat (Van der Putten, 2002). Mechanisms such as competition, resources partitioning, dispersal ability and predation tolerance explain some - but not all - of the abundance of plant species under field conditions (Klironomos, 2002). Experiments have shown that natural plant abundance is related to the different rates at which soil pathogens develop to the roots of bioinvasive species. In their new territories, plants are liberated from their native soil community which results in two benefits: the invading plants escape from their soil pathogens but do not encounter new, species-specific ones. Secondly, mycorrhizal fungi can associate with a broad range of plant species meaning that root symbionts are likely to be available to the invader (Van der Putten, 2002). So plant invaders greatly benefit from the escape of their soil pathogens and benefit from new symbiont associations and soil communities are therefore an important regulator of plant community structure (Klironomos, 2002).

Human activities greatly influence the spreading and invasion on new plants in new environments. This book deals with the invasion of *Piper aduncum* in Papua New Guinea. The plant is probably deliberately introduced, is widely spread now and affects the shifting cultivation systems in the humid lowlands.

1.2. Papua New Guinea

Papua New Guinea is the largest tropical island and because of a great range in climate and topography it has a high diversity of both fauna and flora. Paijmans (1976) gave an overview of the vegetation and provides a wealth of information on the geographical and altitudinal distribution of the flora in Papua New Guinea. The forests of Papua New Guinea are as rich in species as those in Borneo or Malaysia, and richer than the African and South America forest (Paijmans, 1976). Due to logging activities and the expansion of additional cropland and agricultural plantations, forest areas have considerably declined over the past decades (Freyne and McAlpine, 1987; McAlpine *et al.*, 2001). Ningal *et al.* (submitted) found that forest areas in the Morobe Province (34,000 km^2) decreased from 78 to 66% between 1975 and 2000. In addition to the loss of forest cover, there have been changes in the composition of secondary forest vegetation due to invasive plant species.

An overviews of exotic plant species in Papua New Guinea have been given by Orapa (2001) and by Waterhouse (2003), following the earlier account of Henty and Pritchard (1988). Salvinia (*Salvinia molesta*), a small water fern, and the water hyacinth (*Eichhornia crassipes*) aggressively invaded waterways but biological control has been successful (Orapa, 2001). Important introduced plants that are found in various parts of Papua New Guinea include *Rottboelia cochinchinensis*, *Sida acuta*, *Sida rhombifolia*, *Cyperus rotundus*, *Pennisetum purpureum*, *Imperata cylindrica*, *Mimosa invisa*, *Mimosa pudica*, *Mikania micarantha* and *Eicchhornia crassipes*. Orapa (2001) considers the following invasive species to become widespread weeds: *Chromolaena odorata*, *Mimosa pigra*, *Melinus minutiflora*, *Clerodendrum chinensis*, *Partheniu hysterophorus*, *Stachytarpheta urticifolia*, *Sorghum halepens*, *Spathodea campanulata* and *Azadirachta indica*. *Piper aduncum* is also listed by Orapa (2001) as a newly introduced plant and as he wrote ".. has the potential to become an aggressive invader."

Piper aduncum was not recognised as widespread in the early 1970s, but by the 1980s and 1990s, *Piper aduncum* was very common in the lowlands of Morobe and Madang Provinces, and was also appearing in the Central Highlands up to about 2,000 m a.s.l. *Piper aduncum* is frequently observed on fallow sites where it often forms monospecific stands and is also found along logging tracks. This chapter reviews current knowledge on *Piper aduncum* in Papua New Guinea, and has the following objectives: (i) to review the presence of *Piper aduncum* in Asia and the Pacific, (ii) to trace its spread through Papua New Guinea based on botanical, ecological and ethnopharmacological literature, oral history, images, and herbaria collections, and (iii) to discuss explanations for its success. In the subsequent chapters its impact on farming systems and rural livelihoods.

1.3. *Piper aduncum* globally

Piper aduncum was first described scientifically in 1753 by Linnaeus. The plant was known before 1753 (the starting point for nomenclature) for Linnaeus cites three references, namely Plumier, van Royen and Sloane. The original material was collected in Jamaica.

Piper aduncum is a shrub or small tree with alternate leaves and spiky flowers and fruits. It occasionally reaches a height of 7 to 8 m, and has very small seeds which are mostly dispersed by the wind, fruit bats and birds but also by people and logging equipment. The commonest synonyms include *Piper angustifolium, Piper celtidifolium, Piper elongatum, Piper multinervium*, and *Piper stevensonii,* but there are tens of other synonyms for *Piper aduncum.*

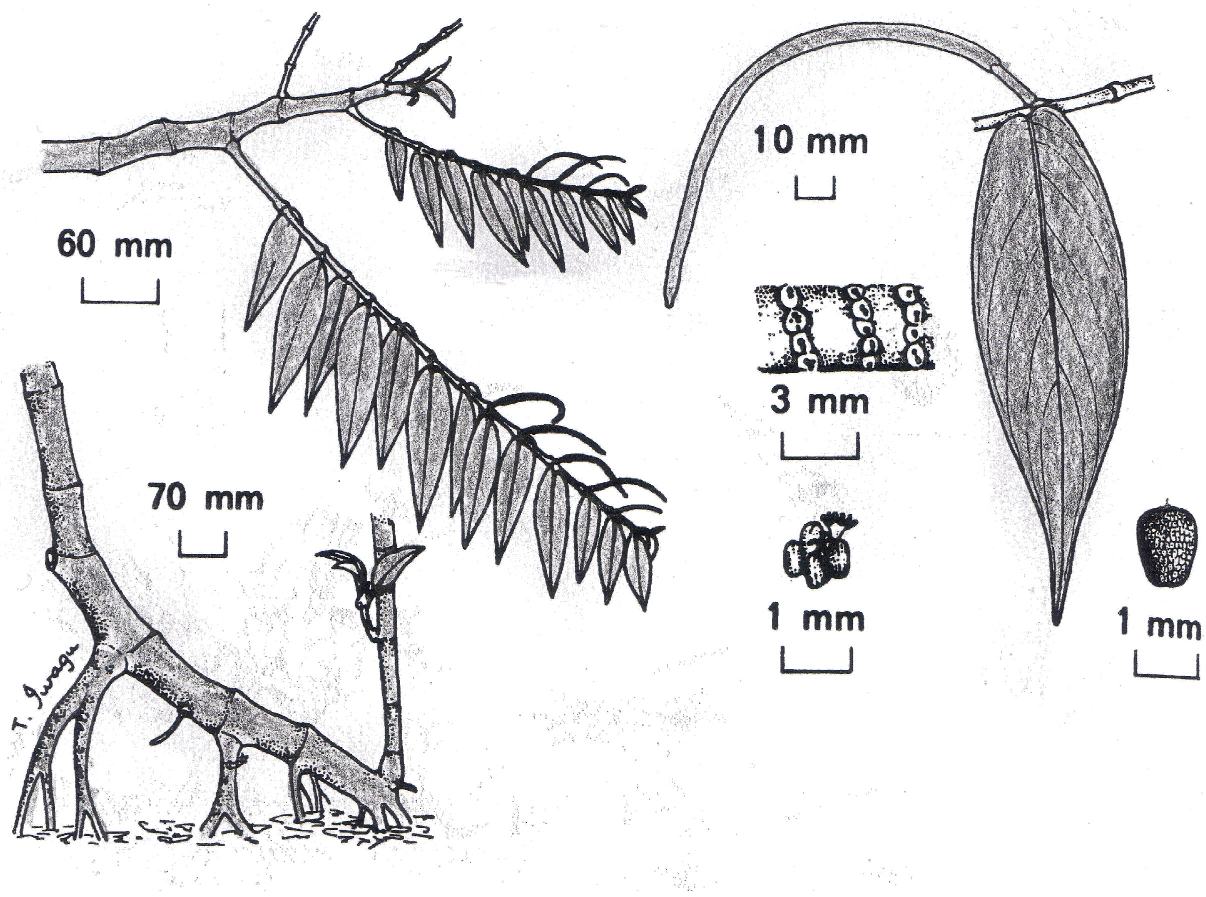

Fig. 1. *Piper aduncum (L)*, stems, leaves, fruits, and seeds. From: Weeds of New Guinea and their Control, by Henty and Pritchard (1988)

Piper aduncum occurs in South and Central America, in North America, south east Asia and Pacific; as far as I know it is not present in Africa. *Piper aduncum* is indigenous to tropical America where it is found from Mexico to Bolivia. It is common throughout Central America where it is found between sea level and 2,000 m a.s.l. along road sides and in forest clearance areas on well drained soils. Its habitat is restricted to evergreen vegetation and near watercourses in seasonally deciduous forests. It occurs in Mexico, Panama, Surinam, French Guiana, Puerto Rico, Cuba, Trinidad and Tobago, Martinique, St. Vincent, Dominican Republic and Jamaica and is very common in Costa Rica on open or partly shaded sites (Burger, 1971; Cicció and Ballestro, 1997; Olander *et al.*, 1998).

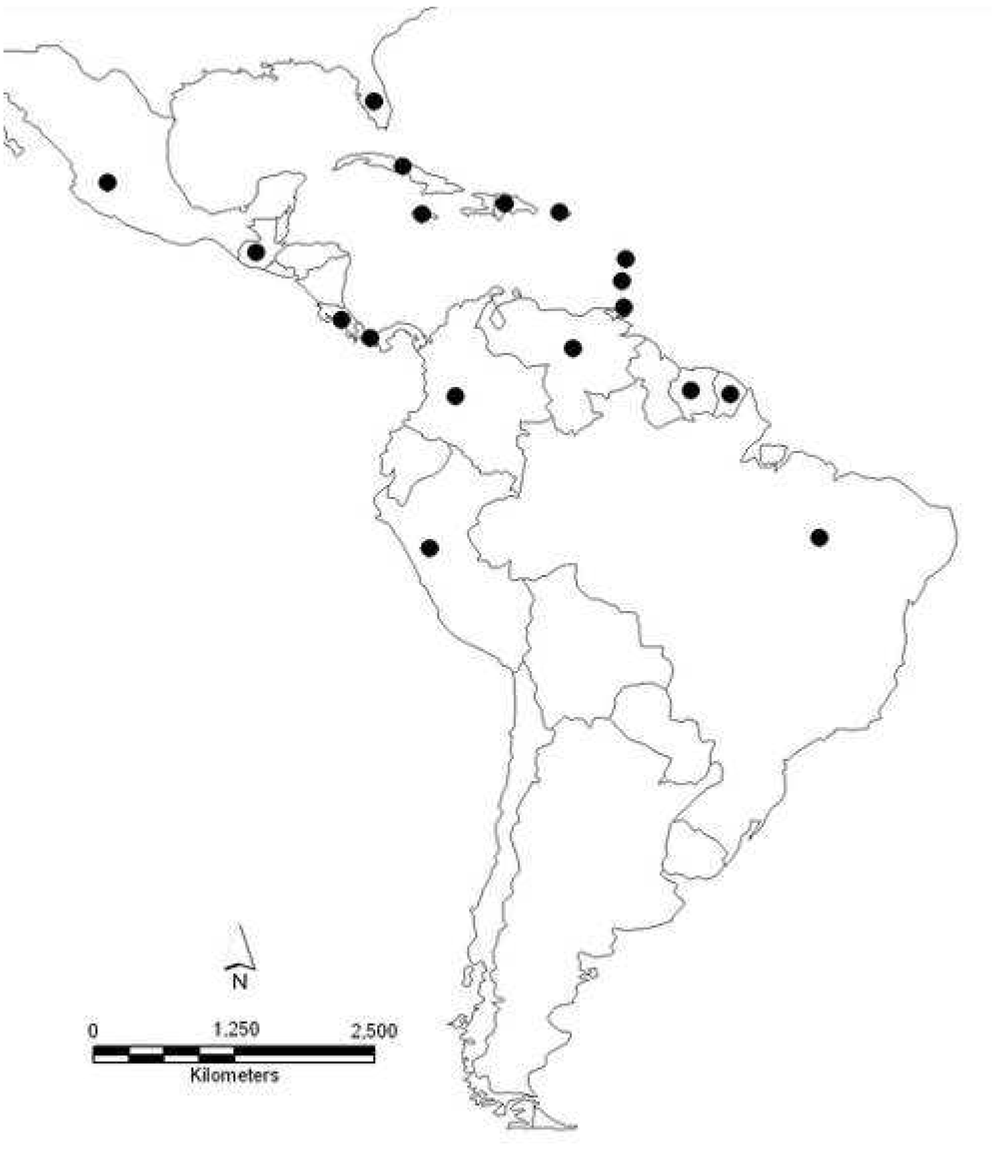

Fig. 2. *Piper aduncum* in Central and South America and the Caribbean. It has been reported in Mexico, Costa Rica, Guatemala, Panama, Brazil, Colombia, Peru, Venezuela, Surinam, French Guyana, Cuba, Trinidad and Tobago, Jamaica, Martinique, St Vincent, Dominican Republic, but also in Southern Florida and Puerto Rico (USA)

It has been described in Guatemala, Colombia, Venezuela, Brazil, and in Southern Florida (Bornstein, 1991) where it is on the unwanted weed species list. It is often represented in tropical indoor-greenhouses in North American gardens (personal communication, A. Bornstein, 1998) and in the USA its leaves and seeds are sold for medicinal purposes commercially via the internet (e.g. www.tropilab.com/spikedpepper.html).

In Central and South America, *Piper aduncum* may be locally abundant but the species rarely dominates the vegetation (R. Callejas, University of Antoquia, 1999, pers. comm.) nor is it found in mature vegetation. In the Amazon areas (Brazil), it has been reported as an invading plant after timber exploitation (Maia *et al.*, 1998).

1.4. *Piper aduncum* in south east Asia

Piper aduncum was introduced to the Botanical Gardens of Bogor (Indonesia) in the 1860s – possibly as an ornamental. It is not known where the plants or seeds came from nor by whom it was introduced. By the 1920s, however, *Piper aduncum* commonly occurred in a radius of 50 to 100 km around the Botanical Gardens in young secondary vegetation, close to rivers and on very steep slopes, locally in dense stands up to 1000 m a.s.l. (Heyne, 1927).

Some idea of its spread in Indonesia can be obtained from specimens at the National Herbarium in Leiden (The Netherlands), which were examined in January 2005 (Table 1). The herbarium has 112 specimens collected in 16 countries; 51 specimens are from Indonesia, 23 from elsewhere in Asia and the Pacific, 31 from South and Central America, and 7 from unknown locations. The earliest specimens were collected in Puerto Rico in 1827 and in Surinam in 1837, whereas the most recent additions date from the 1980s. The first Leiden specimen from Indonesia was collected in 1888 at the Botanical Gardens in Bogor. In total 23 specimens have been collected from other parts of West Java but the herbarium has no specimens from Central or East Java.

In the late 1930s, it was collected in South Sumatra, in the 1950s in West Sumatra, and in the 1970s in North Sumatra. It is probable that the plant had crossed the Sunda Street in the 1930s and spread to the West and East in the following decades. In West Papua (Irian Jaya), it was collected at Biak and Jayapura in the 1950s. On Kalimantan it was first collected in 1952 near Samarinda, whereas in the Moluccas and Sulawesi it was collected in the 1970s and 1980s. Recent surveys have confirmed *Piper aduncum* currently near Jayapura, Nabire and Sorong in West Papua (Waterhouse, 2003) and in Kalimantan (Hashimotio *et al.*, 2000) and Sulawesi (Lee and Riley, 2001).

Table 1. Overview of *Piper aduncum* specimens at the National Herbarium Leiden (Netherlands) grouped by country and province, and first year of collection

Country	Province/region	Number of specimen	Year	Location
Indonesia	Java	23	1888	Bogor (West Java)
			1925	Jakarta (West Java)
			1932	Pelabuan Ratu (South west Java)
			1937	West Banten (West Java)
			1948	Bandung (West Java)
			1959	Gunung Salak (West Java)
			1963	Ujong Kulong National Parc (West Java)
	Sumatra	12	1939	Lampung (South Sumatra)
			1953	Padang (West Sumatra)
			1973	Bukit Lawang (North Sumatra)
			1979	Gunung Leuser (North Sumatra)
			1982	Bukit Tingi (West Sumatra)
	Kalimantan	8	1952	W Samarinda
			1981	Balikpapan
	Sulawesi	1	1985	Dumola Bone
	Moluccas	1	1974	?
	West Papua	6	1955	Waigeo island
			1957	Jayapura
			1960	Biak
Malaysia	Selangor	6 (total)	1960	
	Kuala Lumpur		1968	Gombak
Papua New Guinea	Morobe	10 (total)	1935	Heldsbach
			1952	Lae, Botanic Gardens
			1964	Pindiu, Mongi valley
			1977	Wau-Bulolo road
	Central		1970	Koiari
			1980	Near Sogeri Local government
	Manus		1971	Los Negros Island
Fiji	Viti Levu	3 (total)	1953	
	Vatuwaqa		1955	
Solomon Islands	Ghairanu	3	1969	Nuta river area
Philippines	Manila	1	1929	(by M Clemens)
USA-Puerto Rico		3	1827	
Surinam		6	1827	
Tobago		3	1889	
Colombia		1	1900	
West Indies		1	1904	
Guatemala		3	1906	
Mexico		7	1865/1909	
Peru		1	1947	
Belize		1	1973	
Brazil		5	undated	

In Malaysia it was present in the 1960s (Allen, 1966; Chew, 1972) and currently there are large areas under *Piper aduncum* in the Genteng Highlands and along the road to Kuala Lumpur (observed by Hartemink in 2000). It has been recorded in Singapore in 2003 (pers. comm. J. Vermeulen, 2005). The botanist Mary Clemens collected *Piper aduncum* near Manila in the Philippines in 1929, of which a specimen is in the Leiden Herbarium. She also was the first person to describe *Piper aduncum* in Papua New Guinea (Fig. 4).

1.5. *Piper aduncum* in the Pacific

There are several economically important piper species in the Pacific, including *Piper nigrum (*pepper), *Piper methysticum* (kava), and *Piper betle* of which the fruits are used with betel nut (*Areca catechu*) in Papua New Guinea (Bornstein, 1991). In 1988, Swarbrick (1997) surveyed weeds of Pacific Islands countries and territories, including American Samoa, Cook Islands, Fiji, Kiribati, Nauru, New Caledonia, Solomon Islands, Tonga, Tuvalu, Vanuatu, Western Samoa, Yap, Chuuk, Pohnpei in the Federate States of Micronesia, and Guam and Palau. His report listed 517 species of weeds that have been recorded in the Pacific Islands and provided details on the 18 most important weeds and methods of control. *Piper aduncum* was nót amongst these 18 and was only listed as occurring in Fiji and in the Solomon Islands. In both countries it occurred in pastures and on wastelands and along roadsides (Swarbrick, 1997).

Piper aduncum is widespread in the wet and intermediate zones of Viti Levu in Fiji (Parham, 1972; Smith, 1981). In Fiji it is named 'false kava' and is locally known as *yagoni ni onolulu*. It was first recorded in 1926 (Smith, 1981) and is thought to have arrived with packing materials at the port of Suva, as it seems to have spread out there along roadsides (Englberger, 2001). Contrary to the findings of Swarbrick (1997), *Piper aduncum* is present on Vanuatu where it also named 'false kava' (Englberger, 2001). *Piper aduncum* has been recorded as a naturalised species on Christmas Island, and also occurs on Hawaii (Maui) where it is on the noxious weed list. There was no *Piper aduncum* on Hawaii in the late 1970s, according to Smith (1981).

Piper aduncum is present near Kombe and the Nuta River area in the Solomon Islands where it was described in 1969 (Harvard University Herbarium, pers. comm., 1999) thus confirming the survey by Swarbrick (1997). Swarbrick's survey (1997) has been updated by Space and colleagues. They have resurveyed Micronesia, American Samoa, Niue, the Marianas, Tonga, Samoa, the Cook Islands, and Palau, under the aegis of the Pacific Island ecosystems at Risk (PIER) project (Space, 2002).

Although there was some confusion about the identification of *Piper aduncum*, the surveys showed that it was widely spread throughout all surveyed countries.

Piper aduncum is not present in the humid coastal regions of northern Australia but is on the list of unwanted weed species by the quarantine service (Waterhouse and Mitchell, 1998). Like many weeds, it may already be present and only awaiting discovery (Waterhouse, 2003).

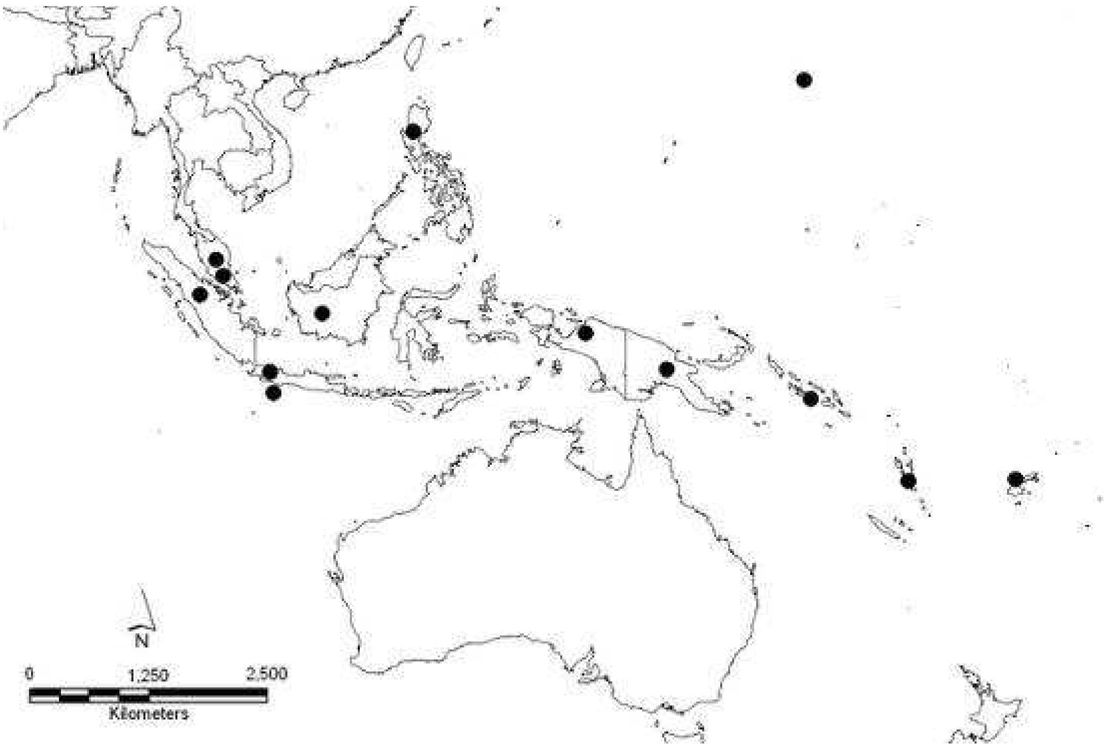

Fig. 3. *Piper aduncum* in South East Asia and the Pacific. It has been reported in: Malaysia, Indonesia, Philippines, Papua New Guinea, Solomon Islands, Vanuatu, Fiji, but also in Hawaii (USA), Micronesia, American Samoa, Niue, the Marianas, Tonga, Samoa, the Cook Islands, and Palau (not all on the map)

1.6. *Piper aduncum* in Papua New Guinea

It is not known precisely when or how *Piper aduncum* arrived in Papua New Guinea. Two theories could be explored based on accidental or deliberate introduction from the east (Pacific) or from the west (Indonesia, south east Asia). *Piper aduncum* could have island hopped from its origin in Central America across the Pacific via Hawaii, or Fiji, where it was found in the 1920s and was brought in through Suva (Englberger, 2001). Seeds could have been transported by travellers or perhaps in the tyres of military trucks and machinery. Kidd (1997) surveyed *Piper aduncum* in the Wau Area of Morobe Province and suggested that it may have been introduced during the Second World War possibly via Finschhafen. However, that is not the case as Mary Clemens first observed *Piper aduncum* in 1935 near the Heldsbach mission station near Finschhafen (Table 1). Even though it was already present on the Huon Peninsula before the Second World War, further importations to Papua New Guinea may have occurred during the war, either accidentally as just explained, or deliberately. The Americans built many roads around Port Moresby and the story goes that *Piper aduncum* was planted as a slope stabiliser to prevent soil erosion.

Alternatively, it may have arrived in Papua New Guinea from Indonesia via West Papua. It had been introduced in the 1860s on West Java (Bogor) and was intentionally, or by accident, taken to West Papua (with the first botanical records dating to the 1950s – see Table 1). The plant could have moved along the north coast of New Guinea from Jayapura to Vanimo and Wewak, and then further east to Heldsbach – the Lutheran mission station where it was described by Mary Clemens in 1935. It may have been transported or imported by missionaries for use as erosion control on steep slopes. In the Dutch East Indies, contour planting was actively promoted by the government in the late 1800s.

Fig. 4. The botanist Mary Knapp (nee Strong) Clemens (1873-1968) who first described *Piper aduncum* near the mission post Heldsbach in the Morobe Province of Papua New Guinea. Left picture: Mary Clemens and Alaseu. Photograph taken by Reverend Bergmann of the Boana Mission at Mt. Saruwaged in the Morobe Province. Clemens spent April through June 1939 in this camp and then spent two weeks at the timberline, ascending the two summits with Alaseu as her only companion. On the back of the photograph it says: "*Alaseu's smile, put on for the photo, or he was thinking of the proud moment when he captured a walla-walla bare handed.*"

Below is a summary of the literature on *Piper aduncum* in Papua New Guinea on the spread and relative significance in different parts of the country. Three periods are distinguished: from the first collection in 1935 to the early 1970s; the 1970s to the 1980s when it spread rapidly in the lowlands and reached the highlands; and the 1990s to the present when it began to receive research attention.

First records 1930 - early 1970s

The first record of *Piper aduncum* in Papua New Guinea was the collection in 1935 of a specimen in the Finschhafen area of Morobe Province (Table 1). The first collection record held in the Lae Botanical Garden of Papua New Guinea is dated 1952 (Henty and Pritchard, 1975). This was followed ten years later by a collection from the same location (Hartley *et al.*, 1973). These three collections (1935, 1952, 1962), two of which came from plants in the Botanical Garden, and all of which were from a small area of Morobe Province, suggest a restricted distribution up to the 1960s. This is supported by the absence of any mention of the plant in the overview of Papua New Guinea weeds (Henty, 1972).

At the CSIRO Herbarium (Canberra), there are only two further collections from Papua New Guinea between 1964 and 1970, and both were from Morobe Province. One was collected at Pindiu on the Huon Peninsula at about 800 m a.s.l. in a swampy area with sago, the other from secondary growth at or near Lae. Two further records from 1970-71 show that the plant was already more widely dispersed. In 1970, it was collected from the Koiari area of Central Province, and in 1971 by Streimann from Los Negros Island in Manus Province.

In the second edition of "Weeds of New Guinea and their Control" published in 1975, *Piper aduncum* was described as widespread at low altitudes in New Guinea (Henty and Pritchard, 1975). This distribution was, however, not reflected in published lists or accounts of vegetation during the 1960s and 1970s (e.g. Paijmans, 1976).

Rapid spread in lowlands, introduction highlands mid 1970s - 1980s

In the mid 1970s, *Piper aduncum* reached the central highlands probably by the direct agency of people (Sterly, 1997). It is unlikely that it had reached the highlands before 1975, as there are a number of localised surveys before then that did not report *Piper aduncum* (e.g. Hays, 1980; Hide *et al.*, 1979; Powell, 1974), and no herbarium collections have been found.

In 1980, in the south of Chimbu Province, it was observed as a planted ornamental or fence plant at the aid post in the settlement of Yuro (1150 m a.s.l.), near Karimui station by Hide (1984). In the north of Chimbu Province in early 1984, Sterly (1997) collected two specimens of a Piper that are likely to be *Piper aduncum* though identified to generic level only. They were said to have been introduced in the late 1970s from the coast. Both trees had been planted and one had been transplanted from lower in the Wahgi valley.

Also in the early 1980s, three collections of *Piper aduncum* were made in coastal villages in the Finschhafen area, at Keregia and Nasingalatu (Holdsworth and Damas, 1986) and at Suquang (Woodley, 1991). Between 1974 and 1985 on Kairiru Island (East Sepik province), Borrell (1989) noted the presence of *Piper aduncum*. In 1987-1988, *Piper aduncum* was collected in the Teptep area of the Finisterre Range on the Morobe-Madang border (Kocher Schmid, 1991) and, in late 1988, at Gawam village, 20 km northeast of Lae at 200-300 m a.s.l. (Baltisberger *et al.*, 1989).

Age of discovery - 1990s

In the 1990s, awareness of the spread of *Piper aduncum* grew, and there was a corresponding increase in research interest in the plant from a range of disciplines (e.g. pharmacology, agronomy, quarantine aspects, entomology, mapping agricultural systems, forestry, taxonomy).

In 1992-95, its significance as an invasive plant in several areas of Morobe, Northern and Central Provinces was documented by teams of the joint survey of agricultural systems by the Australian National University (Canberra) and the Department of Agriculture and Livestock in Papua New Guinea (Bourke *et al.*, 1998). An important part of these agricultural system surveys was the description of fallow types and species.

Hartemink and co-workers started a series of experiments in the mid-1990s focussing on soil seed banks (Rogers and Hartemink, 2000), nutrient and biomass accumulation (Hartemink, 2001), and the effects of *Piper aduncum* fallows on soils and crops (Hartemink, 2003) – the results of these experiments are described in subsequent chapters in this book.

Following pharmacological collections in 1988 (Baltisberger *et al.*, 1989) the chemical properties of the plant were described in a series of papers, which reported on some of the antibacterial and molluscicidal compounds (Orjala *et al.*, 1994). In the early 1990s, scientists from the Christensen Research Institute (CRI) at Madang undertook work on the plant's response to disturbance (Lovelock *et al.*, 1994).

Between 1996 and 1999, botanical inventory surveys in several conservation areas recorded the presence of *Piper aduncum* in Morobe, Madang and Simbu province (Takeuchi, 1999; Takeuchi, 2000), but it was not reported in other provinces, e.g. at Lakekamu in Gulf Province, in the Bismarck-Ramu region in Western Highlands and Madang Province, and in Southern New Ireland (Takeuchi and Wiakabu, 2001). Gardner (2003) published a taxonomic account of six *Piper* species by examining specimens from various herbaria and some fieldwork in the Madang Province of Papua New Guinea. He notes that *Piper aduncum* is abundant at least in drier parts of the Morobe Province, mostly in disturbed secondary vegetation and fallow gardens. He described the altitudinal limit at about 1500 m a.s.l. (Gardner, 2003), which is much lower than the Chimbu data of Sterly (1997) and others.

From the late 1990s, entomological work was carried out in the Madang area by scientists attached to the Parataxonomist Centre (Leps *et al.*, 2002; Novotny, 2003). At the same time, Australian interest in the quarantine aspects of the invasive nature of Piper aduncum increased (Waterhouse, 2003).

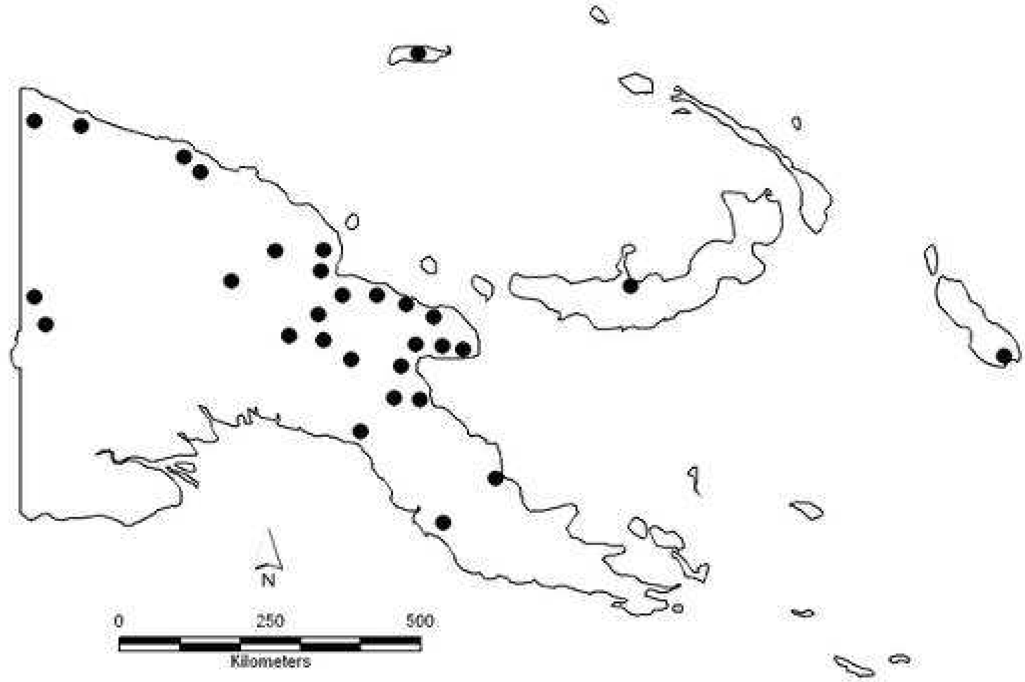

Fig. 5. Presence of *Piper aduncum* in Papua New Guinea. Based on observations and publications by: B.J. Allen, R.M. Bourke, M. Clemens, R.O. Gardner, A.E. Hartemink, R. Hide, S.B. Kidd, C. Kocher Schmid, J. Leps, A.L. Mack, O. Ngere, V. Novotny, P. Vovola, J. Sterly, W. Takeuchi, B. Waterhouse. M. Woruba

1.7. *Piper aduncum* in the shifting cultivation systems

In the 1990s, the Australian National University in collaboration with PNG institutions mapped all agricultural systems in Papua New Guinea. The major purpose was to produce information on smallholder agriculture at provincial and national levels. Information was collected by a combination of rapid survey field observations, interviews with villagers and published and unpublished documents (Allen *et al.*, 1995). For all of Papua New Guinea, over 270 agricultural systems were identified based on fallow type, fallow period, cultivation intensity, the staple or most important crops, garden and crop segregation and soil fertility maintenance techniques

(Allen *et al.*, 2002; Bourke *et al.*, 2002). In several agricultural systems *Piper aduncum* is described; the information is summarised below.

In the Kaiapit area of the Morobe Province over 75% of land in cultivation is planted in a sweet potato-peanut rotation. Short woody regrowth dominated by *Piper aduncum* and 6-10 years old fallows are cleared and burnt. *Piper aduncum* was accidentally introduced but generally thought to be beneficial. The fallow vegetation has changed from mainly cane grass to short woody regrowth, following the introduction of *Piper aduncum* (known locally as 'gum'). The Wantoat Valley was described as a 'densely-populated grass flat' in 1936 and in the late 1950s cane grass was the dominant fallow vegetation – now it is *Piper aduncum* (Bourke *et al.*, 2002).

In the Hiri District of the Central Province fallow vegetation of short woody regrowth is cleared. The fallow comprises of pure stands of *Piper aduncum*, which is generally less than 5 years old. *Piper aduncum* sticks are used to construct barriers across the slope, behind which terraces are constructed, approximately 50 cm high and 150 cm wide. Soil is tilled and mounds are formed from the loose soil. Sweet potato is cultivated on the mounds. Only one planting is made after which there is a long fallow period.

The main valley floors and lower slopes in this area were planted with rubber in the early 1900s. The surrounding hill country was logged over in the 1970s. The hillsides are now covered with short grass, pure stands of *Piper aduncum*, or a much reduced hill forest. A land use system was introduced to the area by settlers from the Morobe Province. *Piper aduncum* sticks are used to prevent soil erosion, and to prevent the invasion of cultivated areas by grasses. During forest clearing, *Piper aduncum* sticks are cut and hammered into the ground with wooden mallets. Other sticks are tied onto these stakes horizontally with vines. Soil is then cut from immediately beneath the fence above and shovelled against the back of the fence to form a terrace. Long fallows are less than 5 years. During this time, the *Piper aduncum* stakes begin to grow and the fallow site quickly becomes covered in a pure stand of *Piper aduncum*, about 3 m to 5 m tall. The plant is said to maintain a friable soil and to prevent the establishment of *Imperata cylindrica* grass. It also provides the material from which the soil retention barriers are constructed at the next cultivation. Terraces cover extensive areas of hillside in this area and large areas of piper fallows also exist (Allen *et al.*, 2002).

Also, in parts of the Northern Province of Papua New Guinea short woody regrowth, dominated by *Piper aduncum*, is the dominant fallow vegetation. *Piper aduncum* is a recent introduction and is known locally as 'poroporo'. It is considered to be a useful introduction, and spread mainly by a small bat.

1.8. Summary and conclusions

Plant invasion is recognised as an important component of the global biodiversity crisis and some have argued that it is a threat more ominous than the greenhouse effect. *Piper aduncum* is a shrub native to Central America. It is found in many Central and South American countries (Mexico, Costa Rica, Guatemala, Panama, Surinam, French Guyana, Brazil, Columbia, Peru, and Venezuela) but also in the Caribbean (Cuba, Trinidad and Tobago, Jamaica, Martinique, St Vincent, and Dominican Republic) and Southern Florida (USA). In Asia and the Pacific, *Piper aduncum* occurs in Indonesia, Malaysia, Philippines, Papua New Guinea, Solomon Islands, Vanuatu, Fiji, Micronesia, American Samoa, Niue, the Marianas, Tonga, Samoa, the Cook Islands, and Palau, and Hawaii (USA).

Piper aduncum arrived in Papua New Guinea before the mid-1930s. It now dominates the secondary fallow vegetation in many parts of the humid lowlands where shifting cultivation is common. In the 1990s, awareness of the spread of *Piper aduncum* grew, and there was a corresponding increase in research interest in the plant from a range of disciplines (e.g. pharmacology, agronomy, entomology, quarantine, mapping agricultural systems, forestry, taxonomy). The subsequent chapters of this book focus on the ecological and agricultural effects of *Piper aduncum* invasion in the shifting cultivation systems of the humid lowlands.

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♦

2. Soil seed bank and growth rates of an invasive species, *Piper aduncum,* in the lowlands of Papua New Guinea *

Abstract

Secondary fallow vegetation in parts of the Papua New Guinea lowlands is dominated by the shrub *Piper aduncum* L. that originates from South America. Here we report on its seed bank, growth rate and biomass accumulation. *Piper aduncum* accounted for 69% (408 m^{-2}) of the seed bank in the forest and 53% (1559 m^{-2}) of the seed bank under fallow. About 90% of the tree seed bank at the fallow site was dominated by *Piper aduncum* whereas this was 78% in the forest soil. Two years old *Piper aduncum* had grown to 4.5 m height and had accumulated 48 Mg dry matter (DM) per ha of aboveground biomass. The rate of biomass accumulation increased from 10 Mg DM ha^{-1} y^{-1} in the first year to 40 Mg DM ha^{-1} y^{-1} in the second year when 76% of the biomass consisted of mainstems. The highest growth rate of 134 kg DM ha^{-1} day^{-1} occurred when *Piper aduncum* was 17 months old. Aggressive invasion and monospecific stands of *Piper aduncum* are explained by its dominance in the seed bank, fast growth, and high rates of biomass accumulation. *Piper aduncum* is a major competitor to indigenous tree species and presents a threat to Papua New Guinea's rich biodiversity.

2.1. Introduction

Introducing plant species into new environments can have many unanticipated ecological effects. Whether deliberately introduced as ornamentals and economic plants or brought in accidentally, new species can have devastating effects on ecosystem quality (van Groenendael *et al.*, 1998) and functioning through out-competing indigenous species and habitat modification. As a result, an endemic flora may become extinct (Lorence and Sussman, 1986). An example which has recently gained attention in Africa and Asia is the small shrub *Chromolaena odorata* L., a native of Central and South America which was brought to Asia in the late 19th century (Slaats, 1995). It then spread rapidly across Asia and arrived in Africa in the 1940s. Its spread is closely related to human activities, in particular frequent disturbances of the natural vegetation from agriculture

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* Rogers, H.R. and A.E. Hartemink, 2000. Soil seed banks and growth rates of an invasive species, *Piper aduncum*, in the lowlands of Papua New Guinea. Journal of Tropical Ecology, 16: 243-251.

and road maintenance (McFadyen and Skarratt, 1996; Slaats, 1995). An example from the Pacific is *Miconia calvescens* DC. It was introduced in Tahiti in 1936 and has become a major plant pest in the Society Islands of French Polynesia (Meyer, 1996).

In the lowlands of Papua New Guinea the exotic tall shrub *Piper aduncum* L., which originates from South America now dominates much of the secondary fallow vegetation in many parts of the lowlands. *Piper aduncum* invaded similarly to *C. odorata* in Asia and Africa and *M. calvescens* in Polynesia. *Piper aduncum* is Indigenous to tropical America where it is found from Mexico to Bolivia. Its habitat in Central America is restricted to evergreen vegetation and near watercourses in seasonally deciduous forests, from sea level to about 1500 m a.s.l. *Piper aduncum* was introduced in Indonesia in 1860, and is now commonly found in Irian Jaya and Malaysia. In the Pacific it occurs in Fiji but is not found in Hawaii or Northern Australia.

It is unknown how and when *Piper aduncum* arrived in Papua New Guinea but it was firstly described in the Morobe Province in 1935 (J.F. Veldkamp, Rijksherbarium Leiden, *pers. comm.*, 1999). *Piper aduncum* is found in many parts of the humid lowlands where 20 to 30 years ago it was absent (Kidd, 1997; R.M Bourke, *pers. comm.*, 1998). It occurs widely in the Morobe and Madang Province at altitudes up to 600 m a.s.l., and is also found in the highland provinces. *Piper aduncum* is frequently observed along logging tracks and on fallow sites where it often forms monospecific stands. It occurs in soil seed banks (Saulei 1989) and appears to be fast growing.

Despite the rapid invasion of *Piper aduncum*, very little is known about its growth characteristics and how it can establish monospecific stands. We therefore conducted a seed bank study in fallow and forested areas in addition to measurements on its rate of height growth and biomass accumulation. These aspects are considered vital attributes (Drury and Nisbet, 1973) that might explain *Piper aduncum's* spread across the humid lowlands of Papua New Guinea.

2.2. Methods

The sites

The study was conducted at two sites reflecting contrasting environments where *Piper aduncum* is invasive. The first site at Oomsis (6º 45' S, 146º 47'E), 40 km west of Lae, at *c.* 400 m a.s.l. is in a mixed species lowland rainforest (Paijmans, 1976). The forest at Oomsis was selectively logged 30-35 years ago. Lowland forests in Morobe Province commonly have a basal area of 25-35 m^2 ha^{-1}, but basal areas at Oomsis are about 18 m^2 ha^{-1}

suggesting the forest had not fully recovered from the logging. This was reflected by fewer large stems (> 0.5 m diameter at breast height), otherwise the forest appeared little different in structure from unlogged forest. Shifting cultivation is practised in irregular patches of less than 0.5 ha within the forest and *Piper aduncum* is often abundant and sometimes dominant in abandoned fields. Within the forest, occasional stems of *Piper aduncum* were present in the understorey and along hunting tracks. *Piper aduncum* saplings occurred in some small gaps, often in association with saplings of *Musa* and *Macaranga* spp. Mean annual rainfall at the nearest weather station (Lae airport 20 km E, altitude 10 m a.s.l.) is *c.* 4,800 mm. The mean daily temperature is about 26 °C. The soils are well drained and derived from schist. They are tentatively classified as chromic Luvisols (Kubo, 1992).

The second site was located at Hobu (6°34'S, 147°02'E) at 405 m a.s.l. This site was chosen as an example of a secondary vegetation fallow site where *Piper aduncum* is abundant forming monospecific stands. Hobu is located north-east of Lae at the footslopes of the Saruwaged range. The mean annual rainfall of 3,000 mm is fairly evenly distributed throughout the year. The mean annual temperature is 26 °C. Soils are derived from a mixture of colluvial and alluvial deposits of mostly igneous rocks. The soils have a high base status and are classified as Eutric Cambisols.

Seed bank study

Plot locations were chosen to reflect representative sites of where *Piper aduncum* had invaded closed forest (Oomsis) and fallow (Hobu) sites. For the closed forest site care was taken to ensure there were no fallow sites within 200 m. At each site 2 m^2 of soil and associated leaf litter was collected by taking eight samples measuring 0.5 m x 0.5 m to 0.05 m depth from random points within a 50-m x 50-m plot at the University of Technology, Lae. Each sample was thoroughly mixed and a subsample (3,780 cm^3) of approximately 50% of total volume (7,500 cm^3) was spread to a depth of 0.03 m in plastic germination trays (0.42 m x 0.30 m), over a base of 0.02 m of autoclaved soil to provide a deeper rooting environment. Each tray (subsample) represented a germination test of 30.2% (0.0756 m^2) of the original sample. Autoclaved soils were heated to 121 °C for 90 min. For each site, a control was prepared from autoclaved soil to assess contamination from local seed rain.

Eighteen trays were placed in a germination house under coarse shade netting. Germinating seedlings were counted and removed at biweekly intervals from each tray for 16 weeks from May to September 1998 during which 1,788 mm of rain was recorded. Seedlings that could not initially be identified were tagged and left to grow until identification could be made.

Growth rate study
In October 1996, an area of 0.5 ha was cleared at Hobu. It consisted mainly of five-year old secondary fallow vegetation dominated by *Piper aduncum* and to a lesser extent by *Homalanthus* sp., *Macaranga* sp., *Trichospermum* sp. and *Trema orientalis*. All vegetation debris was removed from the plot and no burning was practised. In December 1996, a block of 90 m^2 was planted with young seedlings of *Piper aduncum*, which were taken from nearby roadcuts. Spacing was 0.75 m x 0.75 m which we have frequently observed in *Piper aduncum* fallows. The plots were manually weeded. After five months, the height of 4 plants was measured and these were cut at ground level and separated into main stems, branches, leaves and litter. Each plant part was weighed and dried at 70 °C for 72 h for dry matter determination. Every 3 months, the biomass was assessed of 4 plants in a stratified sampling scheme leaving a border row between the sampled plants. In total seven samplings were made and the last sampling was done when the plants were 23 months old. Roots were not sampled in this study.

A few herbaceous weeds germinated in the autoclaved control trays, but no tree or shrub seedlings. The herbaceous weeds were confined to the Hobu control soil, and were mainly *Pilea microphylla* and *Cardamine hirsuta*. Because of the negligible numbers of these species, no adjustments were made to counts from the trays containing the samples.

2.3. Results

Seed banks
In total 41 species were recorded of which 15 species were common to both sites (Table 1). Twenty species were identified to genus or family level and 21 to species level. In total 981 seedlings m^{-2} germinated from Oomsis (forest) and 4,826 m^{-2} from Hobu (fallow). At both sites, the shrub *Piper aduncum* was the dominant seed bank species, accounting for 69% of the seed stocks at Oomsis and 53% of the seed stocks at Hobu. About 90% of the woody species seed bank at Hobu was dominated by *Piper aduncum* whereas this was 78% at Oomsis. Other secondary tree species were the second most common seed stock life form at Oomsis (18%) followed by herbs (12%). In contrast, at Hobu herbs were the second most common seed stock (40%), followed by secondary tree species (6%). For both sites, vines and grasses made up less than 1% of the seed stocks.

The progress of germination at each site for the different life forms and *Piper aduncum* is shown in Fig. 1. The first seedlings were observed after 5 days. In the Oomsis soil only a few secondary trees, herbs and *Piper aduncum* had germinated during the first 4 weeks, but thereafter the rate of

Piper aduncum germination increased. In the Hobu soil, the rate of germination for *Piper aduncum* increased dramatically from 4 weeks onwards. For both sites, the rate of *Piper aduncum* germination had reached its peak before 8 weeks.

The number of seedlings emerging per tray was variable. For the Oomsis samples, seedlings of *Piper aduncum* ranged from 10 to 95 per tray (mean 52 ± 31), and secondary tree seedlings ranged from 4 to 24 (mean 13 ± 8). For the Hobu soil, *Piper aduncum* seedlings ranged from 121 to 479 per tray (mean 211 ± 126), and herbs ranged from 21 to 278 (mean 154 ± 93).

Growth rates

After 5 months, *Piper aduncum* at Hobu had grown to about 0.9 m height (Fig. 2a) and total above ground biomass was 3.9 Mg dry matter (DM) ha^{-1} (Fig. 2b). This corresponds to a growth rate of 23 kg DM ha^{-1} day^{-1}. At one year, the average height of the *Piper aduncum* plants was 1.7 m and dry biomass had increased to 8.8 Mg ha^{-1}. In the second year, the *Piper aduncum* height increased from 3.3 m at 17 months to 4.5 m at 23 months. Biomass accumulation was 29.4 Mg ha^{-1} at 17 months, and 48.3 Mg ha^{-1} at 23 months.

More than 50% of the above ground biomass consisted of leaves and less than 25% was found in the main stem after 5 months of growth. We observed a gradual change in the biomass distribution with time. The percentage in leaves and small branches both decreased whereas around 75% of the above ground biomass was found in the main stems after 23 months of growth. Branches and litter accounted for less than 10% of the total dry biomass after 23 months.

The average rate of aboveground biomass accumulation over the two year period was 85 kg DM ha^{-1} day^{-1} but rates were variable. The highest rate occurred between 14 and 17 months and was 134 kg DM ha^{-1} day^{-1}. Between 8 and 11 months, a period with little rain, above ground biomass gain was only 3 kg DM ha^{-1} day^{-1}. It appeared that the growth rate of *Piper aduncum* both in biomass and height is favoured by high rainfall (Fig. 2b). Although rainfall at the site is fairly well distributed throughout most years, 1997 was an exceptionally dry year due to El Niño, which affected most of Papua New Guinea. Only 1,897 mm of rain fell in 1997 compared to 2,067 mm in the first six months of 1998. During the first 11 months of our study, 1,742 mm of rain fell whereas in the second year of growth 3,590 mm fell.

Table 1. Species and number of seedlings germinated (per m^2) from soil samples of Oomsis (forest site) and Hobu (fallow site). Germination period was 16 weeks

		Site	
	Species	Oomsis	Hobu
Vines	*Cissus* sp.	-	2
	Mikania micrantha Kunth	-	2
	*Wedelia biflora (*L.) DC.	-	3
	Total	0	7
Grasses	*Echinochloa colonum* Beauv.	-	2
	*Imperata cylindrica (*L.) P. Beauv.	-	5
	Paspalum cartilagineum L.	3	28
	Rottboellia exaltata L.f.	-	2
	Total	3	37
Herbs	*Alocasia* sp. *(*Schott) G. Don. F.	3	5
	Amaranthus *sp.*	-	2
	Cardamine hirsuta L.	-	104
	Compositae	-	5
	Dichrocephala bicolor (Roth) Schltdl.	2	38
	Eupatorium odoratum L.	36	686
	Zingiberaceae	-	20
	Hedyotis corymbosa (L.) Lamk	-	2
	Musa sp.	66	25
	Oxalis sp.	2	38
	Peperomia pellucida (L.) Kunth	-	2
	Physalis angulata L.	-	12
	Pilea microphylla (L.) Liebm.	13	845
	Solanum sp.	-	15
	Sonchus oleraceus L.	-	38
	Urticaceae	-	81
	Total	122	1918
Primary trees	*Alstonia spectabilis* Monach.	2	2
	Neonauclea sp.	-	2
	Total	2	4
Secondary trees	*Anthocephalus chinenesis* (Lamk) Rich	33	-
	Cordia dichotoma Forst.	-	10
	Elaeocarpus sp.	2	-
	Ficus sp.	-	17
	Gardenia sp.	15	2
	Glochidion sp.	35	-
	Homalanthus sp.	7	3
	Macaranga sp.	43	40
	Muntingia calabura L.	3	-
	Octomeles sumatrana Miq.	3	20
	Phyllanthus sp.	-	2
	Pipturus sp.	18	170
	Trema orientalis (L.) Bl.	-	7
	Trichospermum sp.	20	8
	Total	179	279
Shrubs	*Piper aduncum*	675	2578
	Mussaenda sp.	-	3
	Total	675	2581
	Grand Total	981	4826

-, not present

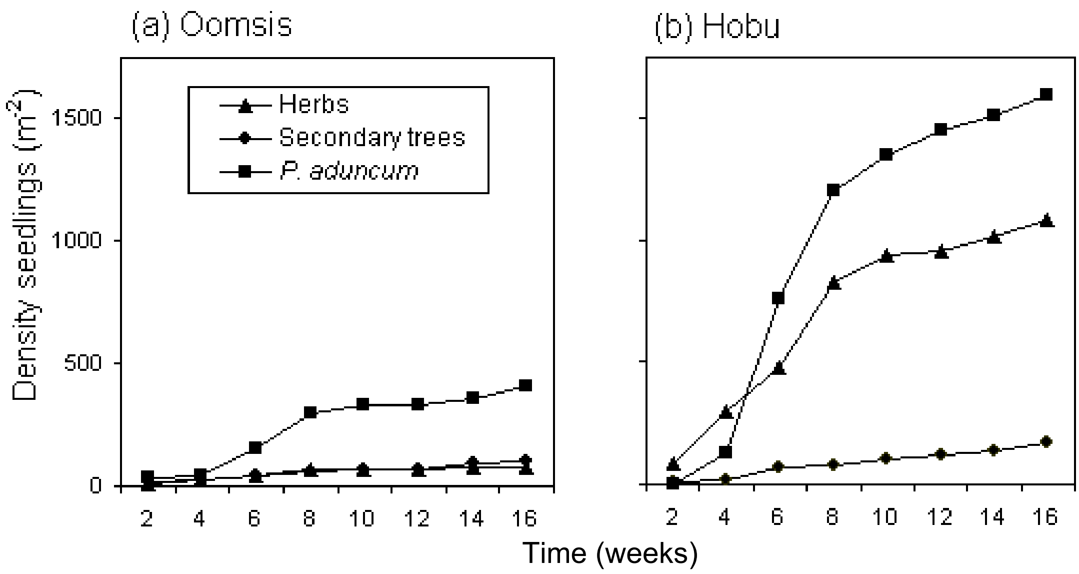

Fig. 1. Cumulative germination of herbs, secondary trees and *Piper aduncum* from soil samples of (a) Oomsis and (b) Hobu, Papua New Guinea

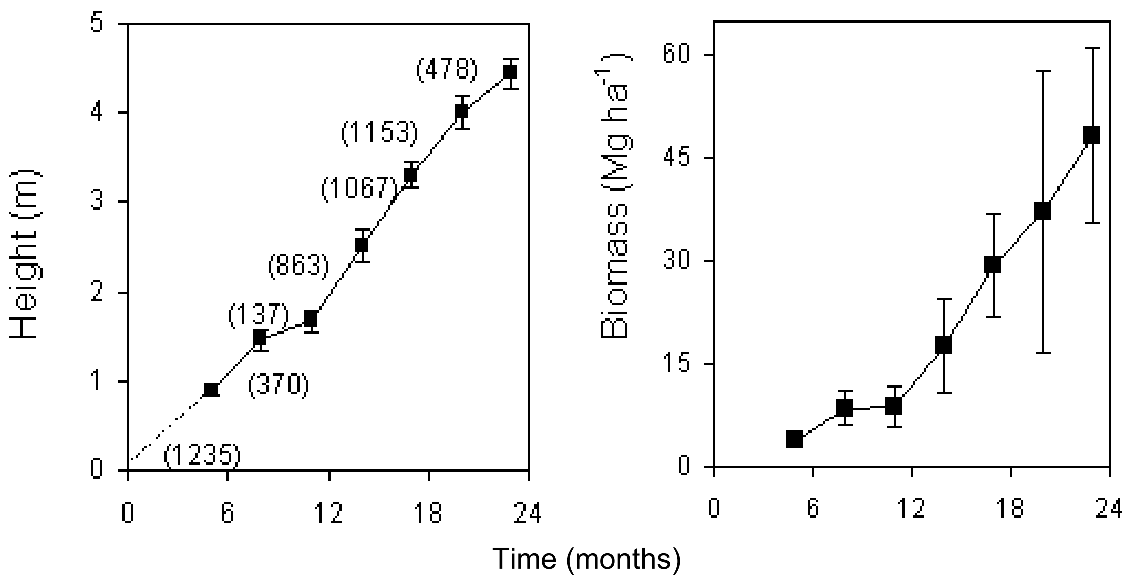

Fig. 2. Mean (± SD) growth (m), and biomass accumulation (Mg ha^{-1}) of *Piper aduncum* at Hobu, Papua New Guinea. Amount of rain (mm) between sampling times in parenthesis

2.4. Discussion

Large numbers of viable *Piper aduncum* seeds occurred in forest and fallow soils. The size of the seed banks were comparable to those of lowland tropical forests and regrowth sites in other parts of the world (Garwood, 1989), with the forest soil seed bank being typically smaller than that of fallow soils (Thompson, 1992). However, the *Piper aduncum* seed bank occurred in numbers greater than other species conferring a competitive advantage during regeneration. There was considerable variation in number of seedlings per tray. The large variations may be attributed to non-uniform dispersal of seeds in the soil, non-uniform incorporation of seed into the top 0.05 m of soil, or the influence on germination of spatial variation of the soils at each site (Thompson, 1992).

The difference in size of the *Piper aduncum* seed bank between Oomsis and Hobu may simply reflect differences in seed rain because of high parent tree density at Hobu. However, frequency and scale of disturbance, and litter layer can also influence seed bank size. The soils at Hobu are frequently disturbed by clearance for cultivation, which favours establishment of species that are fast growing and can reach reproductive maturity at a young age (< 5 years). Repeated occupancy of pioneers at a site maintains a high density of their seed in the soil (Saulei and Swaine, 1988). By contrast, within closed forest at Oomsis disturbances by smaller scale single treefalls appear to be more common, where opportunities for massive establishment by *Piper aduncum* and replenishment of the soil seed bank are less common. Another explanation for seed bank differences is the difference in the depth of the litter layer at Hobu and Oomsis. Oomsis soils had a litter layer of up to 0.05 m depth compared to a thin or non-existent litter layer at Hobu. Accumulated litter might delay or prevent seeds reaching the soil giving more chance for predation (Cintra, 1997).

Piper aduncum height growth of 1.7 m year^{-1} is rapid in comparison with pioneers from other tropical forests. For example in lowland Caribbean forests, common pioneer trees have a mean height growth of only 0.4 m year^{-1} to 1.3 m year^{-1} (Vandermeer *et al.*, 1998). *Piper aduncum*'s fast height growth enabled it to quickly outgrow associated pioneer tree species like *Macaranga* and *Pipturus* sp. Maximum growth rates of *Piper aduncum* were 134 kg DM ha^{-1} day^{-1}, which is high. Slaats (1995) found rates up to 24 kg DM ha^{-1} day^{-1} for the pioneer shrub species *Chromolaena odorata* in lowlands of Ivory Coast. Apparently, the humid conditions in combination with the relatively fertile soils in the Papua New Guinea lowlands favour rapid growth.

Although fast growth rate and abundant seed bank are characteristic of tropical pioneer species (Swaine and Whitmore, 1988), in this study *Piper aduncum* had a mega seedbank in relation to associated pioneers (e.g. *Macaranga*), and had a particularly high growth rate. We consider these two factors vital attributes (Drury and Nisbet, 1973), partly explaining its persistence. However, *Piper aduncum* also has the ability to resprout once damaged, which is a trait that would favour persistence in disturbance prone environments where the vegetation is not completely removed.

Piper aduncum's presence in small gaps in closed forest, and its proliferation on frequently disturbed fallow sites suggest it has a catastrophic and gap-phase regeneration pattern (Veblen, 1992). Therefore, in Papua New Guinea's lowland forests, which are subjected to catastrophic natural disturbances, such as landslides or stand-devastating windthrow (Johns, 1985), *Piper aduncum* may pose a serious threat to the indigenous flora by out-competing other pioneer species. Moreover, anthropogenic factors contribute to the spreading of *Piper aduncum* through logging and shifting cultivation. Forest fires, which were particularly severe in the 1997/98 El Niño Southern Oscillation, may present new frontiers for *Piper aduncum* invasion. A possible advantage of the *Piper aduncum* invasion is, however, that man-made grasslands (mainly *Imperata cylindrica*) may revert to bushfallow vegetation.

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Part II
Biomass and nutrient characteristics of *Piper aduncum*

Chapter 3

Hartemink, A.E., 2001. Biomass and nutrient accumulation of *Piper aduncum* and *Imperata cylindrica* fallows in the humid lowlands of Papua New Guinea. Forest Ecology and Management, 144: 19-32.

Chapter 4

Hartemink, A.E., 2004. Nutrient stocks of short-term fallows on a high base status soil in the humid tropics of Papua New Guinea. Agroforestry Systems, 63: 33-43.

Chapter 5

Hartemink, A.E. and J.N. O'Sullivan, 2001. Leaf litter decomposition of *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea. Plant and Soil, 230: 115–124.

3. Biomass and nutrient accumulation of *Piper aduncum* and *Imperata cylindrica* fallows in the humid lowlands of Papua New Guinea *

Abstract

Shifting cultivation with short fallow periods (<3 y), is an important form of land use in the humid lowlands of Papua New Guinea. The secondary forest vegetation is dominated by the shrub *Piper aduncum* which originates from South America and *Imperata cylindrica* grasslands in areas where annual bush fires are common. No information is available on the rate of biomass and nutrient accumulation of these two fallow types. Plots with *Piper aduncum* and *Imperata cylindrica* were planted on a Typic Eutropepts and sampled every three months for 23 months to assess above ground biomass and nutrient content. Total biomass of imperata was slightly higher than that of piper during the first year, but remained around 23 Mg dry matter (DM) ha^{-1} in the second year. Above ground biomass of piper increased linearly, and reached 48 Mg DM ha^{-1} at 23 months when three-quarter of the biomass consisted of wood. Growth rates of piper were on average 69 kg DM ha^{-1} day^{-1}, and increased with higher rainfall. Nutrient content of imperata was 100 kg N, 12 kg P, 62 kg K, 64 kg Ca, 40 kg Mg and 9 kg S per ha at 23 months. The concentration of K and Ca was high in piper leaves but declined over time. At 23 months, piper had accumulated 222 kg N, 50 kg P, 686 kg K, 255 kg Ca, 75 kg Mg, and 24 kg S per ha. More than half of the P, K, Ca and Mg was found in the stem (wood) which is removed from the field and used as firewood when farmers slash the fallow. Piper biomass (excluding wood) returned about three times more K to the soil than imperata, but differences between total P and S contents were small. For the accumulation of biomass and nutrients, imperata fallows should not exceed one year. Piper accumulated large amounts of biomass and nutrients, particular K, which is an important nutrient for root crops that dominate the cropping phase in the shifting cultivation systems of the humid lowlands.

3.1. Introduction

About three-quarter of Papua New Guinea (460,000 km^2) is under primary forest (McAlpine and Quigley, 1995). No exact figures are available on the current rate of deforestation, but estimates from the 1980s vary between

* Hartemink, A.E., 2001. Biomass and nutrient accumulation of *Piper aduncum* and *Imperata cylindrica* fallows in the humid lowlands of Papua New Guinea. Forest Ecology and Management, 144: 19-32.

113,000 and 200,000 ha per year (FAO, 1990; Freyne and McAlpine, 1987). Deforestation takes place for logging, mining, agricultural plantations and shifting cultivation. Aerial photographs from the early 1970s compared with LandSat^{TM} imagery from 1996, revealed that the area under shifting cultivation has increased by only 7% (J.R. McAlpine, CSIRO, 1999, unpublished data) despite the fact the human population doubled between 1966 and 1990 (Allen *et al.*, 1995). It implies that land is cropped more often and fallow periods are shortened, which puts a greater demand on the soil resource (Nye and Greenland, 1960), particularly as virtually no inorganic fertilizers are being used on food crops in Papua New Guinea (Hartemink and Bourke, 2000). Forest regrowth is uncommon in the humid lowlands and the woody shrub *Piper aduncum* and *Imperata cylindrica* grasslands dominate the fallow vegetation.

Piper aduncum is a member of the family Piperaceae of which there are some economically important species in the Pacific, including *Piper nigrum (*pepper), *Piper methysticum* (kava), and *Piper bettle* of which the fruits are used with betel nut (*Areca cathecu*) in Papua New Guinea (Bornstein, 1991). *Piper aduncum* is a shrub or small tree with alternate leaves and spiky flowers and fruits. It occasionally reaches a height of 7 to 8 m, and has very small seeds which are mostly dispersed by the wind, fruit bats and birds. *Piper aduncum* is common throughout Central America where it is found between sea level and 2,000 m a.s.l. along road sides and in forest clearance areas on well drained soils. It occurs in Mexico, Central America, Surinam, Cuba, Southern Florida, Trinidad and Tobago, and Jamaica and is very common in Costa Rica on open or partly shaded sites (Burger, 1971). In the Neotropics, *Piper aduncum* may be locally abundant but the species rarely dominates the vegetation (R Callejas, University of Antoquia, *pers. comm.*, 1999,) or is found in mature vegetation. In the Amazon areas, it has been reported as an invading plant after timber exploitation (Maia *et al.*, 1998). Extracts of *Piper aduncum* are used as folk medicine in South America. The species is mentioned in several ethnopharmalogical databases, and has antifungal and antibacterial compounds (Nair and Burke, 1990).

Piper aduncum was introduced in the Botanical gardens of Bogor (Indonesia) in the 1860. By the 1920s it commonly occurred in a radius of 50 to 100 km around the Botanical Gardens in young secondary vegetation, close to rivers and on very steep slopes, locally in dense stands (Heyne, 1927). *Piper aduncum* was noted in Jayapura in 1955 and in Biak in 1960 on Papua (Irian Jaya), and in Malaysia and Borneo in the 1960s (Allen, 1966; Chew, 1972). It has also been recorded in Singapore and Sumatra, and is on the list of unwanted weed species by the quarantine service of Australia. *Piper aduncum* was introduced into Fiji in the 1920s and is now widespread in the wet and intermediate zones of Viti Levu (Smith, 1981). It is not found on Hawaii.

The botanist Mary Clements first observed *Piper aduncum* in 1935 near the mission station Heldsbach in the Morobe Province. It was not very widespread in the early 1970s and *Piper aduncum* is not separately listed in the standard text on New Guinea vegetation (Paijmans, 1976). However, by the late 1990s *Piper aduncum* is very common in the lowlands of the Morobe and Madang Provinces, and is also observed in the Central Highlands above 2,000 m a.s.l. (Rogers and Hartemink, 2000). Seeds are being spread by flying foxes (Kidd, 1997) and logging equipment. Causes for its rapid spreading remain unclear but evidence is being accumulated that areas of high native plant species richness and cover, like many areas in Papua New Guinea, and areas high in soil fertility may be highly invasible (Stohlgren *et al.*, 1999). The invasion of *Piper aduncum* in the humid lowlands of Papua New Guinea appears similar to the spreading of *Chromolaena odorata* in Asia and parts of West Africa (McFadyen and Skarratt, 1996; Slaats *et al.*, 1996), and to the invasion of *Miconia calvescens* which was introduced as an ornamental but is now one of the major pests in the Society Islands of the Pacific (Meyer, 1996) where it is nicknamed the "green cancer" (Stone, 1999).

Another fallow type in the humid lowlands of Papua New Guinea is grasslands consisting of *Imperata cylindrica* (spear grass, cogon grass, alang-alang, kunai). Such grasslands occur widely in the humid tropics on various soil types (Menz *et al.*, 1998; Santoso *et al.*, 1996), and *Imperata cylindrica* is generally considered one of the world's worst weeds, especially in Southeast Asia (NRI, 1996; Turvey, 1994). In Papua New Guinea, *Imperata cylindrica* grasslands cover millions of hectares and are found from sea level to nearly 2,000 m a.s.l., with annual rainfall varying from 1,250 to 4,000 mm and on soils with a pH ranging from 5 to 9 (Holmes *et al.*, 1980). They have been mostly formed because of annual bushfires which hinders the regrowth of woody vegetation.

Despite the widespread occurrence of *Piper aduncum* and *Imperata cylindrica* fallows in the humid lowlands of Papua New Guinea, there is no information available on the amount of biomass and nutrients. This is no exception as there is a paucity of information on total biomass and nutrient stocks in tropical secondary vegetation (Szott *et al.*, 1994). The objectives of this study were therefore to quantify rates of biomass and nutrient accumulation by *Piper aduncum* and *Imperata cylindrica* (hereafter referred to as piper and imperata, respectively). Such information is important as improved or managed fallows may be required to replace existing natural fallows because they accumulate higher amounts of nutrients and biomass in shorter periods (Sanchez, 1999; Szott *et al.*, 1999).

3.2. Methods

Site

The study was performed between December 1996 and November 1998 near Hobu village (6°34'S, 147°02'E), which is 25 km N of the city of Lae in the Morobe Province. The site is at an altitude of 405 m a.s.l. at the footslopes of the Saruwaged mountain range. Rainfall records were only available since the start of the experiment (November 1996) and the daily rainfall pattern during the growing period is shown in Fig. 3. The end of 1997 was an exceptionally dry period and this was caused by the El Niño/Southern Oscillation climatic event that affected the Pacific severely in 1997/98. Consequently there were many bushfires in the study area and most of the fallow fields around the experimental site were burned. Total rainfall in 1997 was 1,897 mm whereas in the first six months of 1998 the amount of rain was 2,067 mm. March 1998 was a wet month with 725 mm of rain, and rainfall for 1998 was 3,667 mm. Total rainfall during the experimental period (23 months) was 5,323 mm. Temperatures were not available for the experimental site but average daily temperatures at the University of Technology, which is situated about 15 km S of Hobu village, are 26.3°C.

The Hobu experimental site is located on an uplifted alluvial terrace with a slope of less than 2%. Soils are derived from a mixture of alluvial and colluvial deposits dominated by sedimentary rocks and coarse to medium grained, basic, igneous rocks. The soils have water-worn gravelly and stony horizons below 0.2 m depth; effective rooting depth is over 0.7 m. Air-dried and sieved (< 2 mm) soil had the following properties in the top 0.12 m: pH H_2O (1:5 w/v) = 6.2, organic C (dry combustion) = 55 g kg^{-1}, available P (Olsen) = 9 mg kg^{-1}, CEC (NH_4Oac, pH 7) = 400 $mmol_c$ kg^{-1}, exchangeable Ca = 248 $mmol_c$ kg^{-1}, exchangeable Mg = 78 $mmol_c$ kg^{-1}, exchangeable K = 16.9 $mmol_c$ kg^{-1}, clay = 480 g kg^{-1} and sand = 360 g kg^{-1}, bulk density = 0.82 Mg m^{-3}. The soils are classified as mixed, isohyperthermic, Typic Eutropepts (USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base). Further details on soil chemical and physical properties can be found in Hartemink *et al.* (2000).

The shifting cultivation system

The experiment was located in an area where shifting cultivation is commonly practised and consists of a short fallow period (< 3 to 5 years) alternated with a cropping period of about one year. At the end of the fallow period, piper is coppiced at 0.2 to 0.5 m above the ground with bushknives.

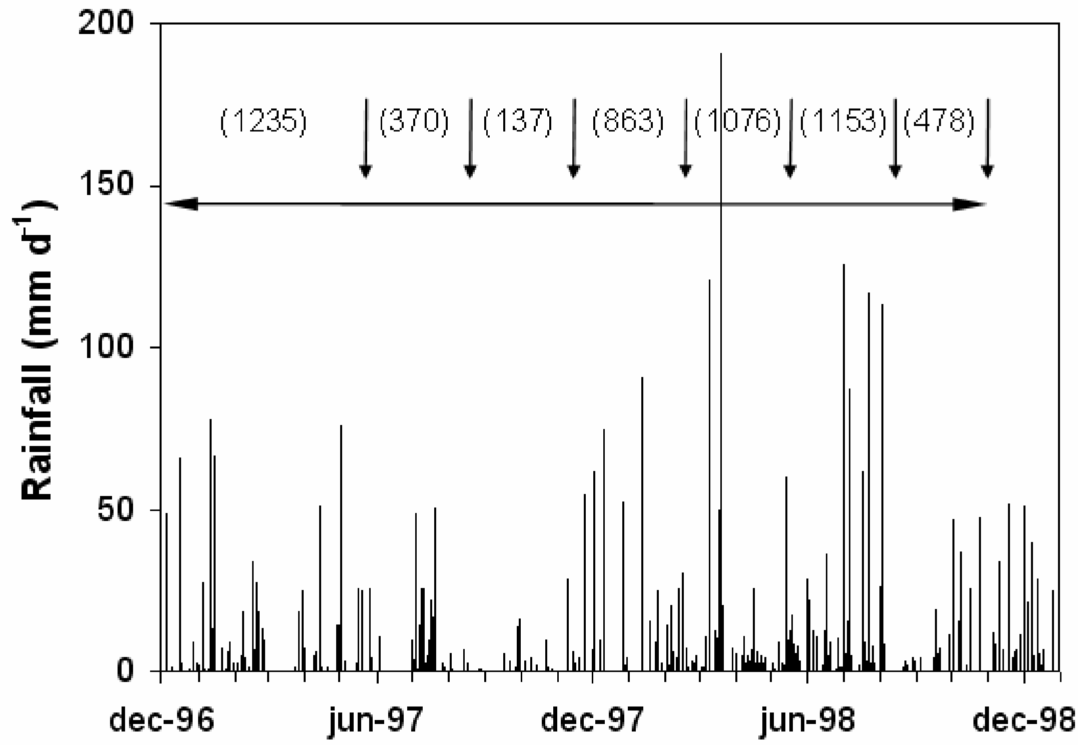

Fig. 1. Rainfall during fallow period (mm per day) at the experimental site in the Morobe Province of Papua New Guinea. Horizontal arrow indicates growing period (23 months), vertical arrows indicate sampling times for biomass and nutrients. Amount of rain between sampling times in parentheses

The vegetation debris is left to dry for some weeks whereafter the woody parts (stems) are removed from the field, which are mostly used for firewood and sometimes for constructing hutroofs. Burning the vegetation debris is uncommon due to the prevailing wet conditions, which hampers proper drying and burning. In addition, piper stems may not sprout after burning. Taro (*Colocasia esculenta*) or maize (*Zea mays*) are commonly firstly planted after a fallow period and these are gradually interplanted with sweet potato (*Ipomoea batatas*), which is the major staple in the lowlands (Bourke, 1985), bananas (*Musa* sp.) and sugar cane (*Saccharum* sp.). After one year, the piper has sprouted, the bananas have grown large and the cropped site reverts back to fallow bush.

Not much is known about the farmers' perception of piper fallows in the Morobe Province although a number of farmers remember that it arrived in their area in the 1970s. Some farmers claim that if the piper is large, good crop yields may be expected and others say the piper makes good firewood. Most farmers know that piper consumes much soil water and quantitative differences have been observed in the volumetric soil moisture contents of soils under piper, imperata, and *Gliricidia sepium* (Hartemink and O´Sullivan, 2001). Soils after one-year piper fallow were drier than under other fallows of the same age, which may be of an advantage since high rainfall depresses sweet potato yield (Hartemink *et al.*, 2000).

Imperata fallows are also common in the Morobe Province of Papua New Guinea particularly in areas where bushfires are common. These fires usually occur when there is a short dry spell which takes place in most years. Fires hinder the regrowth of woody vegetation and the imperata grasslands are therefore anthropogenous (Henty and Pritchard, 1988). Farmers slash the imperata and remove the dried grass which is often used as thatch. The land may be cropped for one or two seasons before opportunity costs for weeding become too large and the site reverts back to imperata grasslands. In Papua New Guinea, imperata is also a problem in young rubber, coconuts or timber plantations (Henty and Pritchard, 1988). However, the grasslands can support an extensive beef production system provided legumes are introduced and cattle stocking rates are low (Holmes *et al.*, 1980).

Experimental set-up

In October 1996, an area of about 0.5 ha was cleared which mainly consisted of five-year old secondary fallow vegetation dominated by *Piper aduncum* and to a lesser extent by *Homalanthus* sp., *Macaranga* sp., *Trichospermum* sp. and *Trema orientalis* (Rogers and Hartemink, 2000). All vegetation debris was removed from the plot and no burning was practised. In December 1996, a plot of 90 m^2 (6 x 15 m) was planted with young piper seedlings (about 0.2 m), which were taken from nearby roadcuts. Plant spacing was 0.75 by 0.75 m, as is frequently observed in fallows dominated by piper. During the first months, plots were manually weeded but thereafter the canopy had closed and no more weeding was necessary. At the same time a plot of 90 m^2 was left fallow. Woody regrowth was removed from this plot and within four weeks the vegetation was dominated by *Imperata cylindrica*.

Plant sampling and analysis

Five months after the piper was planted, the height of four plants was measured. A 0.75 x 0.75 m quadrate was placed around each plant and the litter was removed and put in a paper bag. The four plants were cut at ground level and separated into main stems, (side) branches, and leaves. Each plant part was weighed and subsamples were taken to the laboratory. Every three months, the above ground biomass (i.e. stem, branches, leaves, litter) of four plants was assessed in a stratified sampling scheme leaving a border row between the sampled plants. In total seven samplings were made and the last sampling was done when the plants were 23 months old (see Fig. 1). Flowers and fruits, which appeared after about 18 months, were included in the leaf biomass. Piper fruits were sampled at 23 months for nutrient analysis. Roots were not sampled in this study.

Above ground biomass of the imperata was sampled at the same dates as the piper and four quadrates of 0.75 x 0.75 were randomly placed in the imperata plot. The imperata was clipped at ground level and litter could not be separated from the above ground biomass. Total biomass was weighed in the field and subsamples were taken to the laboratory. The imperata data for 14 months after planting were lost.

In the laboratory, all plant samples were rinsed with distilled water and oven dried at 70°C for 72h. Samples were ground (mesh 0.2 mm) and sent for nutrient analysis to the laboratories of the School of Land and Food of the University of Queensland. One subsample was digested in 5:1 nitric:perchloric acids and analysed for P, K, Ca, Mg and micronutrients (B, Cu, Mn, Zn) using ICP AES (Spectro Model P). A second subsample was digested according to the Kjeldahl procedure and analysed for C, N and S on an Alpkem Rapid Flow Analyser Series 300.

Data analysis
Dry matter contents were calculated based on ovendried data of the subsamples. Biomass data of piper and imperata were averaged and subjected to analysis of variance. Standard error of the difference in means (SED) was calculated for total biomass of piper and imperata and the individual plant parts of piper. Total nutrient uptake was calculated by multiplying dry matter with nutrient concentration and SEDs were calculated for both the piper and imperata data. Since the data for the 14-months old imperata were lost, the degrees of freedom (*d.f.*) were 15 for imperata and 18 for piper. All statistical analysis was conducted using Statistix 2.0 for Windows.

3.3. Results

Accumulation of above the ground biomass
During the first year, above ground biomass of imperata was larger than that of piper, and the biomass of both fallows was on average below 20 Mg dry matter (DM) ha^{-1} (Fig. 2). Total above ground biomass of *Piper aduncum* increased with time, but variation in piper biomass was considerable and data from the first four sampling were not statistically significant (P>0.05). After 14 months, piper above ground biomass increased significantly and reached 48 Mg DM ha^{-1} at 23 months. Imperata biomass increased significantly (P<0.05) between 5 and 8 months. No significant difference was found in the biomass between 8 and 11 months but imperata biomass had significantly increased again at 17 months and remained around 23 Mg

DM ha^{-1} between 17 and 23 months (Fig. 2). Dry matter content of the imperata biomass was 35% at 5 months, 45% at 8 months and around 55% between 11 and 23 months, when a considerable portion of the above ground biomass was dead.

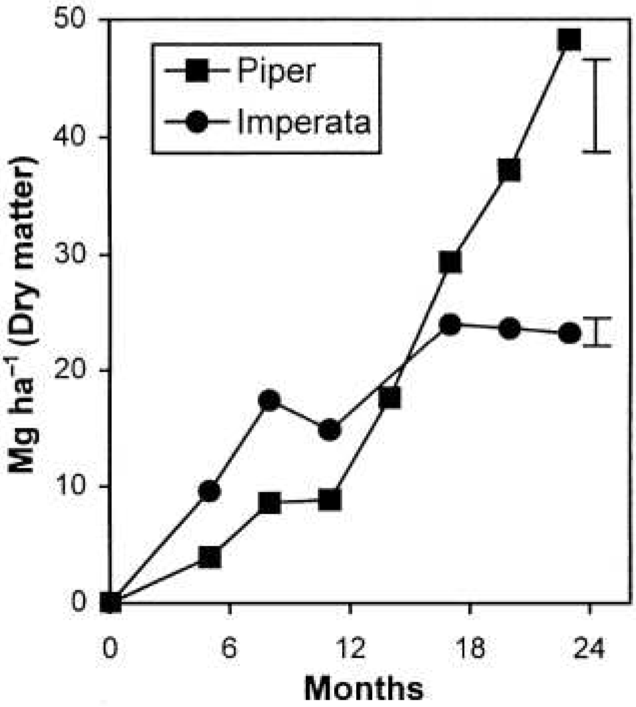

Fig. 2. Total biomass accumulation of *Piper aduncum* and *Imperata cylindrical* during a 23 months period in the humid lowlands of Papua New Guinea. Bars indicate standard error of the difference in means (18 *d.f.* for piper data, 15 *d.f.* for imperata data)

The large increase in above ground biomass of piper was mainly due to the growth of the main stems (Fig. 3) and the piper formed on average three stems per plant. In the first 14 months, piper stems formed less than 50% of the total above ground biomass but at 23 months more than three-quarter of the total biomass consisted of woody stems (Table 2). Leaves formed half of the piper biomass at 5 months, but were less than 16% of the total biomass at 23 months despite the significant increase from 2.0 to 7.8 Mg DM ha^{-1}.

Overall a widening wood-leaf ratio was observed with increasing age of the piper. Litter biomass differed significantly between the various sampling times and ranged from 0.3 and 4.1 Mg DM ha^{-1} (Fig. 3). The growth of the piper will eventually level off and in the Morobe Province of Papua New Guinea it was observed that other secondary species slowly invade monospecific piper stands after about five years.

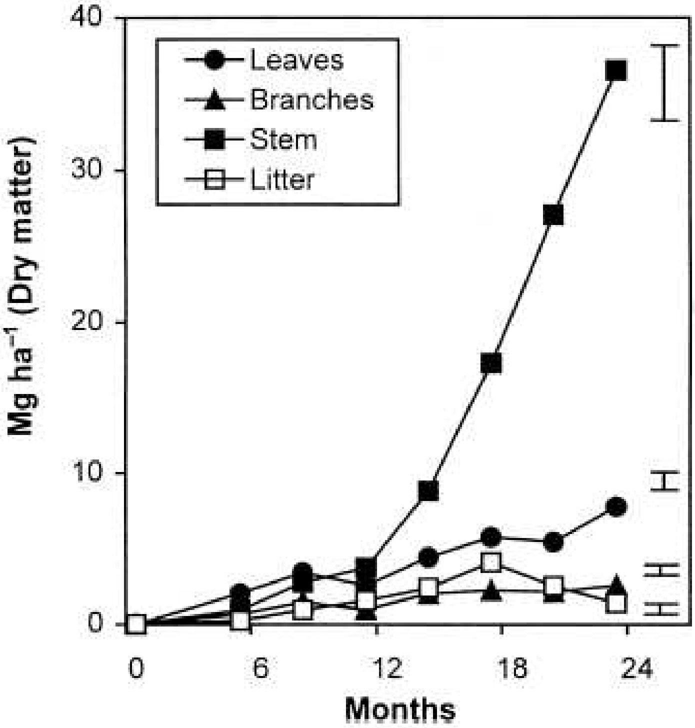

Fig. 3. Biomass accumulation in leaves, stem, branches, and litter of *Piper aduncum* during a 23 months period in the humid lowlands of Papua New Guinea. Bars indicate standard error of the difference in means (18 *d.f.*)

Table 1. Biomass in leaves, stem, branches and litter of *Piper aduncum* as percentage of the total above ground biomass, over a 23 months period in the humid lowlands of Papua New Guinea

	Months after planting						
Plant part	5	8	11	14	17	20	23
Leaves	52	40	29	25	20	15	16
Stem	24	32	42	50	59	73	76
Branches	17	17	11	11	8	6	5
Litter	6	11	18	14	14	7	3

Growth rates of piper varied considerably, and ranged from 3.0 kg DM ha^{-1} day^{-1} to 133.5 kg DM ha day^{-1} during the 23 months of observation. Rates of biomass accumulation of imperata were highest between 5 and 8 months when it reached 82.1 kg DM ha^{-1} day^{-1}. Average growth rates over the whole period were 69.1 kg DM ha^{-1} day^{-1} for piper and 31.5 kg DM ha^{-1} day^{-1} for imperata. Piper shrubs were on average about 0.9 m (±0.06 m) at 5 months after planting but the average height increased to 2.5 m (±0.19 m) at 14 months, and to 4.5 m (±0.17 m) at 23 months. During the time of the experiment, it was observed that the height and biomass gain of the piper was affected by the amount of rain between the sampling times which varied considerably (Fig. 1). Between 8 and 11 months after planting, only 137 mm of rain fell and there was no increase in above ground biomass (Fig. 2), although there was a significant increase in the litter biomass during this period (Fig. 3). The amount of rain between a sampling time (in mm per day) was plotted versus the growth rate (kg dry matter per ha per day), and the relation was as follows:

Growth rate (in kg ha^{-1} day^{-1}) = 8.1 x rainfall (in mm day^{-1}) + 13.6
($r^2 = 0.413$, $P<0.05$).

Although the data are few and do no take into account age effects on the growth rates of piper, a clear increasing trend was found in growth rate with increasing rainfall. On average, piper growth rates increased with about 81 kg DM ha^{-1} day^{-1} for each 10 mm of rain per day. No relation could be established between the growth rates of imperata and rainfall.

Nutrient concentration and accumulation

Nutrient concentration was measured in leaves, stems, branches, and litter of piper and the whole above ground biomass of imperata (Table 2). Piper leaves contained on average 22.7 mg N kg^{-1} at 5 months but levels significantly decreased thereafter and were almost halved at 23 months. Nitrogen concentrations in piper stem branches and litter also significantly decreased over time. Imperata contained less than 6.5 mg N kg^{-1} and N concentrations declined significantly between 5 and 8 months, but did not change between 8 and 23 months. The P concentration of piper leaves and stem was similar and declined significantly over time. Piper branches contained relatively high P concentration whereas imperata leaves contained low P levels. Piper leaves and branches contained high concentrations of K, which decreased during the 23 months growing period. Piper litter contained more K than imperata leaves, which had very low concentration of K. Variation in Ca concentration of piper leaves was considerable and concentrations were mostly below those of the piper litter. Concentration of Ca in imperata was low but remained constant over the 23 months period. Piper litter contained the highest Mg concentrations and mostly exceeded those in the piper leaves. Sulphur concentrations were highest in the piper branches.

Piper leaves contained relative high concentrations of B particularly when compared to imperata (Table 3). Manganese concentrations decreased over time in the piper leaves but increased significantly in the above ground biomass of imperata. Piper branches contained relatively high concentrations of Cu and levels decreased with time. Zinc concentrations were highest in piper leaves although branches contained relative high concentrations of Zn.

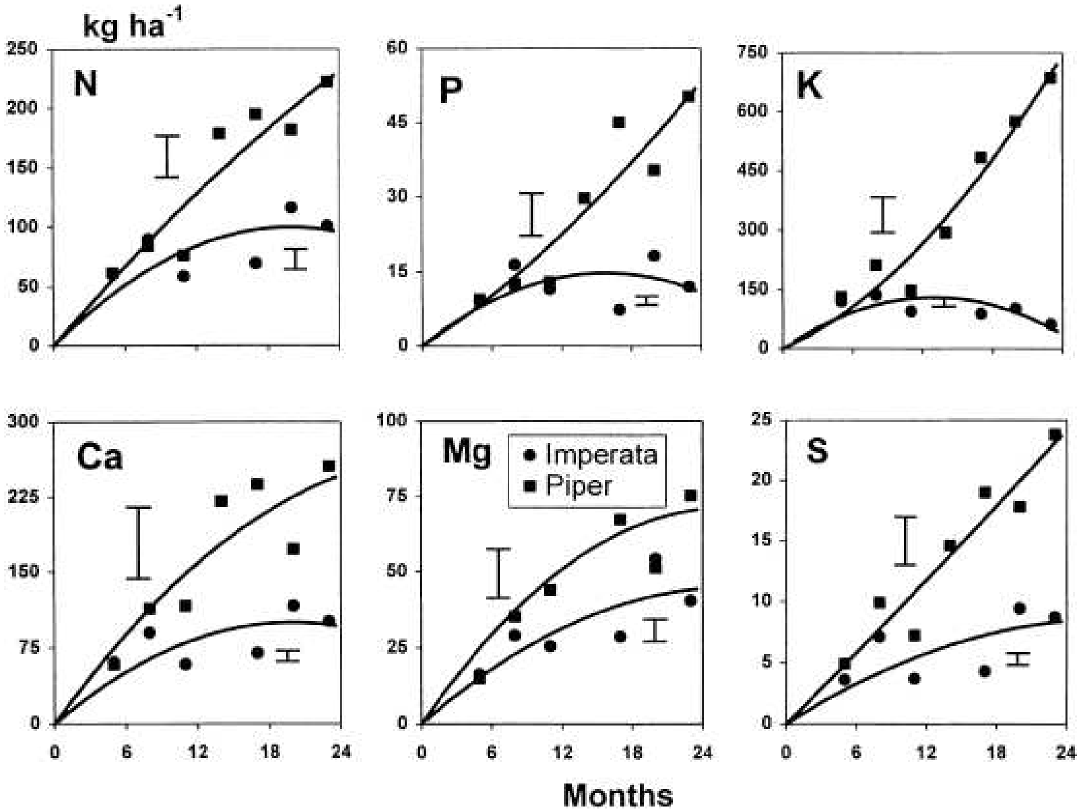

Fig. 4. Total nutrient uptake in the above ground biomass of *Piper aduncum* and *Imperata cylindrica* during a 23 months period. Bars indicate standard error of the difference in means (18 *d.f.* for piper data, 15 *d.f.* for imperata data)

At 23 months after planting fruits of the piper were analysed for their nutrient concentration and the data were compared to the nutrients in the leaves (Table 4). Piper fruits contained on average slightly higher nutrient concentrations than the leaves at 23 months, particularly N, P, S and Cu. However, compared to leaf analytical results of the first 11 months (Table 2), piper fruits were poorer in nutrients except for P which levels are relatively high.

Although imperata accumulated more biomass during the first 12 months (Fig. 2), nutrient accumulation of piper was much higher (Fig. 4). Nitrogen uptake by piper was almost linear and equalled 222 kg ha^{-1} at 23 months. Total N accumulation of piper was more than double the N accumulation by imperata. Accumulation of P was 50 kg ha^{-1} in the above ground biomass of the piper fallows, but varied greatly for imperata. Potassium accumulation in piper was linear and reached 686 kg ha^{-1} compared to 62 kg K ha^{-1} under imperata fallows at 23 months. Piper also accumulated considerable amounts of Ca and two times more Mg than imperata, although there was some variation in the data. Sulphur accumulation by piper reached 24 kg ha^{-1} at 23 months, which was about three times higher than in imperata.

Table 2. Major nutrient concentration (g kg^{-1}) of *Piper aduncum* leaves, stem, branches and litter and *Imperata cylindrica*, over a 23 months period in the humid lowlands of Papua New Guinea

	Fallow species	Plant part	Months after planting							
			5	8	11	14	17	20	23	SED [1]
N	Piper	leaves	22.7	16.2	16.3	15.9	16.5	15.1	13.9	0.56
		stem	8.1	5.4	3.6	6.1	3.3	2.7	2.6	0.21
		branches	8.0	5.7	7.4	7.2	5.4	5.8	5.1	0.22
		litter	9.6	8.5	9.0	8.7	7.1	5.7	5.1	0.52
	Imperata [2]	whole plant	6.3	5.1	4.0	nd	4.2	4.9	4.3	0.57
P	Piper	leaves	2.6	1.8	1.9	1.7	1.7	1.7	1.1	0.30
		stem	2.2	1.2	1.0	1.6	1.4	0.7	0.9	0.15
		branches	2.7	1.6	3.2	2.7	3.1	2.4	2.2	0.25
		litter	0.8	0.9	0.8	0.9	0.8	0.5	0.5	0.04
	Imperata [2]	whole plant	0.9	0.9	0.8	nd	0.6	0.8	0.5	0.07
K	Piper	leaves	34.0	29.4	25.2	20.3	20.9	25.4	16.2	4.09
		stem	31.2	17.8	11.0	15.9	16.2	14.1	13.4	1.50
		branches	44.2	33.6	28.6	25.0	29.1	25.3	22.2	2.40
		litter	15.2	14.6	10.0	2.3	5.4	3.5	3.3	1.42
	Imperata [2]	whole plant	12.6	7.7	6.6	nd	4.5	4.3	2.6	0.65
Ca	Piper	leaves	17.3	18.1	19.3	20.9	14.4	15.5	8.8	2.64
		stem	6.1	3.0	2.2	3.3	2.0	1.6	4.3	1.68
		branches	12.9	9.6	7.9	8.6	11.4	9.8	7.2	0.64
		litter	34.9	30.8	31.7	33.1	24.1	8.8	9.7	2.48
	Imperata [2]	whole plant	2.9	2.6	2.6	nd	2.5	2.6	2.8	0.29
Mg	Piper	leaves	3.6	4.5	7.1	6.7	3.1	3.6	2.3	0.79
		stem	2.6	1.5	1.2	1.6	1.0	0.8	1.2	0.35
		branches	5.2	6.0	8.2	8.1	4.8	3.5	4.0	0.76
		litter	5.3	7.8	8.4	6.7	5.4	2.3	2.0	0.51
	Imperata [2]	whole plant	1.7	1.7	1.7	nd	2.2	2.3	1.7	0.11
S	Piper	leaves	1.3	1.2	1.0	1.0	0.9	1.0	0.5	0.16
		stem	0.8	0.4	0.2	0.3	0.2	0.2	0.3	0.10
		branches	2.1	2.9	2.9	2.7	3.2	3.3	2.9	0.40
		litter	0.7	0.8	0.7	0.8	0.8	0.4	0.5	0.06
	Imperata [2]	whole plant	0.4	0.4	0.3	nd	0.4	0.4	0.4	0.06

[1] SED - standard error of the difference in means (18 *d.f.* for piper, 15 *d.f.* for imperata)
[2] For imperata whole plants (excluding roots) were sampled
nd - not determined

Table 3. Minor nutrient concentration (mg kg^{-1}) of *Piper aduncum* leaves, stem and branches and *Imperata cylindrica,* over a 23-months period in the humid lowlands of Papua New Guinea

	Fallow species	Plant part	Months after planting							
			5	8	11	14	17	20	23	SED [1]
B	Piper	leaves	34.5	42.8	19.7	22.7	33.0	26.2	14.1	3.93
		stem	14.7	21.1	7.5	14.1	14.6	2.6	8.3	5.25
		branches	18.0	34.0	11.5	16.4	20.2	13.1	10.0	5.04
	Imperata [2]	whole plant	2.9	9.8	10.7	nd	8.4	5.9	3.1	2.24
Cu	Piper	leaves	6.8	11.0	4.1	0.2	2.0	3.1	0.8	1.06
		stem	18.5	13.5	10.9	5.4	4.5	3.9	0.5	2.26
		branches	29.2	16.3	8.5	3.5	5.4	6.8	4.8	4.47
	Imperata [2]	whole plant	12.0	7.5	3.7	nd	2.8	4.2	0.1	1.79
Mn	Piper	leaves	28.0	28.3	29.9	23.2	11.9	18.6	10.8	3.57
		stem	8.7	4.5	3.7	6.3	2.5	2.0	4.5	1.51
		branches	13.6	10.6	9.3	9.6	6.2	7.6	6.3	0.87
	Imperata [2]	whole plant	22.6	27.8	24.9	nd	28.7	32.6	35.6	3.25
Zn	Piper	leaves	40.7	44.7	37.9	37.0	29.9	23.2	15.0	5.21
		stem	31.2	15.7	20.1	15.7	7.6	4.8	9.5	2.87
		branches	40.6	37.4	31.2	29.3	29.6	18.4	15.4	2.88
	Imperata [2]	whole plant	18.3	10.6	13.0	nd	11.8	13.2	7.7	2.47

[1] SED - standard error of the difference in means (18 *d.f.* for piper, 15 *d.f.* for imperata)
[2] For imperata whole plants (excluding roots) were sampled
nd - not determined

Table 4. Major and minor nutrient concentration of *Piper aduncum* fruits and leaves at 23-months after planting in the humid lowlands of Papua New Guinea

Plant part	Major nutrient g kg^{-1}						Minor nutrient mg kg^{-1}			
	N	P	K	Ca	Mg	S	B	Cu	Mn	Zn
Fruits	17.0	3.7	17.1	9.9	2.3	1.5	11.6	3.7	10.2	16.7
Leaves	13.9	1.1	16.2	8.8	2.3	0.5	14.1	0.8	10.8	15.0

Variation in the nutrient uptake data was considerable which resulted from variation in both dry matter production and nutrient analysis. Despite this variation it was found that the order of nutrient accumulation for piper followed: K >> Ca > N > Mg > P > S whereas the order for imperata was found to be N > K = Ca > Mg > P> S. Total C accumulation by 23 months for piper was 19.6 Mg ha^{-1} (±5.1) whereas 9.5 Mg C ha^{-1} (±1.3) was accumulated in the above ground biomass of the imperata.

Nutrient cycling
Accumulation of some major nutrient was more or less linear whereas the contents of other nutrient levelled off or decreased with time (Fig. 4). As the fallows will eventually be slashed and the nutrients will be returned to the soil when the biomass is decomposed, the pattern of nutrient accumulation has implications for the optimum time for slashing the fallows. The data suggest that there is no obvious advantage of having imperata fallows for longer than one year because no extra biomass or nutrients will be accumulated. However, for piper it was found that accumulation of biomass and N, P, K and S was found to be almost linear which implies that longer fallow periods means more biomass and nutrients. Accumulation of Ca and Mg showed, however, a plateau after 18 months.

After the piper fallows are slashed, farmers in the area remove the woody biomass (stems) from the fallow fields. Therefore, the amount of nutrients returned to the soil is the total amount of nutrients in the above ground biomass minus nutrients removed with the wood (Table 5). This makes the difference with the imperata smaller (Fig. 4) as considerable amounts of nutrients, particularly K and Ca, are removed with the wood. Piper returned about three times more K to the soil than imperata but differences between total P and S contents were small.

Table 5. Major nutrient content of *Piper aduncum* stem and total above ground biomass at 23-months after planting in the humid lowlands of Papua New Guinea

	Content in kg ha^{-1} ± 1 SD					
	N	P	K	Ca	Mg	S
Total biomass [1]	222 ±58	50 ±17	686 ±289	255 ±259	75 ±44	24 ±12
Stems (wood)	93 ±23	35 ±12	495 ±220	155 ±226	44 ±38	11 ±11
Difference	129 ±36	15 ±5	191 ±76	100 ±52	31 ±13	13 ±4

[1] Nutrients in leaves, stem, branches, and litter (see Fig. 6)

3.4. Discussion

Biomass accumulation
Variation in the rate of biomass accumulation by *Piper aduncum* was considerable and caused by the irregular amount of rain between the sampling times. Growth rates were increased with higher rainfall, and after 23 months large amounts of above ground biomass had accumulated. Total biomass of piper is even higher but no measurements were made on

below ground biomass. Various root-shoot ratios have been reported in the literature. In the humid lowlands of Venezuela, pioneer trees allocated high amounts of energy to root production and root-shoot ratios varied between 0.14 and 0.41 (Uhl, 1987). Below/above ground ratio for the fast growing *Inga edulis* in the humid lowlands of Peru were between 0.12 and 0.15 at 17 – 29 months after planting (Szott *et al.*, 1994). Observations on the roots of *Piper aduncum* were made 7 months after planting by digging 0.5 m deep trenches around piper plants. Piper had not an excessive root mat and the majority of the roots were concentrated in the top 0.18 cm. If a root-shoot ratio of 0.15 is assumed, the total above and below ground biomass of the *Piper aduncum* is 56 Mg ha^{-1} at 23 months. This is exceptionally high and caused by the piper's genetic potential, the dense spacing, and the fertile soils as the site had been fallow for about five years prior to the planting of piper. The large biomass accumulation may explain why *Piper aduncum* is such an invasive species because it shades out native species. In addition, it produces large amounts of seeds which are easily dispersed.

There is only one other study which has reported above ground biomass of *Piper aduncum*. Hashimotio *et al.* (2000) measured the biomass of a forest fallow dominated by *Piper aduncum* in the humid lowlands of East Kalimantan (Indonesia) and found an above ground biomass of about 12 Mg ha^{-1} after two years, and 45 to 56 Mg ha^{-1} in 10 to 12 year old forests fallow dominated by *Piper aduncum*. The soils at the site were very acid and of low fertility (Ultisols), which may explain the lower biomass.

On poor fertility Ultisols in the humid lowlands of Peru, Szott *et al.* (1994) measured above and below ground biomass accumulation and found 19 Mg DM ha^{-1} for the fast growing tree *Inga edulis*. In the humid lowlands of Venezuela above ground biomass accumulation rates of natural regrowth varied from 5 to 9 Mg DM ha^{-1} $year^{-1}$ (Uhl, 1987). In a recent overview of fallows in the humid and subhumid tropics, the highest biomass was about 30 Mg DM ha^{-1} after two years (Szott *et al.*, 1999). Two-year old *Chromolaena odorata* on Ultisols in the humid lowlands of Ivory Coast had accumulated about 16 Mg DM ha^{-1} (Slaats *et al.*, 1996). *Gmelina arborea*, a widely used tree on forest plantations, produced between 56 and 137 Mg ha^{-1} in five to seven years (Halenda, 1993). Above ground biomass of two-year old *Acacia mangium* in Cameroon was 44 Mg ha^{-1} (Duguma *et al.*, 1994) whereas the biomass in six-year old bamboo in Bandung (Indonesia) was 76.7 Mg ha^{-1} (Christanty *et al.*, 1996).

None of the studies on secondary fallow in the humid tropics reported such high rates of biomass accumulation as in this study with *Piper aduncum*. Although some studies were conducted on high base status soils (Szott *et al.*, 1999), growth of secondary vegetation in humid lowlands is mostly nutrient limited (Gehring *et al.*, 1999).

Biomass accumulation of *Imperata cylindrica* (maximum 24 Mg DM ha^{-1}) was much lower than of *Piper aduncum* and rates decreased with time, which is common in non-woody fallows (Szott *et al.*, 1994). Above ground biomass of imperata in SE Asia can reach 18 Mg DM ha^{-1} (NRI, 1996). The above ground biomass of one-year old imperata in East Kalimantan was ranging from 5.5 to 10.7 Mg ha^{-1} (Hashimotio *et al.*, 2000), and in the drier parts of Papua New Guinea biomass of imperata ranged from 7.9 to 16.6 Mg ha^{-1} (Holmes *et al.*, 1980). Again, the large biomass accumulation of the imperata in this study reflects the high soil fertility and favourable rainfall.

Nutrient accumulation

Nutrient concentration of piper leaves was higher than those of imperata which contained low levels of all major and minor nutrients. In both fallow types, nutrient concentrations decreased with time which is usually found. There was little difference in the nutrient concentration of piper leaves and fruits at 23 months, except for P which was high in piper fruits. It appears that nutrient concentrations cannot fully explain why the fruits are favoured by Neotropical bats, which are held responsible for the rapid spread of *Piper aduncum* (Kidd, 1997; Thies *et al.*, 1998).

Except for N, nutrient content in the above ground biomass of piper exceeds those published in the literature for two year old natural and managed fallows. Nutrients in the imperata biomass were low and K contents declined with time possibly due to leaching of K from the biomass because a portion of the above ground biomass was dead after one year. Piper returns large amounts of K to the soil, which is the main nutrient for the root crop dominated farming systems in Papua New Guinea. Piper also contains considerable amounts of S which is often deficient in agricultural crops in the humid lowlands (Hartemink and Bourke, 2000). In the study area, piper is not burned after it is slashed, so most of the nutrients could potentially become available when the vegetation debris decomposes. Burning would accelerate nutrient availability but may also cause considerable losses (Mackensen *et al.*, 1996; Nye and Greenland, 1964). Overall, the piper fallow accumulated more nutrients than the grass fallow with imperata, which is commonly found (Jaiyebo and Moore, 1964; Nye and Greenland, 1960). No estimate could be made of total nutrient stocks and decaying roots provide another important source of nutrients when the fallows are slashed (Greenland and Kowal, 1960).

At 23 months, piper fallows had fixed 19.6 Mg C ha^{-1} which is twice the amount of C fixed by imperata. The sequestration of C by tropical secondary forests is an important sink, which helps to offset the negative effects of anthropogenic CO_2 emission (Lal *et al.*, 1998). Relatively little has been published about C sequestration by fallow vegetation in the humid tropics. On poor fertility soils in Cameroon 10 to 20 Mg C ha^{-1} was found in bush fallow vegetation (Kotto-Same *et al.*, 1997), whereas up to 35 Mg C ha^{-1} has been reported in mature tropical fallows (Houghton, 1995; Lal *et al.*, 1997). The data from this experiment show that *Piper aduncum* can fix large amount of C in a relative short period (23 months) and that it is a better C sink than imperata grassland, which was also concluded for the humid lowlands of East Kalimantan (Hashimotio *et al.*, 2000).

3.5. Conclusions

The trend to shorter fallow periods in the shifting agriculture systems of the Papua New Guinea lowlands calls for management alternatives that accelerate nutrient accumulation like the use of improved fallows (Sanchez, 1999). This study has, however, shown that *Piper aduncum* is an effective nutrient and biomass accumulator out yielding published data on natural and improved fallows (Szott *et al.*, 1999; Szott *et al.*, 1994). Biomass and nutrient accumulation of piper is faster than that of natural regrowth in Papua New Guinea, thus providing a quicker soil cover and capturing nutrients which otherwise may have been leached. An advantage of *Piper aduncum* fallows is that it continues to fix C whereas C fixation stagnates in imperata fallows at about 15 months. In the absence of bush fires, piper may also smother imperata grasslands, which are usually difficult to reclaim (Nye and Greenland, 1960; Santoso *et al.*, 1996). Piper fallows may, however, also have negative effects including a loss of biodiversity (Rogers and Hartemink, 2000) and costly programs to eradicate it as was experienced with other bio-invaders in the Pacific (Stone, 1999). Piper has no N-fixing capacity which is a disadvantage compared to managed fallow species on high base status soils in the humid tropics (Buresh and Cooper, 1999). Additional research is required to evaluate the effects of piper on long-term crop yields in the shifting agricultural systems of Papua New Guinea.

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4. Nutrient stocks of short-term fallows on a high base status soil in the humid tropics of Papua New Guinea *

Abstract

In order to understand nutrient dynamics in tropical farming systems with fallows, it is necessary to assess changes in nutrient stocks in plants, litter and soils. Nutrient stocks (soil, above ground biomass, litter) were assessed of one-year old fallows with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea. The experiment was conducted on a high base status soil (Typic Eutropepts), and in Papua New Guinea such soils are intensively used for agriculture. Soil samples were taken prior to fallow establishment and after one year when the fallows were slashed and above ground biomass and nutrients measured. The above ground and litter biomass of piper was 13.7 Mg dry matter ha^{-1}, compared to 23.3 Mg ha^{-1} of gliricidia and 14.9 Mg ha^{-1} of imperata. Gliricidia produced almost 7 Mg ha^{-1} wood. Total above ground biomass returned to the soil when the fallows were slashed was the same for piper and gliricidia (8 Mg ha^{-1}). Gliricidia accumulated the largest amounts of all major nutrients except for K, which was highest in the above ground piper biomass. Imperata biomass contained the lowest amount of nutrients. The largest stocks of C, N, Ca and Mg were found in the soil, whereas the majority of P was found in the above ground biomass and litter. Almost half of the total K stock of piper and gliricidia was in the biomass. During the fallow period, soil organic C significantly increased under gliricidia fallow whereas no net changes occurred in piper and imperata fallows. The study has shown large differences in biomass and nutrient stocks between the two woody fallows (piper, gliricidia) and between the woody fallows and the non-woody fallow (imperata). Short-term woody fallows are to be preferred above grass (imperata) fallows in the humid lowlands of Papua New Guinea because of higher nutrient stocks.

4.1. Introduction

Shifting cultivation is practiced in many places in the humid tropics. It is a sustainable farming system provided the cropping period is relatively short and there is a long fallow period during which the soil fertility is restored.

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* Hartemink, A.E., 2004. Nutrient stocks of short-term fallows on a high base status soil in the humid tropics of Papua New Guinea. Agroforestry Systems, 63: 33-43.

Due to increased land use pressure, fallow periods have shortened which inevitably results in the collapse of the system. For more permanent cropping systems inorganic fertilisers are essential to sustain crop yields but such inputs are often too expensive for subsistence farmers or may be uneconomical or difficult to obtain. In the past decade, much research has focussed on the use and effects of short-term fallows as a step towards more permanent cropping systems (Sanchez, 1999; Young, 1997). Considerable progress has been made on how fallows work and what are suitable species for different agro-ecological zones (Nair *et al.*, 1999). Relatively much work has been done on the effects of different cropping systems on poor fertility and acid soils (Sanchez and Benites, 1987) but high base status soils (exchangeable Ca > 10 $mmol_c$ kg^{-1}, pH > 5.0) have received far less attention.

High-base status soils may have low levels of available P or N, or both. Fallow species on high base status soils should therefore supply N through biological fixation or deep capture, suppress weeds and/or should supply P through chemical transformations and through a reduction of the P complexation (Buresh and Cooper, 1999). In order to understand these nutrient dynamics in tropical farming systems with fallows, it is necessary to assess changes in nutrient stocks in plants, litter and soils (Szott *et al.*, 1999). It is generally perceived that fallows with trees (i.e. woody fallows) have a larger capacity to enhance nutrient availability on high base status soils than on low base status soils.

In Papua New Guinea, shifting cultivation systems were commonly practiced in the humid lowlands. Soils are relatively young and base-rich soils (Inceptisols) cover about 60% of Papua New Guinea. Such soils are the most intensively used soils for agriculture (Freyne and McAlpine, 1987). A study was conducted on a Typic Eutropepts (Inceptisols) located in a shifting cultivation area. The system consists of a short fallow period (1 to 5 years) alternated with a cropping period of about one year. Common fallow species in the area are *Piper aduncum*, which is a native shrub of South America (Hartemink, 2001), and *Imperata cylindrica* (hereafter named piper and imperata). Piper is a woody fallow which is not burned after slashing, and which is often found as monospecific stands in the humid lowlands. At the end of the fallow period, piper is coppiced at 0.2 to 0.5 m above the ground with bushknives. The vegetation debris is left to dry for some weeks whereafter the woody parts (stems) are removed from the field, and are used for firewood and sometimes for constructing hutroofs. Burning the vegetation debris is uncommon. Imperata fallows are common in areas with frequent bushfires and these usually occur when there is a short dry spell, which takes place in most years. Fires hinder the regrowth of woody vegetation.

Plots were planted with *Piper aduncum*, *Imperata cylindrica* and *Gliricidia sepium* (hereafter named gliricidia). Piper and imperata are considered native or traditional fallows whereas gliricidia is an improved fallow which is generally assumed to be more efficient than traditional fallows in restoring fertility (Buresh and Cooper, 1999). The fallows were grown for one year whereafter the above ground biomass and nutrient content were determined. The objectives of the study were to quantify above ground biomass and nutrient stocks of the three fallow species, and the amounts of nutrients returned to the soil when the fallows are slashed. The study also aimed to compare two woody fallows (piper and gliricidia) to a non-woody fallow (imperata), and to compare traditional fallows (piper, imperata) to an improved fallow (gliricidia).

4.2. Methods

The experimental site

The experiment was conducted between November 1996 and November 1997 near Hobu village (6°34'S, 147°02'E), which is 25 km N of the city of Lae in the Morobe Province. The site is located at an altitude of 405 m a.s.l. at the footslopes of the Saruwaged mountain range. Total rainfall during the experimental period was 1,828 mm. The end of 1997 was an exceptionally dry period and this was caused by the El Niño/Southern Oscillation climatic event. Total rainfall in 1997 was 1,897 mm compared to 3,667 mm of rain for 1998. Temperatures were not available for the experimental site but average daily temperatures at the University of Technology, which is situated about 15 km to the North of Hobu village, are 26.3°C. The climate classifies as Af (Köppen). The Hobu experimental site is located on an uplifted alluvial terrace with a slope of less than 2%. Soils are derived from a mixture of alluvial and colluvial deposits dominated by sedimentary rocks and coarse to medium grained, basic, igneous rocks. The soils have water-worn gravelly and stony horizons below 0.2 m depth; effective rooting depth is over 0.7 m. The soils are fertile with moderately high organic C contents and high levels of exchangeable cations. The topsoils are clayey and have bulk densities between 0.6 and 0.8 Mg m^{-3}. Soils in the area are not enriched by volcanic ashes which has occurred in many parts of Papua New Guinea (Bleeker, 1983). The low bulk density is probably related to the high soil organic carbon contents (Manrique and Jones, 1991). The soils are classified as mixed, isohyperthermic, Typic Eutropepts (USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base).

The experimental set-up

An area of about 0.5 ha secondary vegetation was slashed manually at the beginning of November 1996. The vegetation consisted mainly of *Piper aduncum* and to a lesser extent by *Homolanthus* sp., *Macaranga* sp., *Trichospermum* sp. and *Trema orientalis* (Rogers and Hartemink, 2000). The site was previously used for growing foodcrops (sweet potato, taro, sugar cane) but had been fallow since 1992. All vegetation debris was removed and no burning was practised, which follows the land-clearing practices of local farmers. Plots of 6.0 by 6.0 m each were laid out and treatments were assigned to the plots in a randomised complete block design with four replications. On 27 and 28 November 1996, four plots were planted with seedlings (0.2 m height) of *Piper aduncum* obtained from a nearby roadside. Four plots were planted with *Gliricidia sepium* cuttings (0.4 m length) obtained from a nearby cocoa plantation. Piper and gliricidia fallows were planted at distances of 0.75 by 0.75 m (17,778 plants ha^{-1}). These spacings are often observed in natural piper fallows (Hartemink, 2001). During the first months, piper and gliricidia plots were manually weeded but thereafter the canopy had closed and no more weeding was necessary. At the same time four plots were left fallow. Woody regrowth was removed from this plot and within four weeks the vegetation was dominated by *Imperata cylindrica*. Some minor weeds in the imperata fallow were *Ageratum conyzoides, Sphaerostepanos unitus*, *Rottboellia exalta*, *Sida rhombifolia*, *Polygala paniculata*, *Euphorbia hirta* and *Emilia sonchifolia*.

Soil sampling and analysis

Soil samples for chemical analysis were taken when the fallows were planted (27-28th November 1996) and one day before the fallows were slashed (19th November 1997). Soil samples were collected with an Edelman auger (diameter 0.05 m) at 12 random locations in a plot, mixed in a 20 L bucket and a subsample of about 1 kg was taken. Air-dried samples were ground and sieved (2 mm) and were sent for analysis to the National Analytical Chemistry Laboratories in Port Moresby. The procedures for soil analysis were as follows: pH H_2O (1:5 w/v); organic C and total N by Leco CNS-2000 dry combustion; available P by Olsen; exchangeable cations and CEC by 1*M* NH_4OAc percolation (pH 7.0); particle size analysis by hydrometer. The soil data in Tables 1 and 5 are based on these analytical methods. In order to express soil nutrient content in kg ha^{-1}, bulk density of the soil was measured. In each plot, the 0-0.05 and 0.10-0.15 m soil horizons were sampled using two 100 mL cores per depth and measurements were duplicated in each plot. Bulk density was measured one day before soil samples for chemical analysis were taken. Cores were oven-dried at 105°C for 72h. Topsoil chemical properties (C, N, P, K, Ca, Mg) were multiplied with average bulk density values of the 0-0.05 and 0.10-0.15 m soil horizons to obtain nutrient pools in kg ha^{-1}.

Plant sampling and analysis
After one year of growth (20-24 November 1997), the fallow vegetation was cut at ground level. Piper plants were separated into stems, branches, and leaves whereas gliricidia plants were separated into stems and leaves. The litterlayer was removed from the entire plots and placed in paper bags. As there was no weed growth and the plants were harvested in a dry spell it was relatively easy to gather together the litter layer from the soil surface. For the imperata fallow there was virtually no litter. In each plot, total fresh matter was weighed of the different plant parts, and subsamples were taken to the laboratory for dry matter determination and nutrient analysis. Roots were not sampled in this study. In the laboratory, all plant samples were rinsed with distilled water and ovendried at 70°C for 72h. Samples were ground (mesh 0.2 mm) and sent for nutrient analysis to the laboratories of the School of Land and Food of the University of Queensland. One subsample was digested in 5:1 nitric:perchloric acids and analysed for P, K, Ca, and Mg using ICP AES (Spectro Model P). A second subsample was digested according to the Kjeldahl procedure and analysed for C and N on an Alpkem Rapid Flow Analyser Series 300. Nutrient stocks in the above ground biomass were calculated by multiplying dry mass with the nutrient concentration.

Statistical analysis
For the above ground biomass, nutrient concentration and content, and nutrient removal standard deviations were calculated. An ANOVA was conducted to investigate statistical differences in soil chemical properties and in the discussion of the results the statistically significant difference was set at 5% ($P<0.05$). All statistical analysis was conducted with Statistix 8.

4.3. Results

Above ground biomass
One-year-old piper had produced 13.7 Mg dry matter (DM) ha^{-1}, compared to 23.3 Mg ha^{-1} produced by gliricidia and 14.9 Mg ha^{-1} by imperata fallow (Table 1). The stem biomass of gliricidia was almost three times larger than that of piper. Gliricidia also produced more litter and leaves than piper. Average rate of above ground biomass accumulation in kg DM ha^{-1} day^{-1} was about 38 for piper, 64 for gliricidia and 41 for imperata. In the study area, farmers commonly remove the stems when the fallows are slashed and small branches and leaves are returned to the soil as

surface mulch. Above ground biomass that would be returned to the soil was about 8 Mg ha^{-1} for piper and gliricidia, and 14.9 Mg ha^{-1} for imperata.

Table 1. Above ground biomass production one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea

	Biomass in Mg dry matter ha^{-1} ± 1 SD		
	Piper aduncum	*Gliricidia sepium*	*Imperata cylindrica*
Stems	5.9 ± 1.0	15.2 ± 0.6	
Branches	1.6 ± 0.2		
Leaves	4.2 ± 0.4	5.2 ± 0.3	14.9 ± 2.0
Litter	2.0 ± 0.4	2.9 ± 0.9	
Total	13.7 ± 1.3	23.3 ± 1.6	14.9 ± 2.0

Nutrient stocks – carbon, nitrogen and phosphorus

Carbon and nutrient concentrations of the various plant parts are given in Table 2. Gliricidia leaves contained relatively high N concentrations compared to the leaves of piper and imperata. Phosphorus concentrations were low in most plant parts and little difference was found between the fallow species. Potassium concentrations were high in piper leaves and branches, and also the piper stems and litter had relatively high K concentrations. Concentrations of Ca and Mg were highest in the litter of piper and gliricidia. Imperata had low concentrations of all major nutrients.

Nutrient concentrations were multiplied with the dry biomass in order to calculate nutrient stocks. Total organic C in the above ground biomass of the piper fallow was 5.8 Mg ha^{-1} of which almost half was found in the stems (Table 3). Gliricidia fixed two times more C and about two-thirds of the plant organic C was found in the stems. Total above ground C accumulation by imperata was larger than that of piper and equalled the amount of C fixed in gliricidia stems. In all three fallows, the amount of C in the above ground biomass was only a fraction of the organic C in the topsoil. Above ground biomass C averaged 7% of the total C stock (biomass, litter, soil) for piper and imperata, and about 11 % for gliricidia (Fig. 1). This slightly larger fraction for the gliricidia is caused by the larger wood production of gliricidia as compared to piper (Table 1). Above ground biomass of gliricidia contained 356 kg N ha^{-1} of which half was found in the stems. Nitrogen contents of the gliricidia leaves exceeded the total N content of the piper biomass. Imperata had accumulated the lowest amount of N and the concentrations in its leaves were on average below 6 g N kg^{-1}. Total N in the topsoils (0-0.15 m) under the three fallows was high (about 8200 kg N ha^{-1}). Similar to what was found for organic C, stocks of N in the topsoil largely exceeded N in the above ground biomass. The fraction of N in the biomass from the total N stocks was less than 2% for piper and imperata, and about 4% for gliricidia (Fig. 1). Soil available P stocks at the end of the fallows were very low and around 5 kg ha^{-1} under each of the three fallow species. Piper biomass contained about four times more P than the available P in the topsoils and most P was found in the piper leaves. Seven times more P was found in the above ground gliricidia biomass than in the soil. Most of the P in the gliricidia was found in the stems. Imperata leaves had very low P concentrations (<0.8 g P kg^{-1}) but two times more P was found in the imperata biomass than in the topsoil. Overall, gliricidia fallows had the largest P stock, which was more than two times the P stock of imperata fallows

Table 2. Carbon and nutrient concentration of the biomass of one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea

Fallow species		C	N	P	K	Ca	Mg
		% ± 1 SD					
Piper aduncum	Stems	45.2 ±0.1	0.4 <0.1	0.1 <0.1	1.6 ±0.2	0.2 <0.1	0.1 <0.1
	Branches	41.8 ±0.6	0.7 ±0.1	0.3 ±0.1	3.7 ±0.5	0.6 ±0.1	0.4 ±0.1
	Leaves	41.2 ±1.3	1.6 ±0.3	0.2 <0.1	3.0 ±0.2	1.8 ±0.1	0.5 ±0.1
	Litter	35.4 ±0.8	0.9 ±0.1	0.1 <0.1	1.2 ±0.2	2.9 ±0.2	0.5 ±0.1
Gliricidia sepium	Stems	45.4 ±0.4	1.1 ±0.2	0.2 <0.1	1.0 ±0.1	0.6 ±0.1	0.1 <0.1
	Leaves	45.9 ±0.4	2.8 ±0.2	0.2 <0.1	1.6 ±0.2	2.4 ±0.3	0.5 ±0.1
	Litter	39.6 ±2.9	1.6 ±0.1	0.1 <0.1	0.3 <0.1	3.4 ±0.5	0.6 ±0.1
Imperata cylindrica	Whole plant	44.7 ±0.4	0.5 ±0.1	0.1 <0.1	0.6 <0.1	0.4 ±0.1	0.2 <0.1

Nutrient stocks – cations

Piper biomass contained large amounts of K (Table 3) due to the high K concentration of its leaves (Table 2). More than 40% of the total K-stock of piper fallows was found in the above ground biomass (Fig. 1). Gliricidia biomass contained also high amounts of K of which about two-third was found in the stems. Imperata contained the lowest amount of K, but had the highest soil K stocks. Gliricidia biomass contained 312 kg Ca ha^{-1} of which 127 kg ha^{-1} was found in the leaves (Table 3). Piper biomass contained two-time less Ca than gliricidia whereas imperata had accumulated only 56 kg Ca ha^{-1}. For piper most of the Ca was found in the leaves. For all three fallow species, Ca stocks in the topsoil largely exceeded the Ca in the above ground biomass and for piper and gliricidia less than 7% of the total Ca was found in the above ground biomass (Fig. 2). The amounts of Mg in leaves of piper and gliricidia were similar but total Mg accumulation by gliricidia was almost 20 kg ha^{-1} higher. One-third of the Mg in the above ground biomass of the gliricidia was found in the litter. Less than 7% of the Mg stocks of gliricidia and piper were found in the above ground biomass whereas less than 3% of the Mg stock was in the imperata biomass.

Table 3. Carbon (Mg ha^{-1}) and nutrient content (kg ha^{-1}) of the topsoil and above ground biomass of one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea, partly after Hartemink (2003)

Fallow species	Compartment	C	N	P	K	Ca	Mg
		Mg ha^{-1}			kg ha^{-1}		
Piper aduncum	Stems	2.7 ±0.4	23 ±2.8	7.4 ±0.6	92 ±7.9	10 ±1.6	5 ±1.4
	Branches	0.6 ±0.06	11 ±2.1	4.5 ±1.2	58 ±9.1	10 ±1.7	6 ±1.2
	Leaves	1.7 ±0.1	67 ±8.6	8.2 ±1.5	125 ±13.8	78 ±7.0	23 ±3.7
	Litter	0.7 ±0.1	19 ±3.8	1.7 ±0.3	23 ±3.0	59 ±15.5	11 ±34
	Total vegetation	5.8 ±0.6	120 ±11.5	21.8 ±1.7	299 ±24.6	157 ±19.8	45 ±8.2
	Soil (0-0.15 m)	80.3 ±7.8	8081 ±642	5.9 ±1.0	377 ±163	4981 ±790	879 ±265
	Total	86.1 ±7.4	8201 ±638	27.7 ±2.5	657 ±150	5138 ±771	924 ±258
Gliricidia sepium	Stems	6.9 ±0.3	164 ±24.0	24.2 ±4.5	159 ±11.3	90 ±22.4	23 ±3.5
	Leaves	2.4 ±0.2	145 ±11.9	8.6 ±0.6	81 ±11.2	127 ±13.9	24 ±6.9
	Litter	1.1 ±0.3	47 ±11.7	3.0 ±1.2	8 ±2.0	95 ±16.4	17 ±6.2
	Total vegetation	10.4 ±0.7	356 ±10.6	35.9 ±4.1	248 ±14.7	312 ±37.7	64 ±12.3
	Soil (0-0.15 m)	86.2 ±9.6	8059 ±776	4.7 ±1.1	327 ±147	4600 ±533	868 ±162
	Total	96.6 ±9.1	8415 ±780	40.6 ±3.8	575 ±157	4912 ±549	932 ±170
Imperata cylindrica	Whole plant	6.7 ±0.9	76 ±23.9	11.9 ±3.7	89 ±15.5	56 ±17.5	29 ±8.5
	Soil (0-0.15 m)	85.7 ±8.9	8311 ±911	5.2 ±1.8	508 ±148	5329 ±472	871 ±192
	Total	92.4 ±8.6	8387 ±913	17.1 ±3.0	597 ±149	5385 ±458	900 ±197

The soil content of Ca, Mg, K and P is based on extraction and not on total analysis

Changes in soil properties
Soil properties were measured before the fallows were planted and after one year when the fallows were slashed. Statistical analysis revealed that the pH H_2O had significantly ($P<0.01$) declined under piper and imperata fallow by 0.4 to 0.5 pH unit (Table 4). The smaller pH change under gliricidia fallow was not significant. Levels of organic C and total N were both significantly ($P<0.05$) increased under gliricidia but had not changed significantly under the other two fallow species.

No significant changes were found in available P, CEC, exchangeable Ca and Mg and base saturation under the three fallows. Exchangeable K was significantly ($P<0.01$) reduced by 4.1 $mmol_c$ K kg^{-1} in the topsoils under piper but no changes were apparent after gliricidia or imperata fallows. Soil bulk densities had slightly increased under all three fallow species but data were insufficient for a statistical comparison.

Nutrient cycling
Although the above ground biomass of gliricidia was almost two times higher than that of piper, the amount of C returned to the soil is the same for piper and gliricidia due to the removal of large quantities of gliricidia stems (Fig. 2). Imperata biomass returns the highest amounts of C to the soil because no biomass is removed from the plots. Gliricidia had accumulated large amounts of N and returned almost 200 kg N ha^{-1} with the leaf and litter biomass. Little N was removed with the piper wood and one-year old piper fallows returned almost 100 kg N ha^{-1}.

The amount of P returned to the soil was around 13 kg P ha^{-1} for the three fallow species. Piper accumulated the largest amount of K and returned more than 200 kg ha^{-1} with its leaves, litter and small branches; gliricidia and imperata returned less than half of the piper. Large amounts of Ca were returned with the gliricidia leaves, intermediate amounts with piper and relatively little Ca was returned with the imperata biomass.

Similar amounts of Mg were returned with the piper and gliricidia biomass. Fig. 2 shows that considerable amount of all major nutrients are removed with the wood of the gliricidia wood (stems). Less nutrients were removed with the piper wood compared to the gliricidia wood.

Table 4. Soil chemical properties before and after one-year fallow with *Piper aduncum, Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea. Sampling depth 0-0.15m (except for bulk density), partly after Hartemink (2003)

Fallow species	Sampling time	pH H_2O 1:5 w/v	Organic C g kg^{-1}	Total N g kg^{-1}	Olsen P mg kg^{-1}	CEC pH7 $mmol_c$ kg^{-1}	Exchangeable cations $mmol_c$ kg^{-1}			Base Saturation %	Bulk Density [1] ($Mg\ m^{-3}$)	
							Ca	Mg	K		0-0.05	0.10-0.15
Piper aduncum	Before the fallow	6.2	68.4	6.2	8.4	407	242	60	12.5	77	0.61	0.71
	After the fallow	5.8	71.0	7.2	5.2	440	219	63	8.4	67	0.70	0.81
	Difference	$P<0.01$	ns	ns	ns	ns	ns	ns	$P<0.01$	ns		
Gliricidia sepium	Before the fallow	6.2	67.8	6.2	5.9	393	252	63	9.5	83	0.57	0.64
	After the fallow	5.9	82.2	7.7	4.5	416	220	68	7.9	71	0.64	0.75
	Difference	ns	$P<0.05$	$P<0.05$	ns	ns	ns	ns	ns	ns		
Imperata cylindrica	Before the fallow	6.3	70.1	6.7	6.5	409	279	60	11.6	86	0.59	0.74
	After the fallow	5.7	76.9	7.5	4.6	450	239	65	11.6	71	0.67	0.81
	Difference	$P<0.01$	ns	ns	ns	ns	ns	ns	ns	ns		

ns – no statistical significance ($P>0.05$)

[1] for bulk density there were insufficient data to conduct a t-test

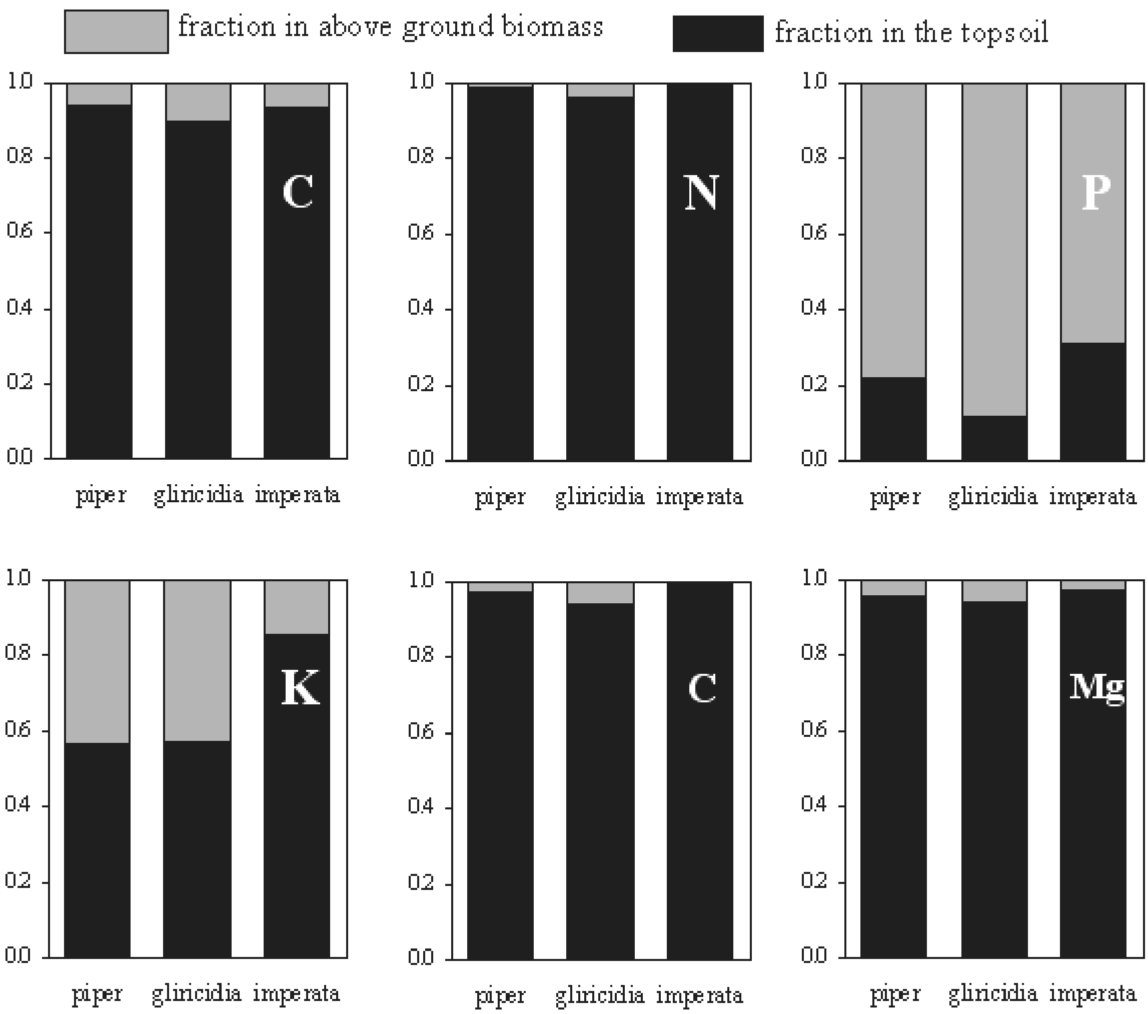

Fig. 1. Fraction of nutrients in the above ground biomass of one-year old *Piper aduncum, Gliricidia sepium and Imperata cylindrical* fallows and in the topsoil (0-0.15 m) in the humid lowlands of Papua New Guinea. The soil content of Ca, Mg, K and P is based on extraction and not on total analysis

4.4. Discussion

There were considerable differences in biomass and nutrient stocks between the two woody fallows (piper, gliricidia) and between the woody fallows and the non-woody fallow (imperata). This discussion focuses on biomass and nutrient stocks, changes in soil properties and the cycling of nutrients and the implications for cropping systems on high base status soils in the humid lowlands of Papua New Guinea.

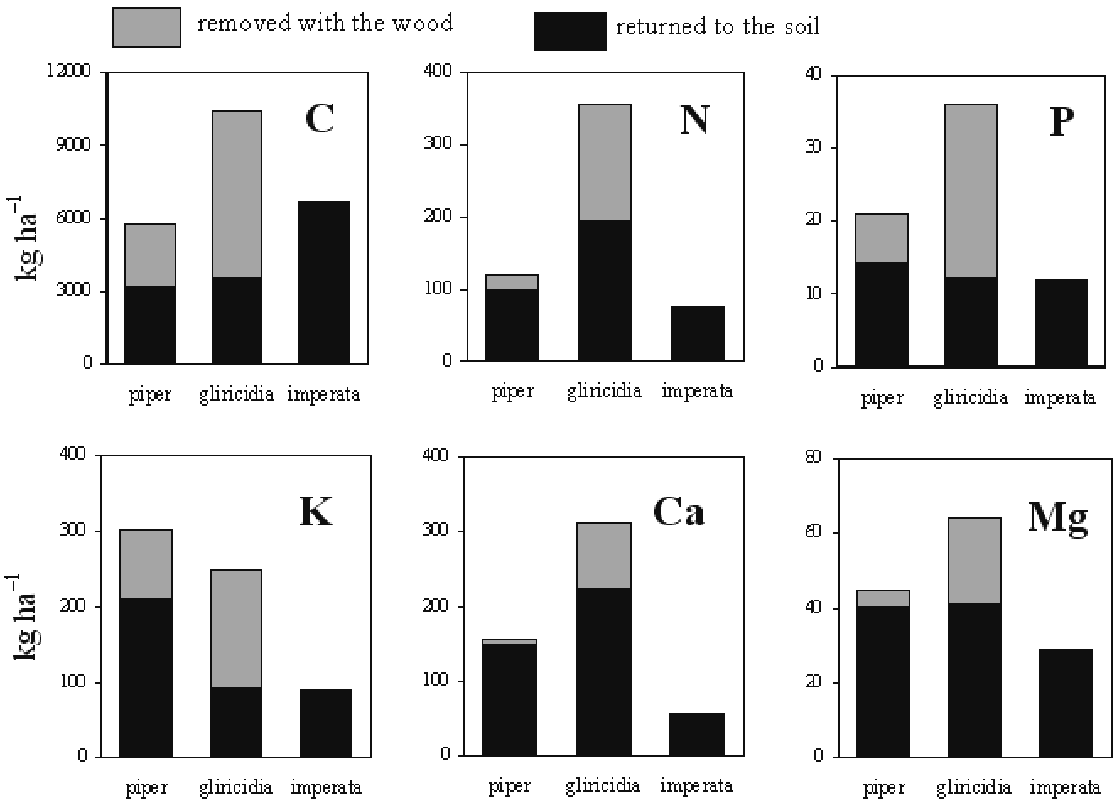

Fig. 2. Carbon and nutrients removed with the wood and returned to the soil of one-year old Piper *aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea

Biomass

Total above ground biomass accumulation (including litter) ranged from 13.7 Mg DM ha^{-1} year^{-1} (piper) to 23.3 Mg ha^{-1} year^{-1} (gliricidia). These are relatively high rates of biomass accumulation. In the humid tropics, accumulation of above ground biomass during the first ten years of fallow growth generally ranges between 4 and 15 Mg DM ha^{-1} year^{-1} (Szott *et al.*, 1999). High rates of biomass accumulation result in high nutrient accumulation and quick soil cover, which helps to reduce nutrient losses, and may also result in high N gains by leguminous crops and trees. The high rates found in this experiment are influenced by the high base status of the soils, but more biomass could have been produced. In another experiment at the same experimental site it was found that *Piper aduncum* biomass accumulation was linearly related to the amount of rain. In that experiment piper had accumulated 48 Mg ha^{-1} after 23 months (average 25 Mg DM ha^{-1} year^{-1}). Total rain during the 23 months was 5,323 mm (mean 231 mm month^{-1}) compared to 1,828 mm of rain (mean 152 mm month^{-1}) during the experimental period reported in this paper. In the experiment reported in this paper, growth of *Piper aduncum* was retarded due to the relatively dry conditions. The data confirm the general trend that fallow biomass accumulation increases in the tropics with increasing rainfall (Szott *et al.*, 1999).

Total biomass accumulation of the fallows was higher as below ground biomass was not assessed due to the stoniness of the soils which makes quantification difficult (Hartemink, 2001). Szott and Palm (1996) based on the work of Uhl (1987) and others, worked with a ratio below ground/above ground biomass of 0.1 to 0.2 for natural and improved fallows. Assuming a ratio of 0.15, total biomass (including litter) is 15.8 Mg ha^{-1} for piper, 26.8 Mg ha^{-1} for gliricidia, and 17.1 Mg ha^{-1} for imperata. Again, these are large amounts of biomass accumulated in a short period and that is exactly what a fallow in the tropics should do (Sanchez, 1999).

Nutrient stocks and cycling

In all three fallow types, the bulk of the C, N, Ca and Mg was present in the soil and only a small fraction was found in the above ground biomass. In the humid tropics it is mostly found that more C is found in the soil than in vegetation (Houghton, 1995), and the data reported here confirm this. It is partly due to the fact that the soils have relatively high C concentrations (around 50 g kg^{-1}). The bulk of N was present in the soil (1 to 4% of the total) and not in the above ground biomass, which is also commonly found in tropical rainforests. Contrary, most of the P and a considerable part of the K stock of these short-term fallows is found in the above ground biomass. These findings suggest that the transfer of nutrients in fallow-cropping systems should be differently appraised for different nutrients.

Total nutrient stocks in the fallows is higher because (i) nutrients in roots were not measured, (ii) only nutrients in the 0-0.15 m soil horizon were measured, (iii) only extractable P and cations were measured whereas total contents of these nutrients is higher. Organic C and total N are the total figures but P is extracted by bicarbonate and Ca, Mg and K by an NH_4-acetate so P and cations are a fraction of the total amounts present in the soil. The soil nutrient data for P and the cations are thus lower than the total nutrient stocks (Hartemink, 2003). On the other hand, the data give a fair quantification of the amounts of nutrients that are potentially available for crop production. Due to the stoniness of the subsoil most roots were found in the top 0.15 m, deep capture of nutrients which is important in many fallow systems (Hartemink *et al.*, 2000a), is not relevant for this study site. Therefore, nutrient stocks reported for the topsoil are more or less equal to the amount of nutrients available (Hartemink, 2003).

Gliricidia had accumulated the largest amounts of all major nutrients (except for K) and more than 350 kg N ha^{-1} was accumulated in the above ground biomass of gliricidia. Giller (2001) summarised estimates of N content of one-year old gliricidia prunings and values ranged from 19 to 204 kg N ha^{-1}. Although the roots of N fixing trees may contain large amounts of N it was found that gliricidia contains little N below ground (Giller, 2001; Schroth and Zech, 1995) so that most of the N is found in the above ground biomass. Much of the N in the gliricidia leafs and litter (192 kg ha^{-1}) is rapidly mineralised when the gliricidia fallow is slashed and becomes available to the succeeding crop (Hartemink and O'Sullivan, 2001).

The major function of fallows is to recycle and conserve nutrients rather than to cause net increases in ecosystem nutrient stocks (Buresh and Cooper 1999). Gliricidia and piper fallow recycled larger amounts of nutrients than imperata which may induce greater losses. Hartemink (2003) compared nutrient budgets of the fallow-crop systems with changes in soil nutrient contents. It was found that more N and Ca were lost from the soil than could be explained by the input-output budgets and it is likely that leaching losses were high (Hartemink, 2003).

Soil changes

The observational period was only one year and changes in soil chemical properties using conventional analytical techniques are not always found within such period (Young, 1997). Nonetheless some interesting changes in soil properties and differences between the fallow species were found. Exchangeable K decreased significantly under piper fallow which reflected the high K uptake by piper. Soil organic C significantly increased under gliricidia fallow which is related to the high biomass and litter production compared to the other two fallow vegetations. Restoration of soil organic matter is one of the main functions of fallows (Greenland and Nye, 1959) and apparently gliricidia fallows can relatively quickly increase soil organic C contents. On the other hand, reports from the literature have shown that there is often a decrease in soil C-stock during first 8 months of a fallow period and then and increase in the remainder (Szott *et al.*, 1994). Juo *et al.* (1995) observed an increase in newly established fallows during the first year and the data reported in this paper confirm this observation.

There were also some significant soil physical changes during the fallow period. Soil moisture measured directly after one-year piper fallow was significantly lower than under gliricidia fallow. Soil moisture content in the topsoil under piper was 0.29 $m^3 m^{-3}$ as compared to 0.36 $m^3 m^{-3}$ under gliricidia (Hartemink and O'Sullivan 2001). This effect lasted for several weeks after the fallows were slashed and a sweet potato crop was planted. The lower soil moisture contents after piper is an advantage since high rainfall depresses sweet potato yield (Hartemink *et al.*, 2000b, Hartemink, 2003).

Implications

Although piper biomass production was high, growth was depressed due to the relatively dry conditions. As a result, gliricidia produced much more biomass and accumulated more nutrients than piper. Imperata produced lowest amounts of biomass and nutrients. The imperata fallow is not preferable as its nutrient accumulation is limited, fixes no N and is also difficult to clear and yields no additional products (firewood). Farmers might not consider improved fallows unless they provide functions and products in addition to soil fertility restoration (Buresh and Cooper, 1999). However, for most farmers the effects of the short-term fallow vegetations on subsequent crop yield may be an overriding factor. Piper returned largest amounts of nutrients (particular K) to the soil and as most of the cropping systems in the humid lowlands of Papua New Guinea are dominated by root and tuber crops which are large K-consumers (Hartemink, 2003), it is a suitable fallow species.

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5. Leaf litter decomposition of *Piper aduncum, Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea *

Abstract

No information is available on the decomposition and nutrient release pattern of *Piper aduncum* and *Imperata cylindrica* despite their importance in shifting cultivation systems of Papua New Guinea and other tropical regions. We conducted a litter bag study (24 weeks) on a Typic Eutropepts in the humid lowlands to assess the rate of decomposition of *Piper aduncum, Imperata cylindrica* and *Gliricidia sepium* leaves under sweet potato (*Ipomoea batatas*). Decomposition rates of piper leaf litter were fastest followed closely by gliricidia, and both lost 50% of the leaf biomass within 10 weeks. Imperata leaf litter decomposed much slower and half-life values exceeded the period of observation. The decomposition patterns were best explained by the lignin plus polyphenol over N ratio which was lowest for piper (4.3) and highest for imperata (24.7). Gliricidia leaf litter released 79 kg N ha^{-1} whereas 18 kg N ha^{-1} was immobilised in the imperata litter. The mineralization of P was similar for the three species, but piper litter released large amounts of K. The decomposition and nutrient release patterns had significant effects on the soil. The soil contained significantly more water in the previous imperata plots at 13 weeks due to the relative slow decomposition of the leaves. Soil N levels were significantly reduced in the previous imperata plots due to immobilisation of N. Levels of exchangeable K were significantly increased in the previous piper plots due to the large addition of K. It can be concluded that piper leaf litter is a significant and easily decomposable source of K which is an important nutrient for sweet potato. Gliricidia leaf litter contained much N whereas imperata leaf litter releases relatively little nutrients and keeps the soil more moist. Gliricidia fallow is more attractive than an imperata fallow for it improves the soil fertility and produces fuelwood as additional saleable products.

5.1. Introduction

The key component of a shifting cultivation system is the recycling of nutrients through the addition of above and below ground biomass of the

* Hartemink, A.E. and J.N. O'Sullivan, 2001. Leaf litter decomposition of *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea. Plant and Soil, 230: 115–124. © Springer; reprinted with permission.

fallow vegetation. Fallows in the tropics mean large biomass accumulations and such fallows can be natural, enriched or improved (Sanchez, 1999). Natural fallows consists of indigenous secondary vegetation which grows after a cropping period, whereas improved fallows are deliberately planted species which are usually N_2-fixing (Sanchez, 1999). The amount of nutrients recycled in a fallow system depends on the quality and quantity of the fallow biomass but the rate of decomposition and nutrient release of the biomass is, however, determined by its chemical composition and the climatic conditions (Cadisch and Giller, 1997).

Shifting agriculture is widely practised in the humid lowlands of Papua New Guinea where each year approximately 200,000 ha of forest, secondary fallow or grassland are cleared for village-based food and cash crop production (Freyne and McAlpine, 1987). Two types of secondary fallow vegetation are common in the humid lowlands: *Piper aduncum* (L.) and *Imperata cylindrica* (hereafter referred to as piper and imperata, respectively). Piper is a shrub indigenous to tropical America and it was introduced into Papua New Guinea in the 1930s (Rogers and Hartemink, 2000). Piper has invaded aggressively in the lowlands of the Morobe and Madang Province where it forms locally monospecific stands (Kidd, 1997) and its invasion of secondary forests can be degenerative (Rogers and Hartemink, 2000). Farmers favour piper on short-fallowed land because it can be easily cut and is suitable as firewood, and many farmers claim that piper fallows makes the soil fertile and dry. Imperata grasslands in the Papua New Guinea lowlands are man-made and have resulted from annual bushfires, which hampers regrowth of woody vegetation.

The shifting agricultural system in parts of the Morobe lowlands consists of a short fallow period (< 3 to 5 years) alternated with a cropping period of about one year. At the end of the fallow period, piper is usually coppiced at 0.2 to 0.5 m above the ground, and the vegetation debris is left to dry for some weeks whereafter the woody parts are removed and are mostly used for firewood. Burning the slashed vegetation is uncommon due to the prevailing wet conditions, which hampers drying. Taro (*Colocasia esculenta*) or maize (*Zea mays*) are commonly firstly planted after a fallow period and these are gradually interplanted with sweet potato (*Ipomoea batatas*), which is the major staple food in the lowlands (Bourke 1985), and bananas (*Musa* sp.) and sugar cane (*Saccharum* sp.). After one year, the piper has sprouted forming large branches, the bananas have grown large and the cropping site reverts back to bush. No information is available on the amount of nutrients cycled in these short fallow shifting cultivation systems.

In the large body of literature on decomposition, a considerable number of studies have been conducted under laboratory conditions (Palm and Sanchez, 1991; Tian *et al.*, 1992b; Handayanto *et al.*, 1997; Lupwayi and

Haque, 1998) or under field conditions with no crop after the fallow (Budelman, 1988; Oglesby and Fownes, 1992; Handayanto *et al.*, 1994; Mwiinga *et al.*, 1994). Although such information is essential to quantify maximum rates of decomposition, the absence of a crop is unrealistic as most farmers would plant shortly after the fallow vegetation is slashed. To our knowledge no decomposition fieldstudy has been conducted with sweet potato as the first crop after a fallow. Sweet potato has a complete soil cover within 6 to 10 weeks after planting, which may affect the decomposition of fallow vegetation debris.

In October 1996, we started an experiment aiming to investigate the effects of piper and imperata fallows in comparison to an improved fallow with *Gliricidia sepium* (hereafter referred to as gliricidia) in the humid lowlands of the Morobe Province of Papua New Guinea. We planted plots with piper, imperata and gliricidia, which were slashed after one year and planted with sweet potato. Litter bags were installed in the plots with the planting of sweet potato to assess leaf decomposition and nutrient dynamics. The main objectives of our experiments were to quantify (i) the chemical contents and decomposition rates of the fallow vegetation leaves, (ii) nutrient release pattern during decomposition, and (iii) the effects of decomposition on some selected soil chemical and physical soil properties.

5.2. Methods

Experimental site

The experiment was conducted near Hobu village (6°34'S, 147°02'E) which is 25 km N of the city of Lae in the Morobe Province. The site is located at an altitude of 405 m a.s.l. at the footslopes of the Saruwaged mountain range. Rainfall records were only available since the start of the experiment (November 1996) and the daily rainfall pattern during the litter bag study is depicted in Fig. 1. The end of 1997 was a relatively dry period caused by the El Niño/Southern Oscillation climatic event that hit the Pacific severely in 1997/98. March 1998 was a wet month with 725 mm of rain. Temperatures were not available for the experimental site but average daily temperatures at the University of Technology, which is situated about 15 km to the S of Hobu, are 26.3°C. The climate classifies as Af (Köppen).

The Hobu experimental site is located on an uplifted alluvial terrace with a slope of less than 2%. Soils are derived from a mixture of alluvial and colluvial deposits dominated by sedimentary rocks and coarse to medium grained, basic, igneous rocks. The soils are layered with water-worn gravelly and stony horizons below 0.2 m depth; effective rooting depth is over 0.7 m. Air-dried and sieved (< 2 mm) soil had the following properties in the top 0.12 m: pH H_2O (1:5 w/v) = 6.2, organic C (dry combustion) = 55 g kg^{-1}, available P (Olsen) = 9 mg kg^{-1}, CEC (NH_4Oac, pH7) = 400 $mmol_c$ kg^{-1}, exchangeable Ca = 248 $mmol_c$ kg^{-1}, exchangeable Mg = 78 $mmol_c$ kg^{-1}, exchangeable K = 16.9 $mmol_c$ kg^{-1}, clay = 480 g kg^{-1} and sand = 360 g kg^{-1}, bulk density = 0.82 Mg m^{-3}. The soils are classified as mixed, isohyperthermic, Typic Eutropepts (USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base). Further details on soil chemical and physical properties can be found in (Hartemink *et al.*, 2000). Inceptisols cover about 60% of Papua New Guinea and are the most intensively used soils (Freyne and McAlpine, 1987).

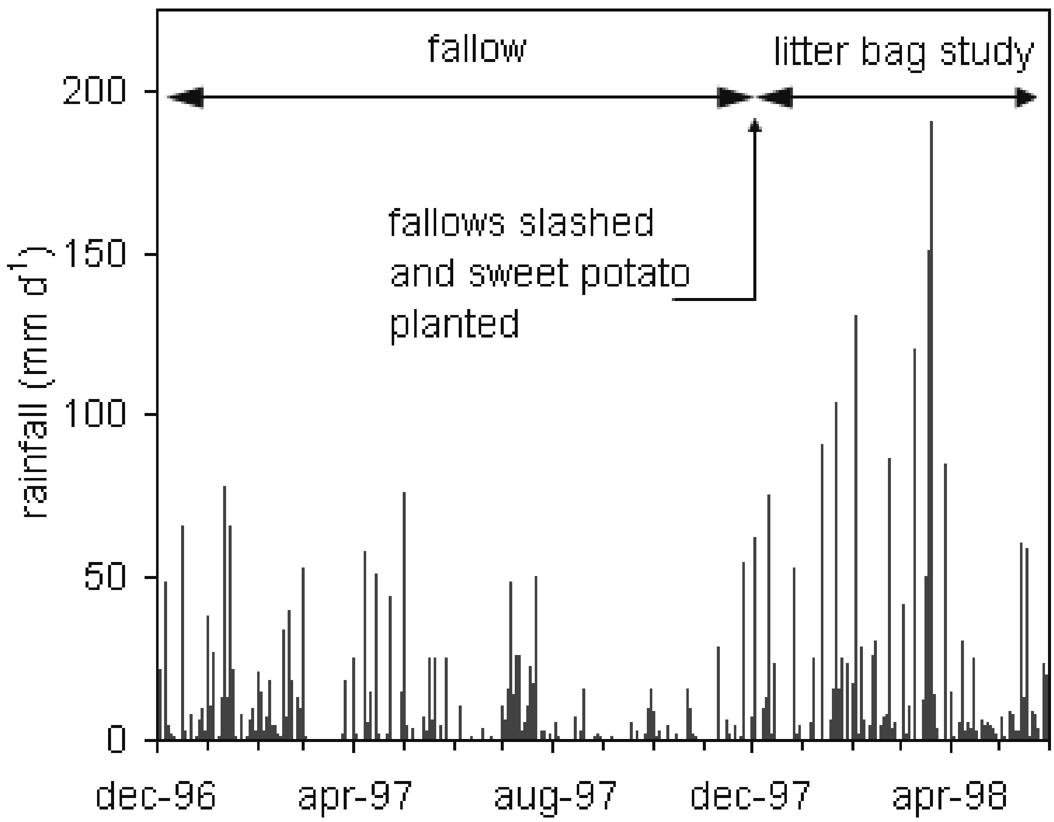

Fig. 1. Daily rainfall between December 1996 and June 1998 at the experimental site in the Morobe province of Papua New Guinea

Litter bag experiment

The litter bag study took place in an existing fallow experiment which was undertaken to investigate the effects of natural and improved fallows on sweet potato yields. In short, the experiment consisted of replicated plots (n = 4) planted with piper, imperata and gliricidia (27th November 1996) which were cut at ground level one year after growth (20-24th November 1997). Woody parts were removed from the piper and gliricidia plots and all plots were planted with sweet potato one week after the vegetation was slashed. Directly after the planting of sweet potato, litter bags were installed. No inorganic fertiliser was applied.

Leaves for the litter bags were hand-picked from piper and gliricidia trees in the experiment prior to the cutting, and included a mixture of new and old leaves. For imperata about 2 kg of leaves was cut at ground-level in each plot prior to the slashing. Leaves were washed with distilled water and ovendried at 70°C for 72h. Although ovendrying may affect mass loss rates (Taylor, 1998), in nearly all studies conducted on litter decomposition leaves were ovendried (e.g. Palm and Sanchez, 1991; Mwiinga *et al.*, 1994; Mafongoya *et al.*, 1998) and in order to allow comparison with other studies we also dried the leaves before they were put in the litter bags. Ovendrying also increases the homogeneity of the leaves.

Litter bags of 0.20 x 0.20 m were constructed from nylon mosquitowire with a mesh size of 1 mm (Palm and Sanchez, 1990; Mwiinga *et al.*, 1994). For each of the three species, 40 bags with 20 g ovendried leaf material were filled. Litter bags were randomly placed in the 16 plots (4 plots per species) two days after sweet potato was planted (29 November 1997). The bags were slightly covered with leaf litter to allow maximum influence of meso and macrofauna. Litter bags were sampled at 9, 16, 24, 29, 38, 51, 65, 86, 108, and 169 days, with one litter bag randomly selected from each plot and transported to the laboratory. So for each sampling time there were four bags (replicates) per treatment. Undecomposed litter was carefully separated from the litter bags and roots and soil particles were removed. The cleaned samples were put in paper bags and ovendried at 70°C for 72h to determine leaf litter mass remaining. Samples were ground (mesh 0.2 mm) before being sent for nutrient analysis at the laboratories of the School of Land and Food of the University of Queensland.

As the mulch applied to each treatment was the leaf material produced in the previous fallow, the quantity of mulch in each treatment varied. Imperata produced the largest leaf biomass (14.9 Mg ha^{-1} dry weight) while piper and gliricidia plots received 4.2 and 5.2 Mg ha^{-1} leaf mulch respectively. Both the quantity and quality of the mulch may have affected the growth of the sweet potato crop. Vine yield at harvest was much lower in the previous imperata plots (20.7 Mg ha^{-1} fresh weight) than in the previous piper and gliricidia plots which both yielded over 30 Mg vines ha^{-1}.

Leaf litter analysis

A sample of the leaves which were used to fill the litter bags was analysed for lignin, polyphenol and nutrients. Lignin was determined by the procedure of Van Soest and Wine (1968), and polyphenol by that of Dalzell and Kerven (1998), using purified *Leucaena pallida* condensed tannin as standard. Leaf litter samples were analysed for nutrients whereby one subsample was digested in 5:1 nitric:perchloric acids and analysed for P, K, Ca, Mg and S using ICP AES (Spectro Model P). A second subsample was analysed for C and N using a Leco CNS-2000 dry combustion analyser.

Soil sampling and analysis

Soil samples for chemical analysis were taken before the fallows were slashed (19th November 1997) and after one season with sweet potato (15th May 1998). Soil samples (0-0.15 m depth) were collected with an Edelman auger (diameter 0.05 m) at 12 random locations in a plot, mixed in a 20 L bucket and a subsample of about 1 kg was taken. Airdried samples were ground and sieved (2 mm) and were sent for analysis to the National Analytical Chemistry Laboratories in Port Moresby. The procedures for soil analysis were as follows: pH H_2O (1:5 w/v); organic C and total N by Leco CNS-2000 dry combustion; available P by Olsen; exchangeable cations and CEC by 1*M* ammonium acetate percolation (pH 7.0); particle size analysis by hydrometer.

Bulk density of the soil was measured on 19th November 1997 before the fallows were slashed and 6th May 1998. In each plot, the 0-0.05 and 0.10-0.15 m soil horizons were sampled using two 100 mL cores per depth and measurements were duplicated in each plot. Cores were ovendried at 105°C for at least 72h. Gravimetric values were multiplied with the bulk density to obtain volumetric water contents. The average bulk density of the two sampling depths was taken for each plot.

Data analysis

Several models were tested but it was found that the single exponential model provided the best fit for the decomposition pattern of the leaves. The single exponential model was fitted to the data:

$$Y = e^{-k \times t}$$

whereby Y is the proportion initial mass remaining at time t, and k is the decomposition factor. To calculate the k values the formula was rewritten as

$$\ln Y = -k \times t$$

hence the slope of the line, calculated by linear regression, is the k value. Although the coefficients of determination were over 87%, it was found that the single exponential equation did not provide the best fit of the piper and gliricidia data over the complete time of observation (i.e. 169

days). Therefore, k values were also calculated for the first 51 days and the first 108 days.

Analysis of variance was run on the decomposition data whereby time and treatment (i.e. species) were treated as main effects. Volumetric soil moisture data were subjected to ANOVA and standard error of the difference in means were calculated. A simple t-test was performed to analyse statistical differences in the soil chemical data. All statistical analysis was conducted with Statistix 2.0 software.

5.3. Results

Chemical composition and decomposition pattern

Gliricidia leaves had the highest N content, which were on average seven times higher than imperata leaves (Table 1). The C:N ratios of imperata leaves were high because of the low N contents of the leaves. Piper leaves had intermediate N levels, but P and K concentrations were highest in piper leaves. Piper leaves were lowest in lignin and contained also much lower polyphenol contents than gliricidia leaves. Imperata leaves had the lowest polyphenol contents. The ratio lignin (L) plus polyphenol (PP) over N concentrations was lowest for the piper leaves despite its much lower leaf N concentration when compared to gliricidia leaves.

Table 1. Chemical characteristics of *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* leaves (g kg^{-1} ± 1 SD)

	Piper aduncum	*Gliricidia sepium*	*Imperata cylindrica*
C	404 ±15.3	438 ±9.8	426 ±4.7
N	15.6 ±2.0	25.2 ±2.0	3.9 ±0.4
P	1.9 ±0.4	1.4 ±0.1	0.8 ±0.2
K	28.2 ±1.4	12.6 ±1.8	4.5 ±1.1
Ca	18.7 ±1.7	27.7 ±6.3	3.0 ±0.7
Mg	5.4 ±1.2	5.5 ±1.6	2.6 ±0.5
S	1.0 ±0.1	1.6 ±0.2	0.3 ±0.1
Lignin (L)	61.3 ±14.4	149.8 ±23.8	93.5 ±8.3
Polyphenol (PP)	4.2 ±0.2	26.2 ±13.5	2.4 ±0.4
C/N	26 ±2	18 ±1	110 ±11
(L + PP)/N	4.3 ±1.2	7.0 ±1.2	24.7 ±4.2

The decomposition pattern of piper, gliricidia and imperata leaves is depicted in Fig. 2 whereby the mass remaining is expressed as percentage of the initial ovendry weight of the leaves. During the first four weeks of the decomposition there was little difference between piper and gliricidia, which both lost about 30% of the initial mass. Thereafter, piper leaves decomposed more readily. Gliricidia leaves decomposed slightly slower despite its higher N contents than piper, but gliricidia leaves had relatively high polyphenol levels. Rates of decomposition of piper and gliricidia leaves decreased five weeks after the bags were installed in the field and decomposition had virtually stopped after 15 weeks. Imperata leaves decomposed slowest and at the end of the experiment (24 weeks), more than 55% of the imperata leaf mass had not decomposed. Thus the time taken for decomposition of half the biomass was 7 weeks for piper, 12 weeks for gliricidia and greater than 24 weeks for imperata.

Decomposition constants k were calculated for different periods (i.e., 51, 108 and 169 days). The three k factors differed significantly ($P<0.001$) if k was calculated based on the data of the first 51 days (Table 2). When k was calculated for 108 or 169 days no statistical difference was found between piper and gliricidia but both were significantly higher than the calculated k values for imperata leaf litter decomposition.

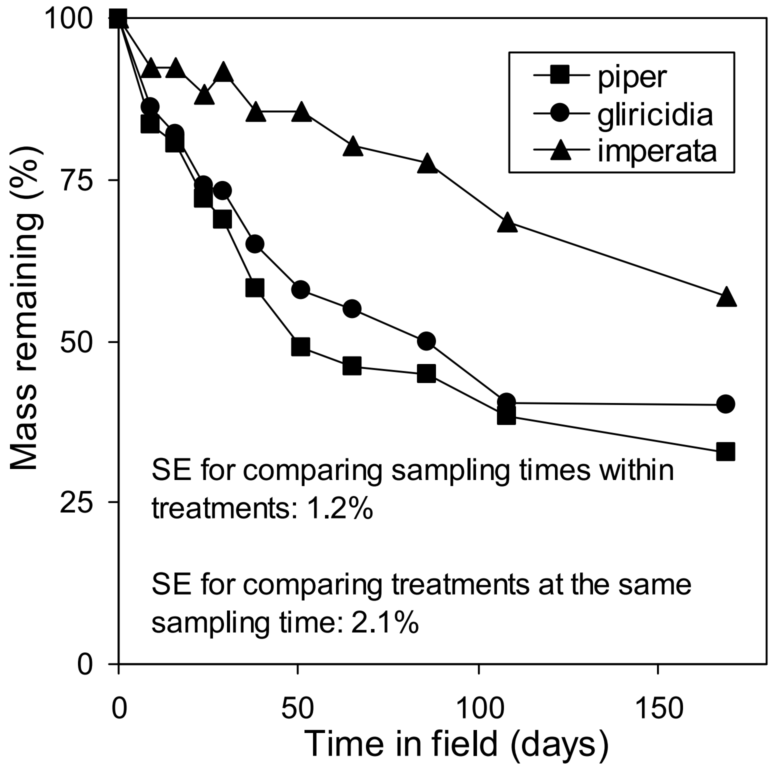

Fig. 2. Decomposition pattern of *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea

Nutrient change and release

Changes in major nutrient concentrations in the leaf litter are depicted in Fig. 3. For most nutrients, changes appeared to be irregular over the first 51 days, perhaps reflecting variable rates of colonisation of individual litter bags by soil biota. There was a rapid initial loss of K but concentrations of other nutrients (Ca, Mg) tended to be maintained or slightly increased over the period of measurement. Soil contamination of the samples was judged to be low, as C concentrations were maintained or increased compared to the initial concentrations in the plant material, but both Al en Fe concentrations increased with time.

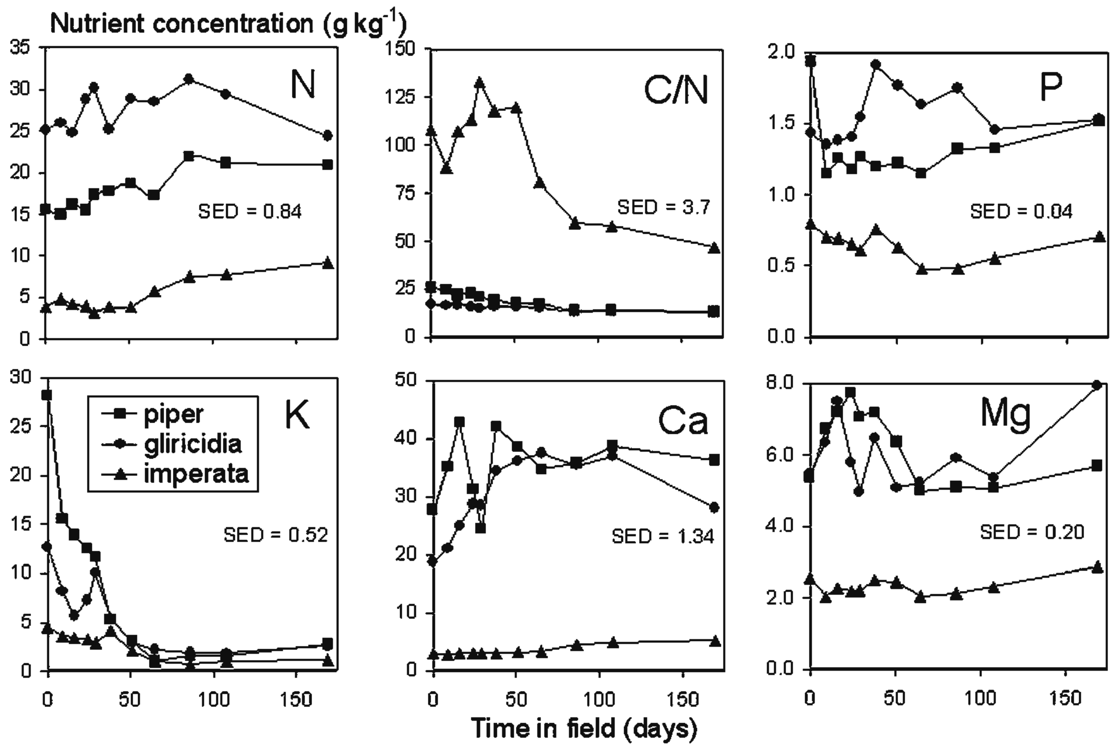

Fig. 3. Changes in nutrient concentration during decomposition of *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* leaves. SED is standard error of the difference in means, (96 *d.f.*)

Table 2. Decomposition constants (k $year^{-1}$) calculated for different periods (t). Values were calculated with single exponential model ($Y = e^{-k \times t}$), coefficient of determination (r^2) indicates goodness of fit

	t = 51 days		t = 108 days		t = 169 days	
	k	r^2	k	r^2	k	r^2
Piper aduncum	9.73	0.990	2.94	0.922	1.43	0.875
Gliricidia sepium	7.44	0.987	2.64	0.972	1.21	0.879
Imperata cylindrica	2.08	0.812	1.01	0.949	0.69	0.978
SED [1]	0.890		0.277		0.133	

[1] SED standard error of the difference in means (6 *d.f.*)

Table 3. Major nutrients in the leaf litter biomass at the beginning of the decomposition experiment and after 51, 108 and 169 days (kg ha^{-1})

Nutrient	Time (days)	Fallow species			SED[1]
		Piper aduncum	*Gliricidia sepium*	*Imperata cylindrica*	
N	0	67	130	59	9.5
	51	39	86	49	6.9
	108	35	61	78	8.6
	169	29	51	77	6.6
	Total released	38	79	-18	9.5
P	0	8	7	12	2.0
	51	3	5	8	1.9
	108	2	3	6	1.0
	169	2	3	6	0.4
	Total released	6	4	6	2.2
K	0	119	65	67	8.1
	51	7	9	27	8.5
	108	3	4	10	3.1
	169	4	6	10	1.1
	Total released	115	59	57	8.5

[1] SED standard error of the difference in means (6 *d.f.*)

While nutrient concentrations in the mulch may have remained relatively stable, these nutrients were released as the quantity of biomass declined (Table 3). At the start of the experiment, gliricidia litter contained about twice as much N than that of piper or imperata. Total amounts of N, P and K on a kg ha^{-1} basis, declined steadily, but there were differences between these three nutrients. More than half of the N in the piper and gliricidia leaf litter was mineralised during the 24 weeks, but the imperata leaf litter showed a net gain in N, indicating that soil N was being immobilised by the decomposition organisms. Phosphorus contents were similar for the three litters but piper leaf litter contained significantly more K than the leaf litter of gliricidia and imperata (P<0.001). No significant differences were found in the P release of the three leaf litters and about half of all P in the leaf litter was released after 24 weeks. The amount of K released by the piper was about two times higher than for gliricidia and imperata, which both released similar amounts. Nearly all K was released within the 24 week period.

Effects on soil properties

Volumetric soil moisture content was measured a few days before the one-year old fallows were slashed, and 13 and 24 weeks thereafter (Table 4). Moisture contents prior to the slashing of the fallows were significantly lower under piper than under gliricidia despite the fact that gliricidia had produced nearly 10 Mg ha DM ha^{-1} more above ground biomass than piper. The difference between the soil moisture contents of piper and imperata was not significant (P>0.05). Twelve weeks after the fallows were slashed, volumetric moisture contents under imperata were significantly higher, but at 24 weeks, after a comparatively dry period, there was no significant difference in volumetric soil moisture contents.

The effect of the different fallow mulches on soil chemical properties is shown in Table 5. In all soils it was found that the CEC declined and the base saturation had increased during the period of the litter bag experiment. In the piper plots, pH and available P were significantly increased and also exchangeable K levels were increased. Total nitrogen levels were significantly decreased in the previous imperata plots (Table 3).

Table 4. Volumetric soil moisture contents[1] ($m^3\ m^{-3}$) at the end of one year fallow with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* and after 13 and 24 weeks with sweet potato

Sampling time (wks) [2]	Sweet potato after one year of fallow with: *Piper aduncum*	*Gliricidia sepium*	*Imperata cylindrica*	SED [3]
0	0.29	0.36	0.32	0.019
13	0.43	0.45	0.47	0.010
24	0.40	0.40	0.42	0.011

[1] Values are the mean of 8 samples taken at 0-0.05 and 0.10-0.15 m depth
[2] Weeks after fallow vegetation was slashed and sweet potato was planted
[3] Standard error of the difference in means (12 *d.f.*)

Table 5. Soil chemical properties at the end of one year fallow with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* and after one season (26 weeks) with sweet potato. Sampling depth 0-0.15m

	Sampling time weeks [1]	pH H_2O 1:5	Organic C g kg⁻¹	Total N g kg⁻¹	Olsen P mg kg⁻¹	CEC mmol$_c$ kg⁻¹	Exchangeable cations mmol$_c$ kg⁻¹ Ca	Mg	K	Base saturation %
	0	5.5	71.0	7.2	5.2	440	219	62	8.4	67
Piper	26	5.7	74.7	6.5	8.0	344	227	62	13.4	89
aduncum	Difference	P<0.05	ns	ns	P<0.01	P<0.01	ns	ns	P<0.05	P<0.05
	0	5.9	82.2	7.7	4.5	416	220	68	7.9	71
Gliricidia	26	5.7	85.2	7.0	5.3	355	241	62	9.7	89
sepium	Difference	ns	ns	ns	ns	P<0.01	ns	ns	ns	P<0.01
	0	5.7	76.8	7.5	4.6	449	239	65	11.6	71
Imperata	26	5.8	76.2	6.4	9.7	350	235	59	12.7	88
cylindrica	Difference	ns	ns	P<0.05	ns	P<0.01	ns	ns	ns	P<0.05

[1] Weeks after fallow vegetation was slashed and sweet potato was planted
ns = not significant: P>0.05

5.4. Discussion

Large differences were found in the chemical composition, decomposition pattern and the effects on soil chemical and physical properties of piper, gliricidia and imperata leaf litter. No information is available in the literature on the chemical composition and decomposition of imperata and piper, but relatively much is known about *Gliricidia sepium* from research in various parts of the tropics (Table 6). Compared to published analytical results on gliricidia leaves our data (Table 1) are on average about 10 to 15 mg N kg^{-1} lower. However, low N contents of gliricidia leaves were also reported by Cadisch *et al.* (1998) and Mafongoya *et al.* (1998). Such differences in the N concentration of leaves of *Gliricidia sepium*, is possibly related to differences in germplasm, the time of sampling and the environmental conditions under which the trees are grown. The lignin as well as the polyphenol contents of the gliricidia leaves in our study were on average above those reported in the literature, but again a wide range of values have been reported (Table 6).

Polyphenols appear to influence rates of decomposition as they bind to N in the leaves forming compounds resistant to decomposition (Fox *et al.*, 1990; Palm and Sanchez, 1990). The mineralization of N is controlled more by soluble polyphenols (PP) than by lignin (L) or N content (Oglesby and Fownes 1992). Palm and Sanchez (1990) were among the first to combine these three parameters for the prediction of decomposition rate, using the ratio L+PP/N. This ratio has been found to be a useful indicator in successive decomposition studies. We found that the piper decomposed fastest followed closely by gliricidia but imperata litter decomposed considerably slower. Lignin contents in imperata leaves were in between piper and gliricidia and although numerous workers have suggested that the initial lignin content is a reasonable predictor of the rate of decomposition (Wieder and Lang, 1982), our data suggest that lignin content alone is insufficient. Decomposition rates of the imperata can not be explained by the polyphenol content because it was lowest of the three species. The slow decomposition is mainly caused by the very high C/N and (L+PP/N) ratio of the imperata leaves. Gliricidia had the highest N levels and lowest C/N ratio but because of its high polyphenol content which is common in legumes (Palm and Sanchez 1990; Oglesby and Fownes 1992), it decomposed slightly slower than piper. Therefore, the rate of decomposition for these three species in the prevailing environmental conditions is best predicted by the L+PP/N ratio.

An additional factor that may influence the rate of decomposition is the total mulch biomass. The thickness of the layer of imperata mulch may have slowed its colonisation by soil biota, and allowed the micro-environment within the layer to differ to a greater extent from that in the soil, possibly impeding some degradational activities of the biota.

Table 6. Chemical properties of *Gliricidia sepium* leaves as reported in the literature, and found in this study

	Location	Value ($g\ kg^{-1}$)	Reference
N	Nigeria, humid lowlands, Oxic Paleustalf	50.4	Tian *et al.*, 1992
	Ethiopia, highlands, Alfisol?	39.5	Anthofer *et al.*, 1997
	Peru, humid lowlands, Typic Paleudult	37.4	Palm and Sanchez, 1991
	Hawaii, humid lowlands, Typic Gibbsihumox	34.3	Oglesby and Fownes, 1993
	Sri Lanka, dry zone, Ultisols	29.2	Seneviratne *et al.*, 1998
	Indonesia, humid lowlands, Ultisols?	24.7-45.7	Cadisch *et al.*, 1998
	PNG, humid lowlands, Typic Eutropepts	25.2	This study
	Zimbabwe, highlands, ustic Alfisol	18	Mafongoya *et al.*, 1998
Lignin	PNG, humid lowlands, Typic Eutropepts	149.8	This study
	Ethiopia, highlands, Alfisol?	113.2	Anthofer *et al.*, 1997
	Zimbabwe, highlands, ustic Alfisol	111	Mafongoya *et al.*, 1998
	Nigeria, humid lowlands, Oxic Paleustalf	86	Tian *et al.*, 1992
	Hawaii, humid lowlands, Typic Gibbsihumox	86	Oglesby and Fownes, 1993
	Peru, humid lowlands, Typic Paleudult	78	Palm and Sanchez, 1991
	Sri Lanka, dry zone, Ultisols	61.7	Seneviratne *et al.*, 1998
	Indonesia, humid lowlands, Ultisols?	90-110	Cadisch *et al.*, 1998
Polyphenol	PNG, humid lowlands, Typic Eutropepts	26.2	This study
	Zimbabwe, highlands, Ustic Alfisol	23	Mafongoya *et al.*, 1998
	Nigeria, humid lowlands, Oxic Paleustalf	21.2	Tian *et al.*, 1992
	Hawaii, humid lowlands, Typic Gibbsihumox	20.7	Oglesby and Fownes, 1993
	Sri Lanka, dry zone, Ultisols	18.6	Seneviratne *et al.*, 1998
	Indonesia, humid lowlands, Ultisols?	18.0-25.9	Cadisch *et al.*, 1998
	Peru, humid lowlands, Typic Paleudult	10.2	Palm and Sanchez, 1991

The pattern of steadily declining decomposition rates of piper and gliricidia suggests that first the soluble and easily degraded compounds are utilised and the remaining biomass is increasingly resistant to degradation. It appeared that 40 to 50% of the substrate was relatively labile, while the remainder was relatively durable. While the decomposition of imperata appeared near linear throughout the experiment, this could be said also for the other species over the period in which the first 45% of biomass decayed. Besides the chemical composition and its changes over time, decomposition may also be influenced by environmental changes relating to the growth of the sweet potato crop. The vines grew more vigorously in piper and gliricidia plots than in imperata. Thus the cooling effects of crop transpiration and any effects of shading, for example on the light-labile polyphenols, were greater for piper and gliricidia treatments. In addition, in the second half of the litter bag study there was less rainfall (see Fig. 1) which may have retarded the decomposition.

Considerable amounts of nutrients were released from the leaf litter. About 79 kg N ha^{-1} were mineralised from the gliricidia litter and 115 kg K ha^{-1} from the piper litter. The rapid initial loss of K, particularly from the piper leaf litter, is commonly found in litter bag studies (Budelman, 1988; Palm and Sanchez, 1990; Tian *et al.*, 1992a). It may have been slightly increased by ovendrying of the litter samples, as cell disruption makes K more accessible to leaching. However, rapid loss of K is expected from dead plant material, as this element is not chemically bound to the substrate. The divalent cations were bound more strongly by the cation exchange properties of the organic substrates, and released only in proportion to the biomass lost. Nitrogen-rich compounds proteins and nucleic acids) would tend to be relatively labile, but the N is quickly immobilised by the microflora unless it is in excess of their needs. Hence the increase in N concentration of the material in the piper and imperata litter bags (Fig. 3), as these organisms have a higher N concentration than the substrate. Likewise, the microflora immobilise some P, so it is difficult to assess how much of the stability in P concentration (Fig. 3) is due to its resistance to degradation, and how much is due to immobilisation. It should be noted that constant concentration does not indicate that the nutrient is not being released, but that it is released in proportion to the biomass loss (Table 3).

Significant differences were detected in soil chemical properties (Table 5) despite the relative short period (24 weeks) between the soil sampling. A significant decrease in total N in the imperata plots was found which is likely due to the immobilisation of soil N in the leaf litter as the litter contained more N at the end than at the beginning of the experiment (Table 3). The exchangeable K levels in the piper plots increased because of the large release of the K decomposed in the piper leaf litter, and despite the high K demand of the sweet potato crop. Decomposition of the roots of fallow species may also have contributed to changes in soil chemical properties. The pH increase in the previous piper plots might be related to the large addition of K. The addition of crop residues with high concentration of excess cations is known to minimise soil acidification (Tang and Yu, 1999). Likewise, the lower soil pH under piper at the end of the fallow period may be attributable to the large extraction of K by piper during the fallow, and its replacement merely restored the pH to a value similar to the other treatments.

The leaf litter also had some significant effects on soil physical properties. It was found that the volumetric moisture contents at the start of the experiment was much lower under piper which confirms the claim of many farmers that piper make the soil dry in comparison to other fallow species. In the mid-season, moisture contents in the previous imperata plots were significantly higher compared to the piper plots because of the largely undecomposed mulch layer and the reduced growth of sweet potato causing less transpiration. This higher soil moisture is, however, not an advantage as sweet potato is very sensitive to excess soil moisture (Hahn and Hozyo, 1984; Bourke, 1989), and yields are generally depressed in seasons with high rainfall in the humid lowlands of Papua New Guinea (Hartemink *et al.*, 2000).

It can be concluded that piper leaf litter is a significant and easily decomposable source of K which is an important nutrient for sweet potato. Gliricidia leaf litter contained much N of which about two thirds is mineralised during the first season of sweet potato after the fallow. Imperata leaf litter decomposes very slowly, releases relatively little nutrients and immobilises N, and it keeps the soil more moist. Gliricidia fallows are more attractive than imperata fallows for they improve the soil fertility and produce additional saleable products in the form of firewood (Grist *et al.*, 1998).

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Part III
Nutrient management and sweet potato

Chapter 6

Hartemink, A.E. and R.M. Bourke, 2000. Nutrient deficiencies of agricultural crops in Papua New Guinea. Outlook on Agriculture, 29: 2, 97–108.

Chapter 7

Hartemink, A.E., S. Poloma, M. Maino, K.S. Powell, J. Eganae and J.N. O'Sullivan, 2000. Yield decline of sweet potato in the humid lowlands of Papua New Guinea. Agriculture Ecosystems and Environment, 79: 259-269.

Chapter 8

Hartemink, A.E., M. Johnston, J.N. O'Sullivan and S. Poloma, 2000. Nitrogen use efficiency of taro and sweet potato in the humid lowlands of Papua New Guinea. Agriculture Ecosystems and Environment, 79: 271-280.

Chapter 9

Hartemink, A.E., 2003. Sweet potato yields and nutrient dynamics after short-term fallows in the humid lowlands of Papua New Guinea. Netherlands Journal of Agricultural Science, 50: 297-319.

Chapter 10

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6. Nutrient deficiencies of agricultural crops in Papua New Guinea *

Abstract

In Papua New Guinea the population is growing faster than the area under cultivation. As a result, land use is being intensified and soil nutrient depletion may occur, resulting in nutrient deficiencies of agricultural crops. This paper reviews nutrient deficiencies in the agricultural crops of Papua New Guinea using the literature on agronomic trials, expert knowledge and Geographical Information System (GIS) soil fertility databases. One of the aims of this overview is to discuss the spatial distribution of common nutrient deficiencies, which will facilitate the formulation of future strategies on integrated nutrient management research. Nutrient deficiencies have been investigated systematically since the mid-1950s. Research has mainly focused on export tree crops, and relatively little information is available on food crops. Literature analysis and expert knowledge showed consistent trends with deficiencies of B and P in large parts of the highlands. GIS soil fertility databases confirm these observations. The authors' method has been shown to be useful in delineating areas in which nutrient deficiencies occur, and these findings could be used for the planning of nutrient management research and extension activities.

6.1. Introduction

Low levels of available nutrients in the soil may be natural, due to low amounts in the parent material from which the soil is derived, to fixation and immobilization that impair nutrient uptake, or to high rainfall conditions that leach nutrients from the soil. Low nutrient levels may also result from cultivation because of removal by agricultural crops in the absence of nutrient replenishment, and through accelerated losses compared with natural ecosystems. Some soils are resilient and will retain favourable levels of nutrients under cultivation (Lal, 1997) but in the majority of soils, nutrient levels decrease under permanent cultivation resulting in deficiency syndromes of agricultural crops.

In many smallholder agricultural systems in tropical regions, nutrient deficiencies limit food crop production, which is made worse by increasing land pressure. Detailed information on the spatial distribution and

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seriousness of nutrient deficiencies is needed to develop research strategies aimed at alleviating the problem and increasing food production. Such information systems are used for planning research on integrated nutrient management in some tropical countries, but in many countries including Papua New Guinea, the information is scattered or unavailable on a national or regional scale.

Papua New Guinea is the largest country in the Pacific region. Subsistence agriculture is practised by more than three-quarters of the population in a wide range of environmental conditions. Annual rainfall varies from 1,000 mm in the area around the capital, Port Moresby, to over 8,000 mm in the mountains of the far western part (Fig. 1B). The rugged mainland and the surrounding islands form part of a highly mobile zone of the earth's crust where volcanic activity occurs. Many areas have been covered by volcanic deposits, while weathering and denudation of the steeply sloping mountains have caused the deposition of extensive alluvial plains (Bleeker, 1983) Due to the great variety of parent materials, climatic conditions and differences in topography, there are many different soil types. Relatively more agriculture is found on young soils such as Andisols and Eutropepts. Agriculture takes place from sea level to 2,850 metres above sea level.

The population doubled between 1966 and 1990 (Allen *et al.*, 1995). Analysis of land-use intensities using aerial photographs from the early 1970s with LandSat^{TM} imagery from 1996 revealed, however, that the area under cultivation had increased by only 7% over a 24-year period (J. McAlpine, unpublished data). This implies increased land-use intensities, which have mainly occurred in areas that had already had high land-use intensities in the past. The land is cropped more often and that puts a greater demand on the soil resource, particularly as few or no inorganic fertilizers are being used on food crops. Nutrient deficiencies are likely to increase with higher land-use intensities. Research on nutrient deficiencies of agricultural crops started in Papua New Guinea in the 1950s, and successive research projects focused on export tree crops. Significant research on nutrient deficiencies in food crops started only in the 1970s. Earlier reviews had revealed that macro- and micronutrient deficiencies were occurring locally in some agricultural crops (Bourke 1983). In this paper, we have assembled the available information on nutrient deficiencies in the agricultural crops, and the information is drawn from three sources:

(i) about 45 years of literature on nutrient deficiencies and soil and plant analysis in most parts of Papua New Guinea;
(ii) field observations throughout PNG on visual symptoms of nutrient deficiency in agricultural and horticultural crops;
(iii) data held in a GIS-based natural resource and agricultural.

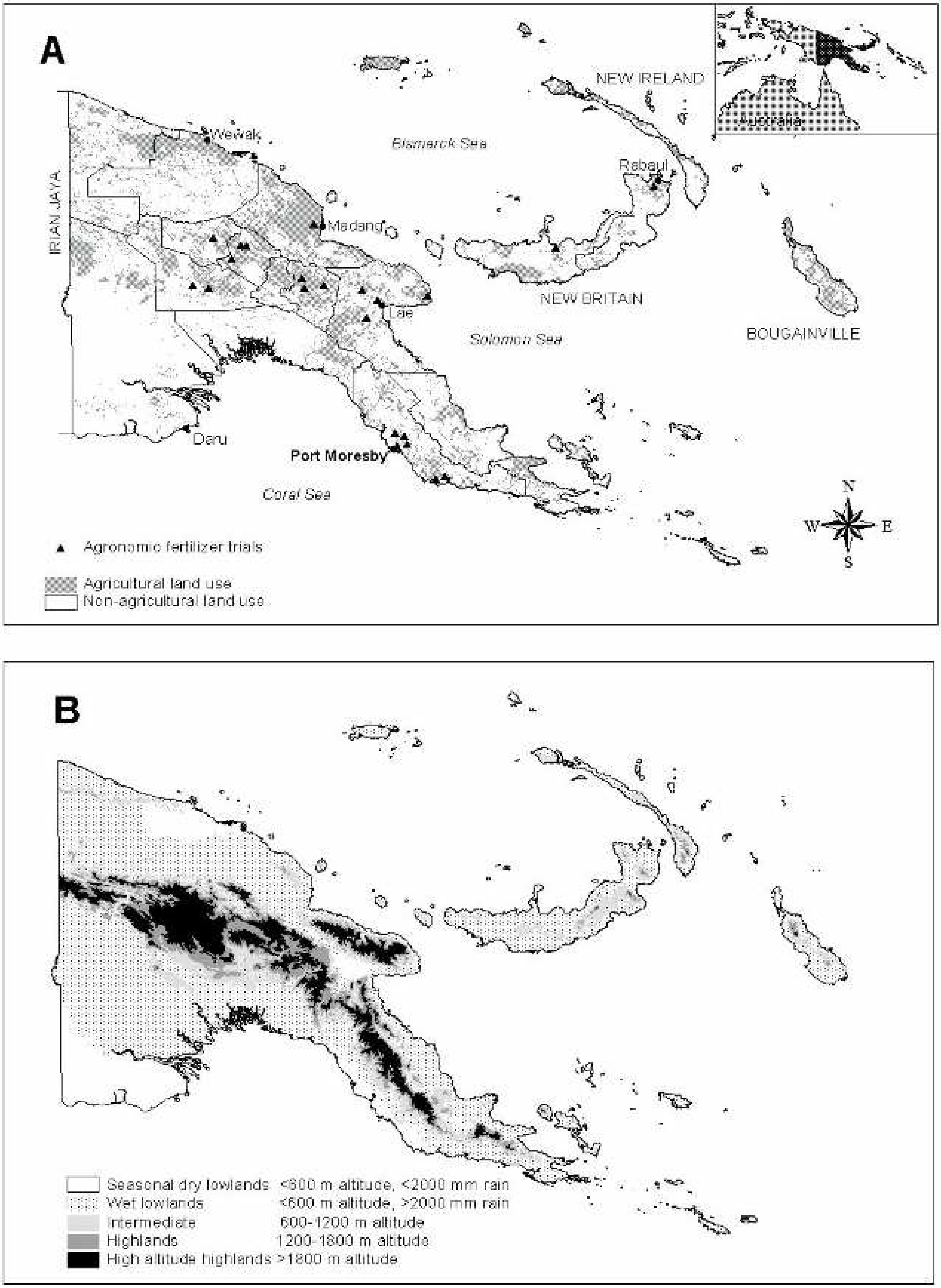

Fig.1. Agricultural land in Papua New Guinea (A), and major agroecological zones based on altitude and annual rainfall (B)

6.2. Data collection

Existing literature

Soil research in Papua New Guinea started in the 1950s (Bleeker, 1983), and was conducted by two almost independently working groups of scientists. At the experiment stations for export tree crops (cash crops), agronomists and soil fertility experts investigated optimum inorganic fertilizer rates and nutrient deficiencies using field experiments, greenhouse trials and on-farm experiments. Fig. 1A gives an overview of where fertilizer trials have been conducted in the past decades. The second group were pedologists and soil surveyors who used broad-scale mapping techniques to map the soils of large parts of the country. This yielded spatial information on soil chemical properties in many parts of Papua New Guinea.

Much of the early agronomic research was focused on the establishment and development of export tree crops, particularly coconuts, coffee and tea. Research occurred on an *ad hoc* basis, i.e. when a problem was observed at the plantation. A clear example is the research on coconut plantations in New Ireland, which started in the mid-1950s. The plantations were established by the Germans between 1910 and 1920, and in the 1950s it was noted that production had drastically decreased, with many palms showing stunted growth and leaf chlorosis (Charles, 1959). A soil survey was undertaken (van Wijk, 1959) and investigations were carried out on leaf nutrient content and soil nutrient levels. It was concluded that, amongst other agronomic problems, K was the main factor limiting coconut production (Baseden and Southern 1959) Subsequent research focused on the use of inorganic fertilizers (Charles and Douglas, 1965). The success of the approach used in New Ireland in clearly defining the nutritional disorder established the value of chemical techniques for plant nutrition diagnosis, as well as guidelines for future plant nutrition research in Papua New Guinea (Fahmy, 1977). In the 1960s and 70s, research focused on the establishment and development of new plantations, following the developments in soil survey and land evaluation techniques. This yielded information on nutrient deficiencies in new export tree crops, particularly oil palm and cocoa.

Overall there is a fair body of literature on nutrient deficiency of agricultural crops in Papua New Guinea, although much more is known about export tree crops than about food crops. Most of the research has been published in annual reports of experimental stations, and concerns the effects of inorganic fertilizer on crop yields, which gives insights into the limiting nutrients. Information on nutrient deficiencies in crops was usually obtained through foliar analysis, but it has been more successful in some crops than others, mainly because of sample size and seasonal variations. There is also some literature on deficiency symptoms in plywood forestry nurseries that started in 1953 (Baseden, 1960).

Field observations

Field observations of visual symptoms of nutrient deficiency in agricultural and horticultural crops were made by R.M. Bourke, who has visited every Papua New Guinean district over the past 30 years. These observations were usually done while surveying village agriculture, crop altitudinal limits and crop seasonality. As the field observations were not made systematically, but incidentally to other survey work, the coverage of observations across the country is uneven.

The occurrence of leaf deficiency symptoms has mainly been recorded, but information on stunted growth, defoliation and die-back was also noted. Nutrient deficiencies were tentatively identified in the field, and slides were taken. In 1996, all slides were shown to experts in the Faculty of Agriculture, University of Queensland, who confirmed the tentative field identifications. They were also checked with texts on nutrient deficiency (O'Sullivan *et al.*, 1996; O'Sullivan, 1997; Bennett, 1993). In cases in which there was doubt as to whether the leaf symptoms were caused by nutrient deficiencies or by pathological, entomological, environmental or genetic causes, these observations were excluded. Several hundred confirmed observations have been made on the deficiency of nine nutrients in 42 crops.

Geographical databases

Soil mapping started in Papua New Guinea in the 1950s, applying the land-system approach developed in Australia in the late 1940s (Bleeker, 1983). As part of the surveys, soil samples were taken for chemical characterization of mapping units. The soil survey work was later used to develop Papua New Guinea Resource Information Systems (PNGRIS). PNGRIS is a natural resource database for the whole of Papua New Guinea at a scale of 1:0.5 million (Bellamy and McAlpine, 1995). It contains 4,852 resource mapping units (RMU), which are differentiated by three physical resource attributes: landform, geology (rock type) and altitude. For each RMU there is information on soil physical and chemical properties. The soil chemical database in PNGRIS includes information on a range of soil fertility parameters including pH, total N, available P and exchangeable bases.

In the 1990s, PNGRIS was used to develop the Mapping Agricultural System Project (MASP) which mapped the agricultural systems of Papua New Guinea at a scale of 1:0.5 million (Allen *et al.*, 1995). MASP contains information on a wide range of agricultural practices, including the dominance and extent of food crops and the significance of export tree crops in all agricultural systems. PNGRIS and MASP were used to map soil chemical properties of agricultural land areas in Papua New Guinea.

6.3. Agricultural crops of Papua New Guinea

About a quarter of the total land area in Papua New Guinea is used for agriculture, with varying intensities. Fig. 1A shows the agricultural land based on aerial photograph information (Sanders, 1993). The largest areas of agricultural land are in a series of valleys and basins in the central highlands; in the mountains and foothills inland of Wewak; along much of the north coast of the main island; land south-west of Lae extending almost to the south coast; in coastal locations in eastern Papua; the islands of Milne Bay; the north coast and north-east of New Britain; the north-east coast of New Ireland, and parts of Bougainville Island.

Fig. 1B shows the distribution pattern of the five major ecological zones based on altitude and rainfall. Most of the lowlands (< 600 m a.s.l.) are wet with annual rainfall exceeding 2,000 mm. In the south-west, part of the Sepik plain and around the capital, Port Moresby, there are extensive areas that are seasonally dry with rainfall as low as 1,000 mm per year. The valleys and basins in the central highlands are located at over 1,200 m a.s.l. and high concentrations of people live between 1,500 and 2,000 m a.s.l. Extensive parts of the highlands are over 1,800 m a.s.l. with a significant number of people living and farming at higher altitudes up to 2,800 m a.s.l.

Export tree crops

Coffee is the main export tree crop in Papua New Guinea and the major source of income for one-third of the population (Harding and Hombunaka, 1998). A few plantations were established during the 1930s, but a rapid expansion of the industry started in the early 1950s. Smallholders produce about 70% of the total production. Arabica coffee accounts for about 95% of production, and is grown in the Central Highlands and mountainous parts of Morobe province. Some Robusta coffee is grown below 600 m a.s.l., mostly in Morobe and East Sepik provinces. Research on Arabica coffee began in the early 1950s.

Coconuts are grown extensively along the coast and in some inland lowland locations. It is estimated that the total area under coconuts is about 250,000 ha (Table 1). Copra production is concentrated in the Islands region, with most copra coming from East New Britain, Bougainville, New Ireland and West New Britain provinces. Most production is done by villagers and few plantations still produce copra. Systematic research on coconuts commenced in the early 1950s.

Cocoa production is concentrated in the Gazelle Peninsula of East New Britain, Bougainville, East Sepik, Madang, New Ireland and West New Britain. About 65% of cocoa is grown by smallholders, and research commenced in the early 1950s.

Oil palm is grown by estates, settlers and villagers, and production is limited to the north coast of West New Britain, the north-east coast of New Ireland, the area near Popondetta in Oro province, and an area inland of Milne Bay. Production has expanded rapidly over the past 30 years, and continues to do so. Research on the oil palm started in the mid-1960s.

Tea production started in the late 1940s, but is now restricted to several estates in the Wahgi Valley of the Western Highlands. Smallholder production ceased in the late 1970s. Research was conducted between the late 1960s and the mid-1980s. Rubber is produced by several estates and smallholders in a limited number of locations in Central, Western and East Sepik provinces. A limited amount of research was conducted during the 1960s and 70s.

Table 1. Extent and growing areas of major export tree crops in Papua New Guinea

Crop	Botanical name	Extent (ha) [1]	Growing area
Arabica coffee	*Coffea arabica*	50,000	Highlands, dominantly Andisols
Robusta coffee	*Coffea canephora*	5,000	Wet lowlands, various soil types
Coconuts	*Cocos nucifera*	250,000	Wet and seasonal dry lowlands, various soil types
Cocoa	*Theobroma cacao*	30,000	Wet lowlands, mainly Andisols
Oil palm	*Elais guineensis*	80,000	Wet lowlands, mainly Andisols
Tea	*Camellia sinensis*	3,000	Highlands, Histosols and Andisols
Rubber	*Hevea brasiliensis*	5,000	Seasonal dry and wet lowlands, various soil types

[1] Extents of export tree crops are estimates based on published literature and figures provided by research stations

Food crops

Large numbers of food crops are grown in Papua New Guinea, both for subsistence consumption and for sale at local markets. The most important are root crops, sago, banana, maize and green vegetables. Sweet potato is the major food crop and is the staple food for over 60% of the rural population (Table 2). It dominates agricultural production in the highlands and very high altitude highlands, but it is also significant in the wet lowlands. Sago is the staple food for 12% of villagers, mainly in the East

Sepik, West Sepik, Western and Gulf provinces. Banana is the main staple food for 7% of the population, and is widely grown up to 2,200 m altitude. It is important in the seasonally dry lowlands and in areas with very high rainfall (>4,000 mm $year^{-1}$). Other staple foods include yam, taro, Chinese taro, cassava, Irish potato and maize. Some research on food crops was conducted in the 1930s and again after the Pacific War, but continuous research began only in 1970.

Table 2. Major food crops, their main growing areas and importance in Papua New Guinea. Based on data in MASP (Allen *et al.*, 1995)

Crop	Botanical name	Main growing area	Importance [1]
Sweet potato	*Ipomoea batatas*	Throughout the country, except in seasonal dry lowlands	61
Sago	*Metroxylon sagu*	Wet lowlands	12
Banana	*Musa cultivars*	Seasonal dry lowlands	7
Yam	*Dioscorea spp.*	Seasonal dry lowlands	5
Taro	*Colocasia esculenta*	Wet lowlands	4
Chinese taro	*Xanthosoma sagittifolium*	Wet lowlands	2
Cassava	*Manihot esculenta*	Seasonal dry lowlands	1
No dominant staple			8

[1] Percentage of the rural population for whom this is the dominant staple, that is the crop occupying more than one-third of the garden area

6.4. Nutrient deficiencies – literature

Macronutrients

Nitrogen is commonly deficient and limiting to crop production in cultivated soils of the tropics (Ahmad, 1996, Sanchez, 1976). Soil nitrogen levels depend largely on the agroecological conditions and soil management practices, causing a large spatial and temporal variability. In general, N levels increase with decreasing temperatures — which lower decomposition rates, and increased rainfall - which favours biomass production (Jenny *et al.*, 1949). In Papua New Guinea, it was found that the N content of soils was generally higher at higher altitudes, and in Andisols where organic matter forms complexes with allophane and aluminium oxides, which retard organic matter decomposition. Poor drainage, hindering decomposition, also results in higher organic matter content and hence higher nitrogen content of the soil (Bleeker, 1983).

Nitrogen deficiencies have been reported under Arabica coffee in conditions of low shade intensity, or when inorganic fertilizers high in S are applied (Southern 1966). Nitrogen deficiency has been widely reported in cocoa except when it is shaded. Under coconuts, N deficiency has been reported from an Andisol that had been frequently burned, inducing N losses (Sumbak, 1969). Nitrogen responses have been reported for various crops, including sorghum on Vertisols (Parfitt and Drover, 1975), oil palm on Andisols (Mendham, 1971), taro on Andisols in the lowlands (Moles *et al.*, 1984) and broccoli on Andisols in the highlands. Nitrogen was the key element for sweet potato on Andisols in the wet lowlands and highlands (Bourke 1977), but Hartemink *et al.* (2000) reported a negative yield response of sweet potato to N fertilizer on alluvial soils with low native N levels.

Phosphorus deficiency is common in highly weathered and acid soils in which the mineral fraction is dominated by kaolinite and sesquioxides, and in Andisols consisting of allophane and its weathering products (Parfitt and Thomas, 1975). Highly weathered soils are not common in Papua New Guinea (Bleeker, 1983), nor are very acid soils (Humphreys, 1998). Soils derived from predominantly Quaternary volcanic ash (Andisols) are common, particularly in the highlands where they cover large areas (Radcliffe and Kanua, 1998) Andisols have a large pH charge dependency, and adsorb P strongly at low soil pH, and the P availability strongly depends on pH and clay mineralogy. The decomposition of organic matter supplies the bulk of the P crop requirement (Kanua, 1995). The deficiency of P was recognized as a problem in food crops only in the 1970s, because until then research had been mainly focused on tree crops, which have a low inherent P requirement.

Available P is low in soils derived from limestone under coconuts, but because of the low P requirements it is not likely to be a seriously limiting nutrient for coconuts (Baseden and Southern, 1959). Mature Arabica coffee is able to extract sufficient P from soils low in P (Southern 1966) and yield responses to P fertilizers are rare (Harding and Hombunaka, 1998; Hart, 1966). D'Souza and Bourke (1986) and Floyd *et al.* (1988) showed that sweet potato yields were slightly increased by applying P fertilizers on an Andisol in the highlands. On Andisols in the lowlands, no response to P fertilizer was recorded for taro (Moles *et al.*, 1984) although a positive response was obtained for maize (Humphrey, 1996). Bourke (1977) reported infrequent small increases in sweet potato yield in response to P on an Andisol in the wet lowlands. Favourable responses to P fertilizer were also obtained by Aburu (1975) and Parfitt and Williams (1974) on alluvial soils (Vertisols, Fluvents) in the lowlands. Sivasupiramaniam *et al.* (1996) showed that sheep manure and P inorganic fertilizer dramatically increased sweet potato yields on Andisols in the highlands. In places like Tambul, 2,300 m a.s.l. there is massive response of edible lupins to applied phosphate fertilizer.

The distribution of soil K generally follows a pattern that is related to rock type and the degree of weathering of the soils (Bleeker, 1983). Deficiency of K is more often found in highly weathered and leached soils that have limited amounts of mineral reserves remaining. Soils developed in volcanic ashes commonly have high K levels because of their high levels of primary minerals (e.g. feldspars). High Ca and Mg levels in the soil may result in K deficiency, which has been reported to occur in very acid soils, and in soils along the coast derived from limestone.

Baseden and Southern (1959) reported K deficiency in coconuts on soils developed over coral limestone, because of an imbalance in cations and the considerable amounts of K that are removed with the husks and nuts. On these soils, coconuts showed a dramatic response to K applications (Charles and Douglas, 1965) which was also found in soils with high Mg/K ratios (Sumbak and Best, 1976). Many coffee plantations have soils deficient in K (Southern 1966; Harding, 1991; Hart 1966). Applications of K are generally favourable, although negative interaction with Ca and Mg can occur (Harding and Hombunaka, 1998). Root crops are large K consumers (Agata, 1992; Kabeerathumma), but K deficiencies in Papua New Guinea have been only partially documented. On Andisols in the wet lowlands, Bourke (1977) reported large yield responses to applied and residual K. D'Souza and Bourke (1986) demonstrated a marked increase in sweet potato yield following K fertilizer applications on Andisols in the highlands. Taro showed no response to K application on Andisols in the lowlands (Moles *et al.*, 1984).

There have been only few reports on Mg deficiencies, which mostly result from a cation imbalance. Deficiency of Mg is common in Arabica coffee (Hart, 1966; Harding, 1991), but no yield responses have been obtained in fertilizer trials due to the low K status of most soils that favours Mg uptake (Southern, 1966). Deficiency of Mg occurs in Andisols under oil palm, and is aggravated by high N fertilizer applications (Mendham, 1971). Recent investigations confirm the widespread deficiency of Mg in oil palm on Andisols (I. Orrell, OPRA, *pers. comm.*, 1999).

Sulphur deficiency has been reported from very different soils and appears to be fairly common, although the occurrence is more likely to be ecological than pedological (Southern, 1967). Contributing factors are high rainfall and leaching, frequent burning of vegetation by which S is lost, the lack of inorganic fertilizer use, and competition with other plants, notably *Imperata cylindrica*. It was found that S deficiencies were common in coconuts on soils derived from limestone (Sumbak and Best 1976). Sulphur deficiencies in coconut were also observed on Andisols and Fluvents on which vegetation burning was common (Sumbak, 1969), and on soils derived from limestone when K deficiency was corrected (Sumbak, 1971). Sulphur deficiencies occur in the Arabica coffee growing areas (Hart, 1966), particularly when high N fertilizer rates are applied (Southern, 1966). Hill (1970) showed a marked response of peanuts to S fertilizers on alluvial soils. There have been no reports of S deficiency in rubber, sweet potato or other staple root crops, but sulphur deficiency has been reported for rice (*Oryza sativa*) grown on alluvial soils (Parfitt and Williams, 1974) and also for tea, sorghum and pasture crops (Vance *et al.*, 1983).

Micronutrients

Until 1965, research focused on macronutrients, partly because problems associated with macronutrients were more obvious, but also because facilities were not available for research into micronutrients (Southern and Dick, 1969). Investigations in micronutrients began in 1966 after routine methods, mainly using atomic absorption, became possible. This review on micronutrient deficiency is largely based on the work of Southern and Dick (1969), who surveyed export tree crops across the whole of Papua New Guinea in the 1960s, and on the work of Bourke (1983) who reviewed the literature up to the beginning of the 1980s. The information on micronutrients is based mainly on foliar analysis, as there is virtually no information about minor elements in the soils of Papua New Guinea (Bleeker, 1983).

Boron deficiency has been reported for Arabica coffee in the highlands (Southern, 1966; Harding, 1991), and dramatic yield increases following B applications occur. In Robusta coffee and rubber, no symptoms of B deficiency have been recorded, but B toxicity is common in some acid coastal soils where rubber is grown (Southern and Dick, 1969). No serious B deficiency has been found in coconuts or cocoa (Southern and Dick, 1969). Casuarina and pinus trees are both susceptible to B deficiency, and casuarina trees have been reported to respond vigorously to B applications, particularly in soils with low organic matter contents (D'Souza and Bourke, 1986). Although B deficiency is widespread in certain tree crops, relatively little information is available on the food crops (Bourke, 1980). Bang (1995) showed that Irish potato yields increased after applications of both B and P on Andisols in the highlands, but D'Souza and Bourke (1986) found a yield reduction in sweet potato after applying B fertilizers. Application of B fertilizer to peanuts, cowpea and winged beans had no effect (D'Souza and Bourke, 1986), but in the high altitude highlands, favourable responses of B applications to pyrethrum have been found (Bourke, 1983).

Research on Zn deficiency in Papua New Guinea started after it was identified in Netherlands New Guinea (Schroo, 1959). In Papua New

Guinea, Zn deficiency occurs in Arabica coffee throughout the highlands and is usually more severe in unshaded coffee (Southern and Dick, 1969), although seasonal variation is considerable (Harding, 1991). In Robusta coffee, Zn deficiency commonly occurs in conjunction with Mn deficiency in alkaline soils (Southern and Dick, 1969). Zinc deficiency is a problem in tea on drained Histosols in the highlands, but no serious Zn deficiency has been reported for coconuts. In cocoa, Zn deficiency ('sickle leaf ') is common, particularly when grown on alkaline soils. Little is known about Zn deficiency in food crops, and the only reports available are for Zn deficiency in rice and peanuts grown on alluvial soils (Fluvents) (Bourke, 1983; Parfitt and Williams, 1974).

Investigations into Mn nutrition have been concentrated on alkaline alluvial soils, neutral to alkaline soils of the coast and atolls, and soils developed in volcanic ash (Southern and Dick, 1969). In general, Mn levels in Arabica coffee leaves are high (Harding, 1991), and no symptoms of Mn toxicity have been observed. There is evidence that Mn contents have increased following the use of acidifying N fertilizers. In cocoa, low Mn levels were found in plants on neutral to slightly alkaline soils, but there is no evidence that Mn applications increase growth or cocoa production. In rubber, Mn deficiency may occur on soils high in exchangeable Mg (Southern and Dick, 1969), and deficiency of Mn was observed in yams grown on soils derived from coral limestone (Johnston, 1996). On a young Andisol in the wet lowlands, Mn deficiency symptoms on pomelo (*Citrus grandis*) and other citrus species disappeared after foliar applications of both Zn and Mn, whereas the sole applications of Zn or Mn had no effect (Bourke, 1993). Sweet potato showed no response to Mn in a field trial on an Andisol in the wet lowlands (Bourke, 1977).

Slight symptoms of Fe deficiency in Arabica coffee are common throughout the highlands, particularly on pruned trees.94 The deficiency of Fe is not a serious problem in Arabica coffee and no corrective measures are necessary (Southern and Dick, 1969). In cocoa, Fe deficiency is fairly common, particularly on soils derived from coral limestone. No symptoms of Fe deficiency have been recorded for rubber, but Fe deficiency was reported in high pH soils of forestry nurseries (Baseden, 1960). There are no records of Cu deficiency in Arabica coffee and fertilizer effects have not been observed in Papua New Guinea (Southern and Dick, 1969). Tentative values indicated that Robusta coffee leaves had locally low Cu levels. Copper deficiency has not been observed in cocoa, but low Cu values were found in trees growing on Andisols (Southern and Dick, 1969). Cu deficiency is unlikely to occur in rubber, except in nurseries. Table 3 summarizes the information on nutrient deficiencies in export tree crops and food crops. Nutrient deficiencies in export tree crops have been more widely reported as they have received more research attention than food crops. Nutrient deficiencies in Arabica coffee have been researched more than in any other crop.

Table 3. Nutrient deficiencies reported in export tree crops and food crops in Papua New Guinea. Based on reconciliation of published literature 1955-1998

		Macro nutrients					Micro nutrients				
		N	P	K	Mg	S	B	Zn	Fe	Cu	Mn
Export tree crops	Arabica coffee	2	3	1	2	2	1	1	1	4	4
	Robusta coffee	–	–	–	–	–	4	3	–	2	2
	Cocoa	1	–	–	–	–	4	2	2	3	3
	Coconuts	2	3	2	–	2	4	4	–	–	–
	Oil palm	2	–	–	2	–	–	–	–	–	–
	Rubber	–	–	–	–	4	4	–	4	4	3
	Tea	–	–	–	–	2	–	3	–	–	–
Food crops	Sweet potato	1	2	2	4	4	2	4	4	4	
	Taro	1	3	2	–	4	–	–	–	–	–
	Irish potato	–	3	–	–	–	3	–	–	–	–
	Citrus spp.	–	–	–	–	–	–	1	–	–	3
	Maize	–	2	–	–	3	–	–	–	–	–
	Rice	–	–	–	–	2	–	3	–	–	–
	Peanuts	–	–	–	–	2	4	3	–	–	–
	Pyrethrum	–	–	–	–	–	3	–	–	–	–

1 = common in many parts of the country
2 = locally
3 = very locally
4 = investigated but no deficiency present
– = not investigated

6.5. Nutrient deficiencies – field observations

Nitrogen deficiency is common in arable crops, especially in areas where soil fertility has declined through extended cropping periods. However, symptoms have not been recorded systematically in the field. The deficiency symptoms of P are widespread throughout the highlands on a wide range of crops. Maize and the weed, Cobbler 's Pegs (*Bidens pilosa*) are good indicator plants of P deficiency. Symptoms are more severe at altitudes over 2,000 m a.s.l. throughout the highlands, and dramatic responses have been observed to P on potato, lupins and soybean at an experimental station 2,300 m a.s.l. Deficiency symptoms of K are uncommon in agricultural crops, but they have been observed on a number of crops on alluvial soils in the Sepik plain and on alluvial soils in coastal Central province. Mild Mg deficiency symptoms occur on on volcanic ash soils in East New Britain and on the north coast of New

Britain. Symptoms are very common on a range of crops in the Bulolo and Wau areas of Morobe province. Symptoms of S deficiency have been noted on citrus at two locations in the highlands. Table 4 summarizes the observations on macronutrient deficiencies as observed in the field.

Table 4. Field observations on macro nutrient deficiencies in Papua New Guinea

	Crop	Botanical name	Location and soil type
N	Arabica coffee	*Coffea arabica*	Highlands, Andisol
	Coconuts	*Cocos nucifera*	Wet lowlands, Andisol
	Sweet potato	*Ipomoea batatas*	Various locations in both Highlands and Lowlands
	Avocado	*Persea americana*	Highlands, Andisol
	Taro	*Colocasia esculenta*	Various locations in both Highlands and Lowlands
	Pineapple	*Ananas comosus*	Wet lowlands, Andisol
P	Maize	*Zea mays*	Widespread in the Highlands
	Sweet potato	*Ipomoea batatas*	Widespread in the Highlands
	Cobbler's pegs	*Bidens pilosa*	Widespread in the Highlands
	Cabbage	*Brassica oleracea*	Widespread in the Highlands
	Lupins	*Lupinus* sp.	High altitude Highlands, Andisols
	Irish Potato	*Solanum tuberosum*	High altitude Highlands, Andisols
	Soybean	*Glycina max*	High altitude Highlands, Andisols
	Chinese taro	*Xanthosoma sagittifolium*	Wet lowlands, soils on limestone
K	Cocoa	*Theobroma cacao*	Wet Lowlands, Fluvents
	Coconuts	*Cocos nucifera*	Wet Lowlands, Fluvents
	Chinese taro	*Xanthosoma sagittifolium*	Wet Lowlands, Andisol, Fluvents
	Maize	*Zea mays*	Wet lowlands, Fluvents
	Aibika	*Abelmoscus manihot*	Wet Lowlands, Fluvents
	Soybean	*Glycine max*	Highlands
	Pueraria	*Pueraria lobata*	Wet Lowlands Fluvents
	Pumpkin	*Cucurbita moschata*	Wet Lowlands, Fluvents
	Taun	*Pometia pinnata*	Wet Lowlands, Fluvents
Mg	Arabica coffee	*Coffea arabica*	Highlands, Andisol
	Robusta coffee	*Coffea canephora*	Wet Lowlands, Andisol
	Avocado	*Persea americana*	Intermediate altitude, Highlands, Andisol
	Loquat	*Eriobotrya japonica*	Intermediate altitude
	Betel nut	*Areca catechu*	Intermediate altitude
	Sweet potato	*Ipomoea batatas*	Wet Lowlands, Andisol
	Taro	*Colocasia esculenta*	Intermediate altitude
	Chinese taro	*Xanthosoma sagittifolium*	Intermediate altitude
	Cassava	*Manihot esculenta*	Wet Lowlands, Andisol
	Yam bean	*Pachyrhizus erosus*	Wet Lowlands, Andisol
	Aibika	*Abelmoschus manihot*	Intermediate altitude
	Pepper	*Piper nigrum*	Wet Lowlands, Andisol
	Winged beans	*Psophocarpus tetragonolobus*	Intermediate altitude
	Legumes		Highlands, Andisol
	Lantana	*Lantana camara*	Highlands, Andisol
S	Orange	*Citrus sinensis*	Highlands, Andisol, Histosol

Symptoms of B deficiency are widespread on casuarina and pine trees and on brassicas in the highlands. They have been noted on a number of other crops, including sweet potato (Table 5). Symptoms of Zn deficiency are universal wherever citrus are grown in the lowlands, intermediate altitude zones and highlands in Papua New Guinea (Fig. 1). They are also common on Arabica coffee in the highlands, but have not been noted on other crops. Manganese deficiency was proven on pomelo at Keravat, together with Zn deficiency, but otherwise there are no observations on Mn deficiency. Symptoms of Fe deficiency have been noted on a number of crops on soils derived from coral limestone, but the area is small and the deficiency is of minor economic significance.

Fig. 2 shows the approximate distribution of macro- and micronutrient deficiencies in agricultural crops of Papua New Guinea, based on field observations by R.M. Bourke.

Table 5. Field observations on micro nutrient deficiencies in Papua New Guinea

	Crop	Botanical name	Location and soil type
B	Casuarina	*Casuarina oligodon*	Widespread throughout the Highlands
	Pine trees	*Pinus* sp.	Widespread throughout the Highlands
	Sweet potato	*Ipomoea batatas*	Highlands, Andisols
	Cape gooseberry	*Physalis peruviana*	Highlands, Andisols
	Tomato	*Lycopersicon esculentum*	Highlands, Andisols
	Brassicas	*Brassica oleracea*	Widespread throughout the Highlands
Zn	Arabica coffee	*Coffea arabica*	Widespread throughout the Highlands
	Orange, lemon, mandarin, pomelo, limes, grapefruit	*Citrus* spp.	Widespread throughout the country
Mn	Pomelo	*Citrus maxima*	Wet Lowlands, Andisols
Fe	Cocoa	*Theobroma cacao*	Wet Lowlands, soils derived from limestone
	Snake bean	*Vigna uniguiculata*	Wet Lowlands, soils derived from limestone
	Chinese taro	*Xanthosoma sagittifolium*	Wet Lowlands, soils derived from limestone

6.6. Nutrient deficiencies - GIS databases

Soil fertility information was derived from the Papua New Guinea Resource Information System (PNGRIS) and plotted for the areas under village agriculture. Soil chemical fertility information for each mapping unit includes: total N, exchangeable K, available P, anion fixation, soil reaction (pH), and base saturation. Maps were derived from the database using ArcView GIS software and small areas were excluded from the map to improve its readability (Fig. 3). Despite the great variation in climatic and soil conditions, the following pattern emerges: The majority of soils in the coastal areas have low to moderate content of N. Many soils in the central highlands have N contents exceeding 5 g/kg soil, which is caused by slower decomposition than occurs in the lowlands. The status of available K is generally favourable in most soils. The majority of the soils have a slightly acid to neutral soil reaction, and alkaline soils occur along the coast and locally in the highlands. Base saturation is moderate to high in most soils, although soils in the highlands have low base saturation. The maps also show that P fixation and low P availability are common problems in the central highlands and on the volcanic active islands, including the northern part of New Britain and Bougainville island.

By overlaying the agricultural systems map on the PNGRIS map it was possible to calculate how much of the agricultural land had soils low in total N. This was calculated for the four major soil chemical properties (N,P,K and base saturation) and the results are presented in Table 6. The analysis shows that about 25% of the soils under agriculture have high total N levels, whereas 15% of the land has low to very low N content. About one third of the agricultural land has soils with low available P, and almost 90% of the land has low to moderate available P levels. Three-quarters of the agricultural land has soils with moderate K levels, and in 82% of the soils base saturation is moderate or high.

6.7. Discussion

In this paper we have reviewed nutrient deficiencies of agricultural crops in Papua New Guinea using literature, field observations and GIS soil fertility databases. In the discussion we will focus on the integration of this information and how it can be used.

Nitrogen deficiencies have been commonly observed in the field and in literature data, and most crops respond favourably to N fertilizer. The GIS map showed that high soil N contents were found in the highlands and on volcanic soils on Bougainville island. Despite these high N contents, fertilizer responses were also common in these areas, and the GIS map does not fully depict the likely occurrence of N deficiencies. The P and anion fixation map showed that about one-third of the soils had low available P, which is consistent with information from fertilizer trials and field observations. There is, however, a difference between food crops and export tree crops in their susceptibility to P deficiency. In general, tree crops are better P scavengers than annual crops, and both deficiencies and P fertilizer responses are less likely to occur in tree crops. However, the most important food crop in PNG is sweet potato, which is an efficient P scavenger. It is unlikely that sweet potato would have dominated highland agriculture in the way that it does without this ability, given the widespread P problems in highland ash soils.

Potassium deficiency has been reported for coffee in the highlands and for coconuts in the coastal areas, which roughly correspond to areas delineated by the GIS map with soils low in exchangeable K. Calcium nutrition has been poorly investigated in the soils of Papua New Guinea, possibly as very acid soils are not very widespread. Magnesium deficiency has been reported very locally, which accords with the pattern of soil reaction and moderate to high base status of the soils. Field observations on micronutrient deficiencies in the highlands correspond fairly well with the literature of agronomic trials, but the GIS database contains no soil micronutrient information. In large parts of the highlands, Zn is deficient and Zn application has been shown to be effective. Boron fertilizer is routinely applied to pine trees managed by the Forest Authority, and B applications are recommended for commercial vegetable growers in the highlands.

This review has shown the effectiveness of delineating major areas of nutrient deficiencies, but there are some limitations that deserve to be mentioned. In the agronomic literature, results from various plant and soil analytical studies have been shown not always to be consistent, which hinders extrapolation of the results. This emphasizes the need for detailed and accurate soil and site descriptions. Although the information in the GIS soil fertility databases presents an overview of areas where nutrient contents in the soils and deficiencies may be expected, the information is too scarce to allow spatial correlation with the agronomic literature. Much of the literature on micronutrients is based on foliar analysis, and there is hardly any information on micronutrient levels in the soils. Such studies might be of interest, particularly B in relation to volcanic ash soils, and Zn and Mn on soils with alkaline reactions.

Currently, much of the agronomic work in Papua New Guinea focuses on crop cultivars and entomology. These are important research areas to sustain and increase agricultural production, but very little research is conducted on nutrient management strategies and nutrient deficiencies. This applies to both export tree crops and food crops. Table 3, which gives an overview of the nutrient deficiencies reported in the literature, could be the base for such research. This review has indicated some of the locations where particular problems, which so far have received little attention, require further investigation. These include K deficiencies in the inland Sepik area; Mg problems in the Wau-Bulolo area and on the north coast of New Britain; and boron deficiencies in many crops in the highlands. Further intensification of land use will affect soil fertility, and nutrient deficiencies are therefore likely to increase, particularly in food crops where inorganic fertilizers are not being used. There is a need to monitor the development of nutrient deficiencies, as well as to ensure proper identification through pot trials and soil and foliar analysis. Comprehensive fertilizer trials could be designed to diagnose minor elements, and nutrient budgets could be used to study inputs and outputs of cropping systems in different agroecological zones.

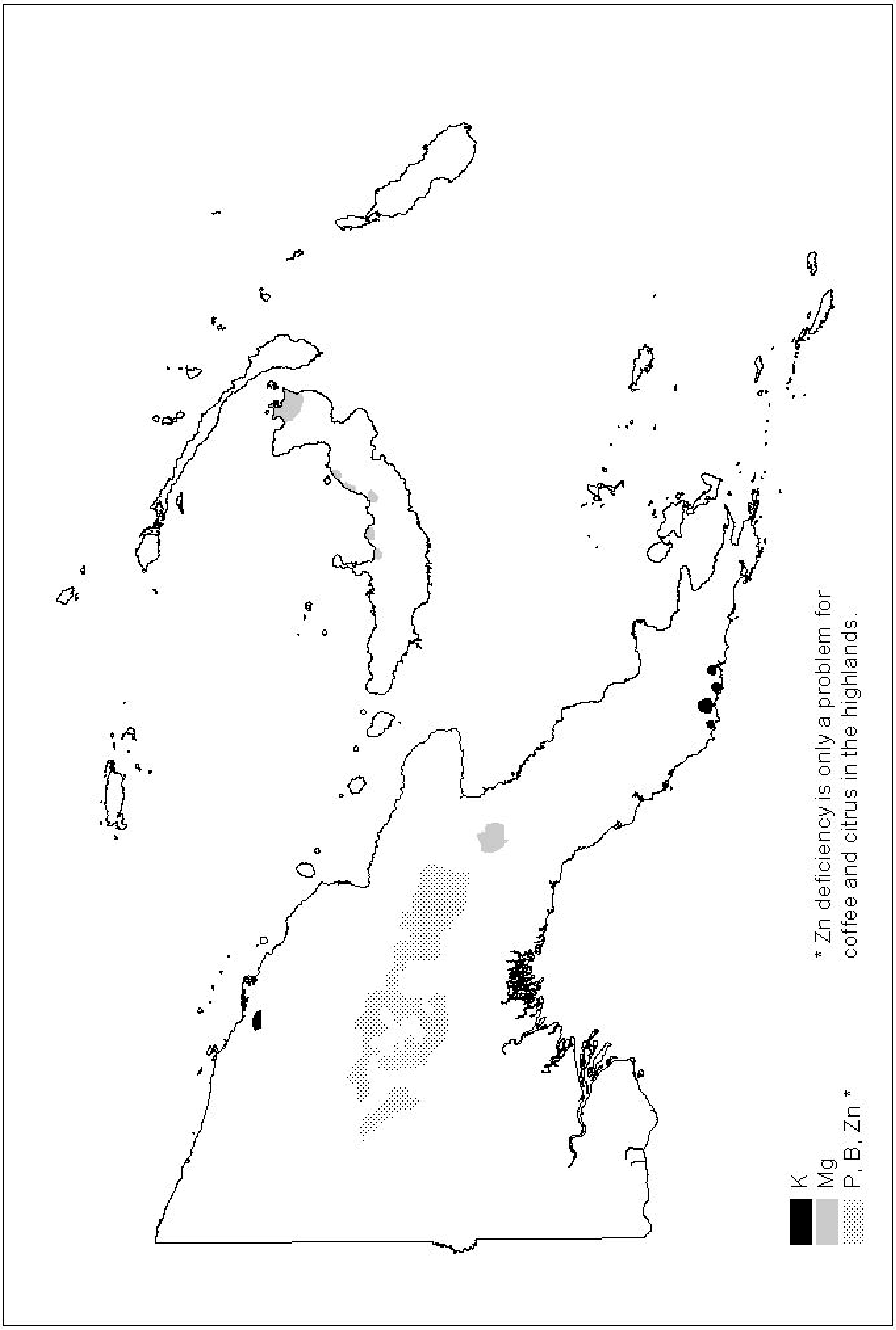

Fig. 2. Macro- and micronutrient deficiencies in agricultural crops of Papua New Guinea based on field observations and expert knowledge

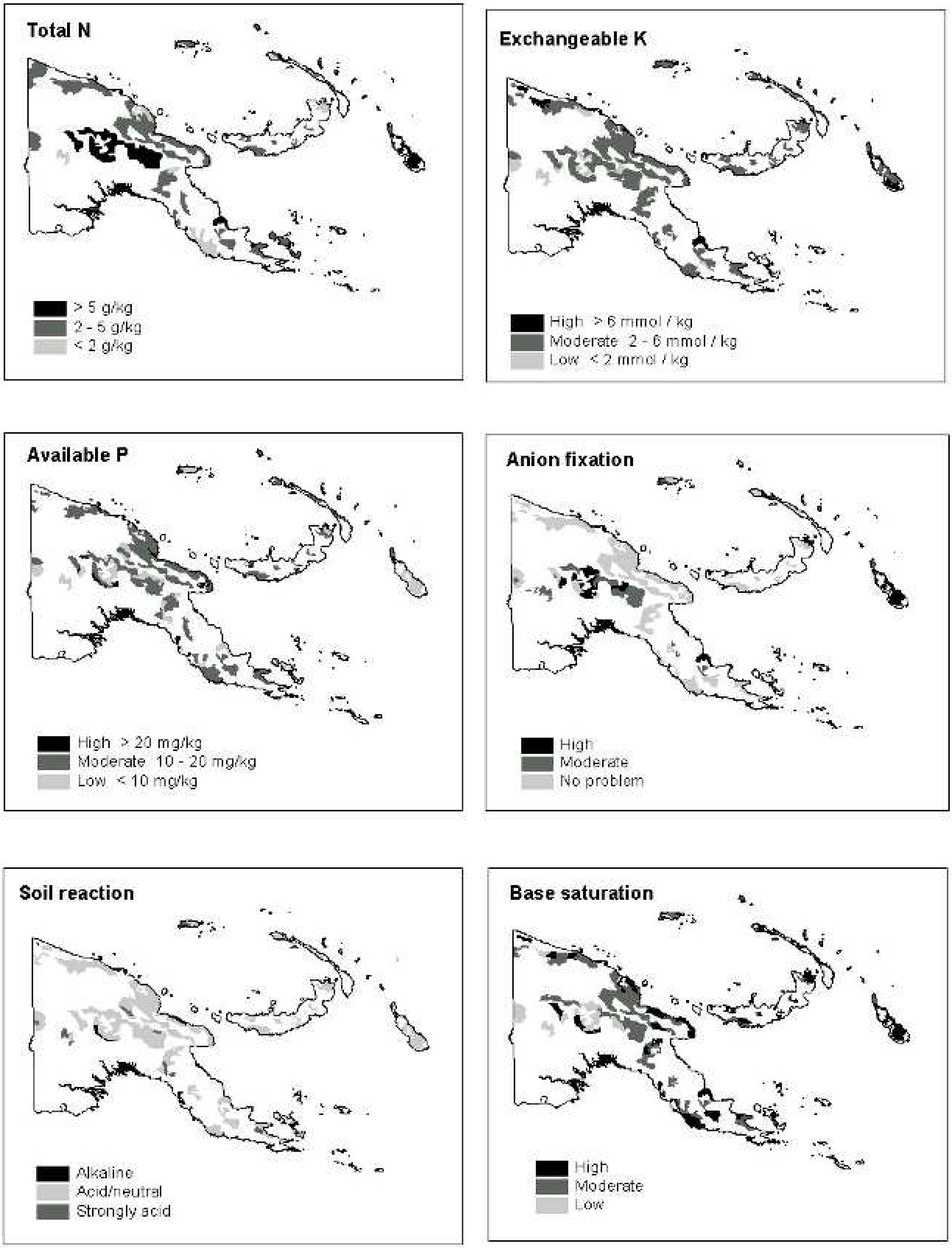

Fig. 3. Soil fertility status of agricultural soils in Papua New Guinea based on the Papua New Guinea Resource Information System (PNGRIS) and data in Bellamy and McAlpine (1995)

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7. Yield decline of sweet potato in the humid lowlands of Papua New Guinea *

Abstract

Sweet potato (*Ipomoea batatas* (L.) Lam) is the major staple crop in Papua New Guinea and experiments were conducted investigating factors affecting yield decline. Yields of unfertilized plots were related to rainfall and measured changes in soil properties, nematode (*Meloidogyne* sp., *Rotylenchulus reniformis*) and sweet potato weevil (*Cylas formicarius*) populations. The research took place at two locations (Hobu and Unitech) on Eutropepts and Fluvents respectively. Yields at Hobu decreased from 18 Mg ha^{-1} in the first season to around 7 Mg ha^{-1} in the third season, but no significant yield trend was observed at Unitech. Vine biomass was not affected by the number of cropping seasons at Hobu but it decreased at Unitech with time. Marketable tuber yield at both sites was significantly correlated to rainfall i.e., the more rain the lower the yield. Significant changes in soil chemical properties included a decrease in pH and base saturation (Hobu) and a decrease in CEC and exchangeable K (Unitech). No significant changes in soil bulk density were found and no obvious pattern was found in the nutrient concentrations of leaf samples with time. Nematodes populations were high and tripled between the first and third season at Hobu. Half of the vines at Hobu and all of the vines at Unitech were damaged by sweet potato weevils, but tuber damage was higher in Hobu although the damage was only superficial. Despite the considerable variation in yield and yield determining factors, the study showed that the decline in sweet potato yield may be attributed to the high nematode infestation, accompanied by an increase in vine damage by weevils and declining soil fertility.

7.1. Introduction

In many tropical regions, increased pressure on the land has resulted in the shortening of fallow periods in slash-and-burn agricultural systems and an increase in the cultivation of marginal lands. This has caused land degradation and a decline in crop production (Greenland *et al.*, 1997). There is a need to develop continuous cultivation systems which sustain

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* Hartemink, A.E., S. Poloma, M. Maino, K.S. Powell, J. Eganae and J.N. O'Sullivan, 2000. Yield decline of sweet potato in the humid lowlands of Papua New Guinea. Agriculture Ecosystems and Environment, 79: 259-269. © Elsevier; reprinted with permission.

crop yield but the development is a fundamental challenge facing both farmers and agronomic researchers in tropical regions (Lal and Ragland, 1993).

There is a fair body of knowledge of indigenous cultivation systems in which crop rotation, composting, and mixed cropping form important components (Torquebiau, 1992). Such systems are generally believed to be sustainable although crop yields are low. As population increases crop production needs to be increased either through a larger area under cultivation or through intensification and continuous cultivation. Sustainable indigenous cropping systems may, however, disintegrate when continuously cultivation is practised which may result in declining crop production. Therefore, for the development of sustainable intensified cropping systems, knowledge is required as to why and how much crop yields will decline under continuous cultivation. This has been investigated for some foodcrops in tropical regions, for example, rice (Cassman *et al.*, 1997) and cassava (Howeler, 1991).

There is limited literature on factors controlling yield decline under continuous sweet potato (*Ipomoea batatas* (L.) Lam), which is an important crop throughout the Pacific region (Parkinson, 1984). Average tuber yields in the Pacific region are below 5 Mg ha^{-1} (de la Peña, 1996). In Papua New Guinea, sweet potato is the major staple crop (Bourke, 1985) but as a result of land-use intensification many agricultural systems are unstable (Allen *et al.*, 1995). As a consequence, sweet potato yields are either declining or almost static and there is tremendous scope for yield improvement (O'Sullivan *et al.*, 1997).

This paper presents yield patterns from continuously cultivated and non-fertilized sweet potato plots with the aim to investigate biophysical factors (soil, pests and diseases) that contribute to yield decline in sweet potato. Data were used from different experiments at two sites and these were collected as part of medium-term experiments dealing with integrated nutrient management strategies for which results have been published elsewhere (e.g. Hartemink *et al.*, 2000). Yields are related to rainfall and the number of cropping seasons, followed by nutrient availability, nutrient removal and nematode and weevil infestation. The relationship between pests and disease and yields have been poorly investigated for sweet potato (Horton, 1988), especially in Papua New Guinea (Bourke, 1985). Although weeds are an important factor in determining sweet potato yields (Levett, 1992), they were not included in the study as all plots were kept weed-free to reduce yield variability which is common in field experiments with sweet potato (Bourke, 1985; Martin *et al.*, 1988).

7.2. Methods

Research sites

The research took place at two sites in the humid lowlands of the Morobe Province of Papua New Guinea. Experiments were conducted on-farm at Hobu village and at the experimental farm of the University of Technology (Unitech) in Lae (Fig. 1). At Hobu experiments lasted from October 1996 to November 1998 and at Unitech experiments were conducted from June 1996 to November 1998.

Hobu (6°34'S, 147°02'E) is located 25 km N of Lae at the footslopes of the Saruwaged mountain range. The altitude at the site is 405 m a.s.l. Rainfall records were only available from the start of the experiments (November 1996) and the monthly pattern is depicted in Fig. 2. In 1997, there was a total rainfall of 1,897 mm which is well below the long-term average because of the El-Niño weather phenomena which hit the Pacific severely in 1997-98. In the first five months of 1998, however, nearly as much rain fell as in the whole of 1997.

The experimental farm at Unitech (6°41'S, 146°98'E) is located 9 km N of Lae on a nearly flat alluvial plain. The altitude of the farm is about 65 m a.s.l. Mean total annual rainfall is about 3,789 mm but in the past 25 years it varied from 2,594 to 4,918 mm. Average daily temperatures at Unitech are 26.3°C and are slightly higher than at Hobu. During the experiments monthly rainfall was higher at Unitech than at Hobu with the exception of the beginning of 1998 (Fig. 2). The amount of rain received for the individual experiments is discussed in the Results section.

The Hobu site is located on an uplifted alluvial terrace with a slope of less than 2 %. Soils at Hobu are derived from a mixture of alluvial and colluvial deposits and gravelly and stony soil horizons occur at about 0.2 m depth. Effective rooting depth is well over 0.7 m. The soils are fertile with moderately high organic carbon contents and high levels of exchangeable cations (Table 1). Topsoils are clayey and have bulk densities between 0.6 and 0.8 Mg m^{-3}. The soils are classified as mixed, isohyperthermic, Typic Eutropepts (USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base).

The soils at Unitech are derived from alluvial deposits. The topsoils are slightly gravelly and have sandy loam textures. The stratified subsoils have fine gravel at irregular depth and sand content is above 50% (Table 1). The moderately acid topsoils are low in organic carbon, and have bulk densities of 1.10 Mg m-3. The soils are classified as sandy, isohyperthermic, Typic Tropofluvents (Soil Taxonomy) or Eutric Fluvisols (World Reference Base).

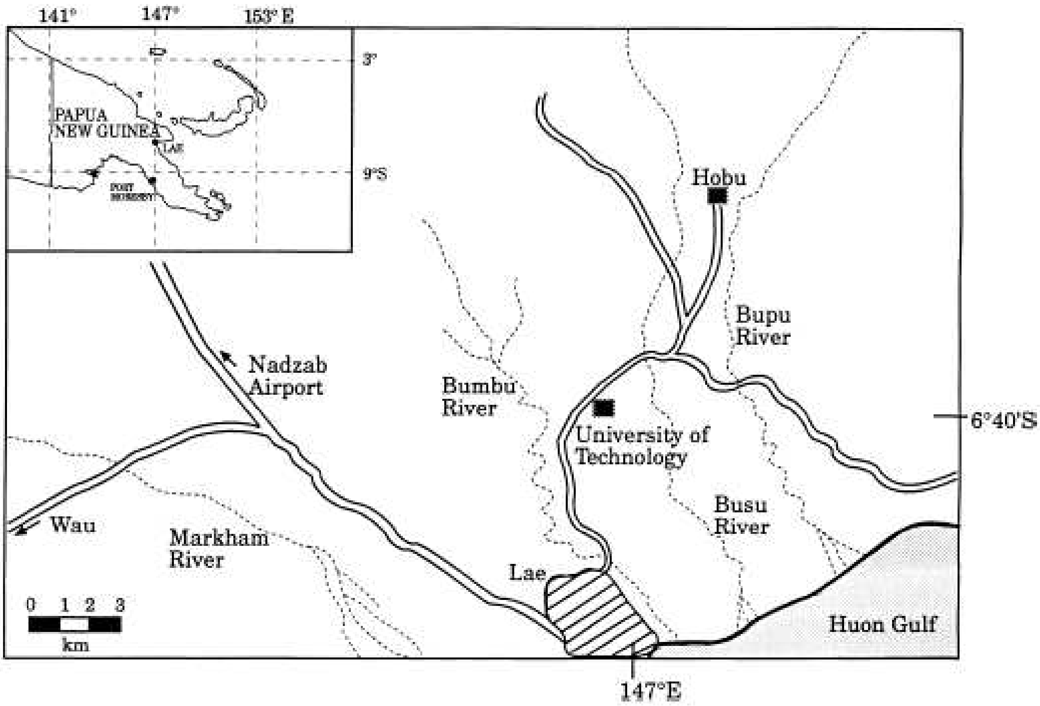

Fig. 1. Location of the research sites in the Morobe Province of Papua New Guinea

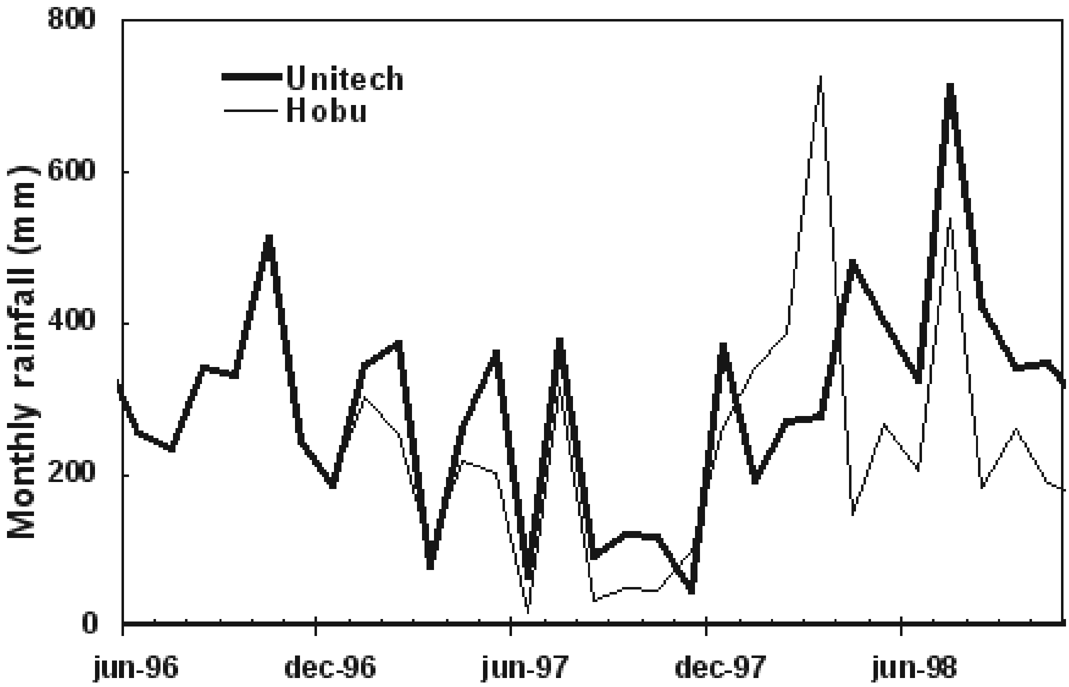

Fig. 2. Monthly rainfall at the experimental sites at Hobu (November 1996–December 1998) and Unitech (June 1996–December 1998)

Experiments

The experiments at Hobu and Unitech were part of nutrient management trials which had a slightly different experimental design at each site. At Hobu, four years old secondary vegetation (mainly *Piper aduncum* L.) was slashed manually in October 1996. At Unitech, the experimental site had been under grassland since 1990 and was chisel ploughed in June 1996. All experiments at Hobu and Unitech were laid out in randomized complete block designs. Plot sizes at Hobu were 4.5 by 4.5m or 6.0 by 6.0m with planting distances of 0.75 by 0.75 m (17,778 plants ha^{-1}). Plot sizes at Unitech were 3.2 by 4.0 m and the sweet potato was planted at 0.4 by 0.8 m (31,250 plants ha^{-1}). All experiments at Hobu were planted with the locally important cultivar 'Hobu1'. The experiments at Unitech were planted with sweet potato cultivar 'Markham'. At both sites, cropping seasons lasted 170 to 190 days. At harvest, vines were cut at ground level, weighed, and removed from the plot. Tubers were manually dug, counted and separated into marketable tubers (>100 g) and non-marketable tubers (<100 g). Plots were replanted directly after a harvest. Weeds were pulled out manually and not removed from the plots. No pesticides were used.

Soil and plant sampling

Soil samples for chemical analysis were taken before the planting of the first crop and after each season. Samples were collected with an Edelman auger at 9 to 12 random locations in a plot, mixed and a subsample of about 1 kg was taken. Airdried samples were ground, sieved (2 mm) and analyzed at the National Analytical Chemistry Laboratories in Port Moresby. The procedures for soil analysis were as follows: pH H2O (1:5 w/v); organic C and total N by Leco CNS-2000 dry combustion; available P by Olsen; exchangeable cations and CEC by 1*M* NH4OAc percolation (pH 7.0); particle size analysis by hydrometer. Bulk density was measured using 100 mL cores at 0-0.15 m depth before the first crop and before each harvest. Cores were ovendried at 105°C for 72h. Mid-season leaf samples were taken in the sweet potato plots at about 80 to 110 days after planting (DAP). The 7th to 9th leaf, starting from the first unfolded leaf were taken from ten randomly selected vines within each plot. At harvest, samples of vines, marketable tubers and non-marketable tubers were taken for dry matter determination and nutrient analysis. Plant samples were analysed for nutrient content at the laboratories of the School of Land and Food of the University of Queensland. One subsample was digested in 5:1 nitric:perchloric acids and analyzed for P, K, Ca and Mg using ICP AES (Spectro Model P). A second subsample was digested according to the Kjeldahl procedure and analyzed for N on an Alpkem Rapid Flow Analyser Series 300. Data from tubers and vines samples taken at the end of the seasons were used to calculate nutrient uptake.

Table 1. Soil chemical and physical properties of the research sites at Hobu and Unitech

Soil type	Sampling depth (m)	pH H_2O 1:5	Organic C (g kg^{-1})	Total N (g kg^{-1})	Olsen P (mg kg^{-1})	CEC pH7 (mmol$_c$ kg^{-1})	Exchangeable cations mmol$_c$ kg^{-1}			Base Saturat-ion (%)	Particle size fractions (g kg^{-1})		
							Ca	Mg	K		clay	silt	sand
Hobu [1]	0-0.12	6.2	54.6	5.0	9	400	248	78	16.9	86	480	160	360
(Eutropepts)	0.12-0.23	6.3	25.4	2.3	2	355	220	84	1.9	86	620	110	270
	0.23-0.39	6.6	13.7	1.3	1	338	200	105	1.4	91	600	140	260
	0.39-0.99	7.4	2.1	0.3	4	357	189	99	1.4	82	340	110	550
Unitech [2]	0-0.23	5.9	23.8	2.0	12	289	212	49	5.1	92	80	130	790
(Fluvents)	0.23-0.42	6.1	5.0	0.4	3	303	216	46	2.2	88	140	190	670
	0.42-0.57	6.4	4.8	0.4	3	352	256	70	0.9	94	140	360	500
	0.57-0.66	6.6	5.5	0.5	7	435	334	109	0.8	100	140	130	730

[1] Samples taken from a soil pit in April 1996; grassland since 1990.
[2] Samples taken from a soil pit in February 1997; bush fallow since 1992

Nematode and sweet potato weevil counts
Counts of nematode (*Meloidogyne* sp. and *Rotylenchulus reniformis*) populations were made on soil samples collected in continuously cultivated plots at the end of the cropping seasons in 1998. For both species, only juvenile stages were considered. In each plot, a composite soil sample was obtained from 12 locations using an Edelman auger. In the laboratory, 200 mL of each soil sample was evenly spread on prepared Baermann's trays. Tap water was added until the soil was moist and left for 72h at temperatures of about 27 °C. Nematodes were extracted on a 38μm sieve and counted on a 20-gridlined counting slide under a light microscope at 40x magnification. The data were log-transformed before average counts of nematodes were calculated.

Sweet potato weevils (*Cylas formicarius* Fab.) were counted using 1 m^2 quadrats repeated three times in each plot before the harvest. Following the weevil counts, all vines were slashed to within 0.15 m of the tuber crown and removed from the plot. Three plants were uprooted and the remaining 0.15 m vine sections were cut and placed in a paper bag. The number of vines, number of damaged vines, number of life-stages in damaged vines and vine weight were recorded. Vines were dissected to assess damage and the number of weevil-stages. Tubers were sub-divided by external appearance of the periderm as either damaged (presence of feeding and/or ovipositor marks) or undamaged (no marks). Damaged marketable tubers were sliced at the zone of maximum surface damage and categorised using the rating scale of Sutherland (1986). Damaged tubers were sliced into 2 to 3 mm sections to count the weevil life stages.

7.3. Results

Yield patterns
At Hobu, in the first season after a five-year fallow period, sweet potato yields varied from 13 Mg ha^{-1} to 18 Mg ha^{-1} (Table 2). In the second season, it was observed that marketable yield could decrease (experiment 1), increase (experiment 2) or remain about the same (experiment 3) when compared with the first season. In the third consecutive cropping season (experiment 1 and 2), however, yields declined to less than half of their levels in the first season. Marketable yield at Unitech after a six year fallow were much lower than at Hobu but varied from 4 to 16 Mg ha^{-1}. Tuber yield at Unitech showed no distinct pattern with time.

Sweet potato vine yield at Hobu was up to 40 Mg ha^{-1} (fresh weight) in the first two cropping seasons, but declined to 26 Mg ha^{-1} in the third season. Vine yield at Unitech was 30 Mg ha^{-1} in the first season but decreased to 13 Mg ha^{-1} in the fifth season. Non-marketable tubers ranged from 1.0 to 4.0 Mg ha^{-1} at Hobu and from 2.3 to 4.5 Mg ha^{-1} at Unitech. The sweet potato at Unitech produced relatively more non-marketable tubers than at Hobu. The harvest index (i.e. marketable tuber yield/total tuber yield + vines) varied from 0.18 to 0.47 at Hobu and from 0.14 to 0.48 at Unitech.

Table 2. Marketable sweet potato yields (in Mg fresh weight ha^{-1} ± 1 SD) under unfertilized conditions. Total rainfall received (in mm) during the growing season in parentheses

Cropping season	Hobu experiment 1		Hobu experiment 2		Hobu experiment 3		Unitech experiment 1		Unitech experiment 2	
1	18.3 (1230)	±3.7	18.3 (1028)	±6.2	13.3 (1203)	±18.0	9.0 (1759)	±3.8	5.4 (1799)	±3.2
2	14.5 (598)	±2.6	24.7 (1034)	±9.2	13.2 (2091)	±7.2	5.8 (1261)	±1.3	4.4 (1538)	±2.0
3	7.8 (1894)	±0.5	6.9 (2214)	±4.4	-		16.3 (811)	±8.3	-	
4	12.8 (1577)	±2.7	-		-		5.7 (1838)	±2.4	-	
5	-		-		-		6.7 (2294)	±2.2	-	

- means no data available; (note: experiments were not run simultaneously)

Table 2 showed a weak relationship between the number of cropping seasons and the yield of sweet potato at Hobu and Unitech. During the experiments the impression was formed that yields were generally higher in seasons with lower rainfall. Sweet potato is reported to be very sensitive to excess soil water during the first 20 days after planting when tubers are formed (Hahn and Hozyo, 1984) and a regression analysis between marketable yield and rainfall received during the first 20 days of growth was conducted (analysis not shown). No obvious relation was found, and instead correlation coefficients were calculated for the tuber yield, vine yield and total rainfall received in the season (Table 3). It was found that rainfall at Hobu was significantly correlated with the marketable and non-marketable tuber yield, as follows: the higher the rainfall the lower the tuber yield. Vine yield was positively correlated with rainfall which suggests that the reduction in tuber yield in wetter seasons favours the growth of vine biomass. The number of cropping seasons at Hobu was significantly correlated with both marketable and non-marketable tuber yield, but not to the vine biomass: tuber yield declined under continuous cultivation but vine yield was not affected. At Unitech correlations among yield, rainfall and cropping seasons were weaker. The number of cropping seasons was not correlated with tuber yield. Marketable yield was also negatively correlated with the rainfall received during the cropping season.

Table 3. Correlation between rainfall, number of cropping seasons, sweet potato tuber yield and vine yield

Site		Marketable yield	Non-marketable yield	Vine yield
Hobu	rainfall during the growing season [1]	– 0.601 **	– 0.814 ***	0.866 ***
	number of cropping seasons [2]	– 0.556 *	– 0.622 **	0.274
Unitech	rainfall during the growing season [1]	– 0.558 **	0.085	– 0.167
	number of cropping seasons [2]	– 0.202	0.018	– 0.628 **

***, **, * indicates significant correlation at $P<0.001$, $P<0.01$ and $P<0.05$ respectively
[1] covariate = number of cropping seasons (i.e. 4 at Hobu and 5 at Unitech)
[2] covariate = rainfall received in the season

Changes in soil properties and plant nutrients

Table 4 shows soil chemical properties before the first planting and after four seasons (± 2 years) of continuous sweet potato cultivation. At Hobu, the topsoil pH had decreased by 0.4 units accompanied by a decrease in base saturation. Changes in topsoil properties at Unitech included a decrease in cation exchange capacity (CEC) and exchangeable potassium. Bulk density was not altered in the Hobu soils under continuous sweet potato cultivation but a slight decrease was found in the bulk density of the Unitech soils up to the fourth season (data not shown). This can be expected as harvesting sweet potato involves topsoil digging with a fork to about 0.2 m depth.

Although no obvious pattern of decline was found in the leaf nutrient concentrations, the highest concentration of all major nutrients was found in the first cropping season at Hobu (Table 5). Nitrogen and sulphur were below the critical concentration for deficiency in all seasons (O'Sullivan *et al.*, 1997) but other major nutrients were above the critical limits. Minor nutrient concentrations were exceeding the critical levels as given by O'Sullivan *et al.* (1997) except for boron which concentrations were only slight below the critical level (Table 6).

A decrease in leaf nutrient concentration was expected because large amounts of nutrient are removed with the sweet potato harvest. Table 7 shows the amount of nutrients removed with the first harvest at Hobu and Unitech. Considerable amounts of potassium are removed with the tubers and vines. The table shows that the largest amount of nutrients is removed with the vines. At Hobu, sweet potato removed per 10 Mg ha^{-1} of fresh marketable tubers about 16 kg N, 7 kg P and 51 kg K ha^{-1} and at Unitech this was found to be similar.

Table 4. Changes in soil chemical properties under continuous sweet potato cultivation (sampling depth 0-0.15m)

Site [1]	Sampling time	pH H_2O 1:5 w/v	Organic C g kg^{-1}	Total N g kg^{-1}	Olsen P mg kg^{-1}	CEC pH7 mmol$_c$ kg^{-1}	Exchangeable cations mmol$_c$ kg^{-1} Ca	Mg	K	Base saturation %
Hobu (Eutropepts)	Before planting	6.2	69.9	6.0	10	405	268	61	12.2	84
	After four seasons [2]	5.8	71.3	5.9	6	466	227	59	8.4	63
	Difference	$P<0.01$	ns	ns	ns	$P<0.01$	ns	ns	ns	$P<0.001$
Unitech (Fluvents)	Before planting	5.9	22.1	1.9	30	342	247	39	11.2	88
	After four seasons [2]	5.9	21.7	1.7	24	299	224	45	8.6	93
	Difference	ns	ns	ns	ns	$P<0.05$	ns	ns	$P<0.05$	ns

[1] Data from experiment 1 at Hobu and Unitech; values are the arithmetic mean of four plots
[2] One season is about 170 to 190 days
ns - not significant ($P>0.05$)

Nematodes and weevils

Nematode counts in soil extracts from the Hobu site showed that the juvenile population of Meloidogyne sp. increased with increasing number of cropping seasons (Table 8). The increase in number of nematodes was significant between the first and second season but the number of nematodes in soils under three or four seasons did not differ significantly.

Although the species of Meloidogyne could not be identified with certainty common root-knot species under sweet potato in Papua New Guinea are *Meloidogyne incognita* and *Meloidogyne javanica* (Bridge and Page, 1984). In the Unitech soils under sweet potato, no root-knot nematodes were observed but a high population of reniform nematodes (*Rotylenchulus reniformis*) was found.

Table 5. Concentration of major nutrients (in g kg^{-1} ± 1SD) in sweet potato leaves of plots under different periods of cultivation

Site	Cropping season	N	P	K	Ca	Mg	S
Hobu	1	33.0 ±2.8	3.7 ±0.4	36.4 ±2.1	11.7 ±1.2	4.6 ±0.4	2.7 ±0.1
	2	28.7 ±3.7	2.8 ±0.1	33.6 ±2.8	9.5 ±0.8	4.0 ±0.5	2.1 ±0.2
	3	19.4 ±0.7	3.2 ±0.3	31.3 ±3.4	8.1 ±0.6	3.8 ±0.2	2.9 ±0.1
	4	28.3 ±2.5	3.1 ±0.4	32.1 ±3.6	10.6 ±0.8	2.9 ±0.4	2.4 ±0.2
Unitech	1	26.6 ±6.3	3.8 ±0.4	32.7 ±1.4	9.6 ±1.2	2.6 ±0.3	2.1 ±0.3
	2	25.1 ±4.6	4.7 ±0.3	36.1 ±1.9	10.7 ±1.7	3.4 ±0.2	2.0 ±0.1
	3	26.9 ±1.0	5.4 ±1.1	36.3 ±2.6	12.9 ±1.9	3.8 ±0.6	2.7 ±0.1
	4	na	4.3 ±0.2	19.9 ±8.9	12.6 ±1.8	4.0 ±0.3	2.0 ±0.2
	5	na	4.9 ±0.6	28.6 ±5.6	9.1 ±0.8	3.2 ±0.1	2.4 ±0.2
Critical concentration [1]		40.0	2.2	26.0	7.6	1.2	3.4

Data from leaf samples taken in the middle of the growing season, i.e. between 80 and 110 DAP
na – not available
[1] Critical nutrient concentration for deficiency from O'Sullivan *et al.* (1997) based on experiments in solution culture

Table 6. Concentration of minor nutrients (in mg kg^{-1} ± 1SD) in sweet potato leaves of plots under different periods of cultivation

Site	Cropping season	Fe	B	Mn	Zn	Cu	Mo
Hobu	1	159 ±48	47 ±4	57 ±3	39 ±6	13 ±2	1.2 ±0.3
	2	105 ±18	32 ±3	57 ±3	45 ±17	12 ±2	1.2 ±0.3
	3	106 ±17	31 ±6	42 ±4	20 ±2	8 ±2	na
	4	270 ±115	39 ±2	52 ±10	33 ±2	15 ±2	0.5 ±0.2
Unitech	1	164 ±15	39 ±8	42 ±7	20 ±1	5 ±3	na
	2	225 ±165	33 ±6	42 ±3	23 ±3	5 ±2	na
	3	198 ±10	45 ±9	51 ±6	25 ±1	9 ±1	na
	4	99 ±31	35 ±7	40 ±5	27 ±3	9 ±1	na
	5	na	34 ±1	45 ±5	26 ±1	13 ±1	na
Critical concentration [1]		33	40	19	11	4-5	0.2

Data from leaf samples taken in the middle of the growing season, i.e. between 80 and 110 DAP
na – not available
[1] Critical nutrient concentration for deficiency from O'Sullivan *et al.* (1997) based on experiments in solution culture

Table 7. Nutrient uptake (in kg ha^{-1} ± 1SD) of sweet potato

Site	Plant part	Fresh yield Mg ha^{-1}	N	P	K	Ca	Mg
Hobu	marketable tubers	18.2 ±3.7	30 ±6	12 ±2	93 ±20	5 ±1	5 ±1
	non-marketable tubers	4.0 ±1.0	8 ±2	3 ±1	25 ±6	1 ±0.5	1 ±0.5
	vines	26.2 ±4.8	80 ±8	18 ±2	180 ±30	61 ±13	20 ±2
	Total		118 ±10	33 ±3	298 ±46	67 ±12	26 ±2
Unitech	marketable tubers	9.0 ±3.8	15 ±17	7 ±3	39 ±19	4 ±2	2 ±1
	non-marketable tubers	2.9 ±1.3	5 ±5	2 ±1	12 ±5	1 ±0.5	1 ±0.5
	vines	30.1 ±8.2	59 ±21	22 ±2	189 ±15	37 ±8	10 ±2
	total		79 ±40	31 ±5	241 ±23	42 ±10	13 ±3

Data from first cropping season of experiment 1 at Hobu and Unitech

Table 8. Nematode counts (number per 200 mL ±1 SD) in soils under sweet potato

Hobu			Unitech		
Cropping season	Sampled plots	Nematodes [1]	Cropping season	Sampled plots	Nematodes [2]
1	12	65 ±52	4	4	1795 ±329
3	4	211 ±73	5	4	1208 ±250
4	4	157 ±52			

[1] root knot nematodes (*Meloidogyne* sp.); [2] reniform nematodes (*Rotylenchulus reniformis*)

Table 9. Weevil counts and vine and tuber damage in unfertilised sweet potato plots of different age

			Tubers		Vines	
Site	Cropping season	Weevil counts no. m^{-2}	Damage %	Life stages per tuber no.	Damage %	Life stages per vine no.
Hobu	3	0.0	78	0.25	52	1.5
	4	0.5	35	5.25	55	0.5
Unitech	4	12.8	0	0	100	3.5
	5	1.1	0	0	100	5.3

Values are the average of 4 sampled plots

At Hobu, the aboveground population of weevils at harvest was very low for both seasons but a considerable portion of the marketable tubers and vines was damaged (Table 9). Damaged tubers over both seasons were predominantly categorised in category 1, i.e., only superficial damage to the periderm (Sutherland, 1986). At Unitech, the aboveground population of weevils was relatively high. The degree of vine damage was very high at the end of the fourth season and slightly decreased in the following season. There was no reduction in the number of weevil life stages per damaged vine in the fifth season. The high level of vine damage was not reflected in tuber damage.

7.4. Discussion

Considerable yield variation was found within cropping seasons which is not uncommon in field experiments (de Steenhuijsen Piters, 1995) especially with sweet potato (Martin *et al.*, 1988). Overall, sweet potato yields were lower at Unitech than at Hobu which could result from differences in soils, weather or the cultivar grown. Yields at both locations fall within the range given for lowland conditions in Papua New Guinea (Bourke, 1985) and are above the average given for Oceania (de la Peña, 1996; Horton, 1989).

Two important trends emerged from the statistics on the yield data. Firstly, it was noticed that yields were negatively affected by rainfall and secondly, tuber and vine yields declined under continuous cultivation. Both trends are discussed below.

Yield and rainfall

Marketable tuber yield was depressed in seasons with high rainfall which was observed at both sites regardless of the cropping history. Although there are cultivar differences (Martin, 1983; Ton and Hernandez, 1978) sweet potato is reported to be very sensitive to excess soil water during the first 20 days after planting but regression analysis failed to show a relation. The boundary of 20 days established in greenhouse trials is apparently different under field conditions. Later in the growing season sweet potato is susceptible to excess water because tubers may rot, but this did not occur in these experiments.

Excess soil moisture may also have indirect effects. In wet seasons, values up to 60% water-filled pores space (WFPS) were measured in the Hobu soils at which denitrification may become significant (Linn and Doran, 1984). In the sandy soils of Unitech, such high levels of WFPS were not found and the potential for denitrification is much lower. Denitrification means loss of nitrogen which may thus affect growth. At Hobu, the lowest leaf nitrogen concentration was found in the season with the highest rainfall (third season, Tables 2 and 5). It would be expected, however, that the loss of nitrogen would reduce vine yield but the opposite

was found. It therefore seems likely that denitrification is not a major explanation for depressed yields in seasons with high rainfall.
There are generally lower levels of photosynthetically active radiation (PAR) because of cloud cover in seasons with high rainfall. Sweet potato is a light-loving plant and sensitive to shading (Roberts-Nkrumah *et al.*, 1986). It is likely that reduced PAR would not only affect tuber yield but also vine growth. Statistics showed, however, that total vine yield was positively related to rainfall at Hobu whereas no significant correlation was found at Unitech (Table 4). This suggests that also a reduced PAR is possibly not a major factor explaining yield depression.

Yield decline
Continuous cultivation of sweet potato had different effects at the different sites: in the more fertile soils (Hobu) continuous cultivation decreased tuber yields but not vine yield. In soils with lower fertility (Unitech) continuous cultivation did not affect tuber yields which were already low, but significantly reduced vine yield. The reduction in vine biomass had no effect on tuber yield. It seems that continuous cultivation first reduces tuber yields and then reduces vine production.
Few changes were observed in most soil chemical properties despite the heavy drain of nutrients by the yield. This is probably because of the relatively short time between the sampling (2 years) as changes in soil chemical properties are commonly not detected with standard soil analytical methods within such periods (Young, 1997). Soil chemical properties had not declined to low levels. For example, the pH of 5.8 at Hobu and 6.0 at Unitech are still favourable for sweet potato (Constantin *et al.*, 1975), as are the levels of available phosphorus and exchangeable cations (O'Sullivan *et al.*, 1997).

Concentrations of major nutrients in the leaves were all adequate except for nitrogen and sulphur which were below the critical level of O'Sullivan *et al.* (1997) at both sites. Boron levels at both Hobu and Unitech were slightly below the critical level. Differences in leaf nutrient concentrations between the sites reflects soil, climatic and cultivar differences (Bruns and Bouwkamp, 1989; Walker, 1987). Despite the low leaf nitrogen levels fertilizer trials generally failed to show a tuber yield response to sulphur-containing nitrogen fertilizers (Hartemink *et al.*, 2000) which supports the observation that sweet potato can produce reasonable yields in soils with low native nitrogen and without nitrogen fertilizer (Hill *et al.*, 1990).

Declining yields could also result from decreasing levels of micronutrients, but no trend in the leaf nutrient concentrations was observed. Complete omission trials in the greenhouse with Hobu soil showed a vegetative growth response to zinc but field trials failed to show a response (Ila'ava and Hartemink, unpubl. data). Although micronutrients limit sweet potato production in many areas of Papua New Guinea (Bourke, 1983; O'Sullivan *et al.*, 1997) micronutrients are possibly not limiting at Hobu or Unitech.

Distinctly different nematode species were found in Hobu and Unitech soils. The difference could either be competition between the two species (Thomas and Clark, 1983) or differences in soil conditions (Barker and Koenning, 1998) and cultivars (Clark and Wright, 1983). Populations of Meloidogyne sp. and Rotylenchulus reniformis in the soils of Hobu and Unitech were high. Both nematode species have destructive effects on sweet potato, reducing yield and quality (Clark and Wright, 1983) as they have a root pruning and damaging effect. Clark and Wright (1983) found that 600 to 4,000 Rotylenchulus reniformis per 200 mL significantly reduced tuber yield. Much lower threshold values have been reported for Meloidogyne sp. (Thomas and Clark, 1983). Nematodes levels exceeded the threshold values in the experiments at Hobu and Unitech and it is therefore likely that nematodes reduced sweet potato yields. This is in line with earlier reports on plant nematodes in Papua New Guinea (Bridge and Page, 1984).

The situation for sweet potato weevils is less clear-cut as there seems to be little relation between number of weevils in the foliage (vines) and damaged tubers and vines. Factors which determine tuber damage are related to aboveground weevil population, soil type, rainfall and cultivar characteristics (Sutherland, 1986). At Hobu, weevil populations were far lower than at Unitech despite the fact that there is less rainfall at Hobu which generally favours weevil populations (Bourke, 1985). Weevils fail to penetrate in wet soil but can penetrate easily in dry soils (Teli and Salunke, 1994). The lower weevil populations at Hobu resulted in less vine damage but tuber damage was higher. The damage was superficial only and has limited effect on the marketability of the tubers. The higher vine damage at Unitech accompanying high number of weevils in the vines agrees with the findings of Sutherland (1986). The high degree of vine damage at Hobu (50%) and Unitech (100%) indicates that weevils were abundant at both sites and it is likely that the vine damage affected tuber yield.

In conclusion, soil and leaf data suggest that declining soil fertility may not be the main cause for the decline in sweet potato yields. A combination of increased levels of nematodes, vine damage by the weevils, and a decline in soil chemical properties contribute to yield decline of sweet potato under continuous cultivation. In addition, it was found that dry weather conditions as a result of the El Niño oscillation favoured sweet potato production under the conditions of the experiments. This is possibly related to better soil aeration.

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8. Nitrogen use efficiency of taro and sweet potato in the humid lowlands of Papua New Guinea *

Abstract

Root crops are an important staple food in the Pacific region. Yields are generally low and inorganic fertilizers are deemed an option to increase root crop production. The effects of inorganic N fertilizers on upland taro (*Colocasia esculenta* (L.) Schott) and sweet potato (*Ipomoea batatas* (L.) Lam.) were quantified with the aim to investigate relationships between inherent soil fertility, N uptake, N application rates and crop yield. The research took place on a sandy, Typic Tropofluvents in the humid lowlands of Papua New Guinea. Five levels of fertilizer N (0,100, 200, 300 and 400 kg ha^{-1}) were given in split applications. The yield of marketable taro corms was not affected by N fertilizer but non-marketable corm yield doubled at high N fertilizer rates. High N applications yielded 8 to 11 Mg ha^{-1} more taro tops. Marketable and non-marketable sweet potato yield was negatively affected by N fertilizers. High N applications yielded 26 Mg ha^{-1} more vines than the control treatment. Nitrogen fertilizer significantly reduced the harvest index in both crops. When no fertilizer was applied, the total N uptake of taro was 32.0 kg ha^{-1} of which 9.7 kg was taken up in the marketable corms. At 400 kg N ha^{-1} the total N uptake was 67.5 kg ha^{-1} of which 23% was taken up by the marketable corms. Uptake of N in the marketable sweet potato tubers was less than 11 kg ha^{-1} and for most treatments more N was taken up in the non-marketable tubers than in the marketable yield. Up to 156 kg N ha^{-1} was taken up with the sweet potato vines. Despite the negative effect of N on sweet potato yield, sweet potato had a higher N use efficiency than taro due to a higher above-ground biomass production. The N fertilizer recovery was 25% for the sweet potato but only 9% for the taro indicating considerable N losses, likely caused by leaching.

8.1. Introduction

Nitrogen is the element most frequently deficient in tropical soils (Sanchez, 1976). It is the only plant nutrient which can be added to the soil by biological fixation (BNF), but for many cropping systems in the tropics,

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addition of N through BNF is insufficient to cover the loss of N with crop removal and leaching and denitrification (Boddey *et al.*, 1997; Giller and Cadisch, 1995). Application of N from organic and inorganic sources is essential to sustain and improve crop yield in continuous cultivation systems.

Root crops are an important staple food throughout the Pacific region (Parkinson, 1984) and de la Peña (1996) estimated that the area under sweet potato in Oceania was about 120 x 10^3 ha, and 47 x 10^3 ha for taro. Average yields in Oceania are about 4.8 Mg ha^{-1} for sweet potato and 7.0 Mg ha^{-1} for taro. Total production of these crops increased considerably between the 1960s and 1990s, but the increase did not keep up with the population growth (de la Peña, 1996). Improved production systems are therefore required and an important option to increase sweet potato and taro yields is through the use of inorganic fertilizers (Blamey, 1996; de la Peña and Plucknett, 1972) as yields decline under continuous cultivation (Hartemink *et al.*, 2000).

There is fair a body of literature on the use of inorganic fertilizers on taro and sweet potato although the information is limited compared to other staple crops. Both taro and sweet potato consume considerable amounts of potassium and responses to K fertilizers are generally recorded (de Geus, 1972; O'Sullivan *et al.*, 1996). In many tropical soils taro and sweet potato yields may be increased using inorganic N fertilizers. Judicious use of inorganic N fertilizers is, however, essential to avoid off-site effects and environmental contamination and to increase farm profitability.

Taro has relatively high N requirements particularly during its early growth stages (Manrique, 1994). Nitrogen applications for optimum taro yields are 30 to 60 kg N ha^{-1} in the Philippines (Pardales *et al.*, 1982; Villanueva *et al.*, 1983), around 100 kg N ha^{-1} in India (Ashokan and Nair, 1984; Das and Sethumadhavan, 1980) and up to 560 kg N ha^{-1} in Hawaii (de la Peña and Plucknett, 1972). Manrique (1994) reviewed the literature on N requirements of taro and concluded that 100 to 120 kg N ha^{-1} is required to attain 95% of the maximum yield.

Sweet potato has high N requirements but can produce reasonable yields in soils of poor fertility (Hill *et al.*, 1990). This may be partly caused by its capacity to fix atmospheric N through association with symbiotic, non-nodulating bacteria. Recent estimates have shown that as much as 40% of the N uptake of sweet potato may be derived from di-nitrogen (Yoneyama *et al.*, 1998), although cultivar differences are large. A very wide range of N fertilizer requirements has been reported for sweet potato (Hill, 1984) but much depends on the cultivar, soil type and climatic conditions (O'Sullivan *et al.*, 1997).

In most N fertilizer trials with taro and sweet potato, yield is plotted as a function of the amount of N applied which often reveals variable results. It makes interpretation of experiments difficult because it is not known how much fertilizer applied to the soil is taken up by the crop and how much is utilized by the storage roots i.e., the marketable product (van Keulen, 1986). Chemical analysis of the harvested material facilitates the interpretation of fertilizer experiments (van Keulen and van Heemst, 1982). It allows a detailed investigation of the efficiency of the N applied in relation to the amount of N taken up from the soil under unfertilized conditions.

This paper presents an analysis of N use efficiency for taro and sweet potato grown on a sandy soil in the humid lowlands of Papua New Guinea. The relationship between inherent soil fertility, N applications, N uptake and crop yield is investigated with the help of the three-quadrant procedure, which was introduced by de Wit in the 1950s (de Wit, 1953) and applied by several others (e.g. Janssen and Wienk, 1990). The procedure has been mostly used to study nutrient use efficiency by grain crops but has, to our knowledge, not been applied for taro and sweet potato. Taro and sweet potato are important staple crops in the humid lowlands of Papua New Guinea and are grown in shifting cultivation systems. Taro is commonly the first crop planted after the fallow vegetation is slashed and is followed by one or two crops of sweet potato before the land is reverted to fallow again.

8.2. Methods

The site

The research took place on the experimental farm of the University of Technology in Lae in the Morobe Province of Papua New Guinea. The farm (6°41'S, 146°98'E) is located at an altitude of 65 m a.s.l. and mean annual rainfall is about 3,800 mm which is fairly well distributed throughout the year. Average daily temperature is 26.3°C, with an average minimum of 22.9°C and an average daily maximum of 29.7°C. Annual evaporation is 2,139 mm, and rainfall exceeds evaporation in each month. The climate is classified as Af (Köppen). During the experimental period 2,270 mm of rain was recorded for the taro and 1,538 mm for the sweet potato (Fig. 1). An exceptional dry spell occurred in March 1997 in which there was no rainfall for almost four weeks.

The soil at the experimental farm is well drained and derived from alluvial deposits. It is classified as a sandy, mixed, isohyperthermic, Typic Tropofluvents (USDA Soil Taxonomy). Some soil chemical and physical properties of a soil profile at the experimental site are given in Table 1.

Airdried soil samples were ground and sieved (2 mm) and analyzed at the National Analytical Chemistry Laboratories in Port Moresby. The procedures for soil analysis were as follows: pH H2O (1:5 w/v); organic C and total N by Leco CNS-2000 dry combustion; available P by Olsen; exchangeable cations and CEC by 1*M* NH4OAc percolation (pH 7.0); particle size analysis by hydrometer (Sparks, 1996).

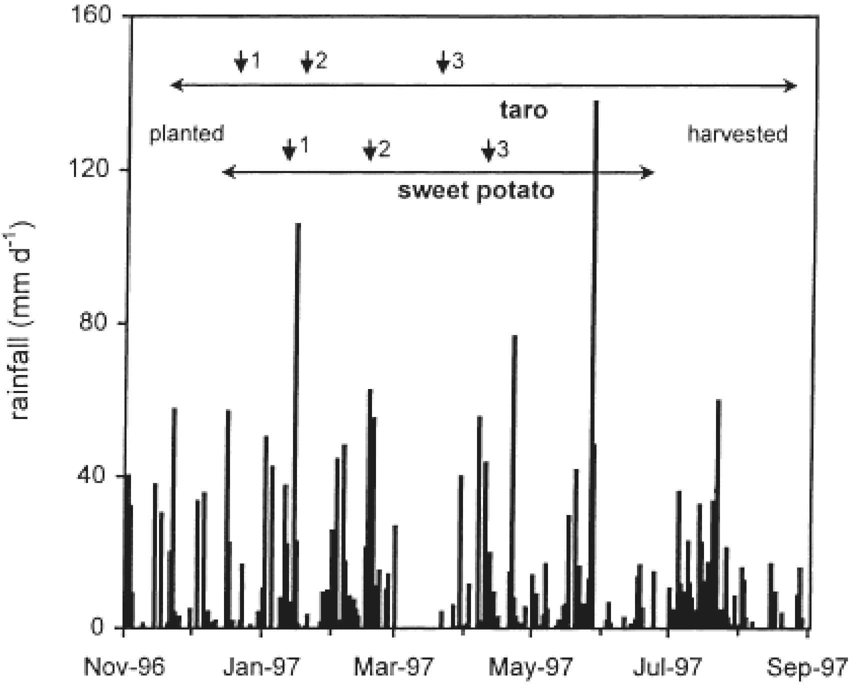

Fig. 1. Daily rainfall (mm) during the experimental period. Vertical arrows indicate timing of N applications

Table 1. Soil chemical and physical properties at the at the experimental farm of the University of Technology in Lae

Sampling depth	pH H_2O	Organic C	Total N	Available P Olsen	CEC NH_4OAc	Exchangeable cations mmolc kg^{-1}			Base saturation	Particle size g kg^{-1}			Bulk density
m	1:5 w/v	g kg^{-1}	g kg^{-1}	mg kg^{-1}	mmolc kg^{-1}	Ca	Mg	K	%	clay	silt	sand	Mg m^{-3}
0-0.23	5.9	23.8	2.0	12	289	212	49	5.1	92	80	130	790	1.10
0.23-0.42	6.1	5.0	0.4	3	303	216	46	2.2	88	140	190	670	1.15
0.42-0.57	6.4	4.8	0.4	3	352	256	70	0.9	94	140	360	500	1.11
0.57-0.66	6.6	5.5	0.5	7	435	334	109	0.8	100	140	130	730	1.05
0.66-0.95	6.7	5.0	0.4	8	397	296	113	0.9	100	140	60	800	1.11
0.95-1.17	6.7	3.2	0.2	7	297	228	91	1.5	100	30	90	880	n.d.
1.18-1.48	6.8	2.2	0.2	6	296	165	72	2.4	82	80	80	840	n.d.

n.d. - not determined

Experimental set-up and management

The experiment was conducted with taro (*Colocasia esculenta* (L.) Schott) local cultivar Nomkoi, and sweet potato (*Ipomoea batatas* (L.) Lam.) cultivar Markham. The experimental design consisted of a replicated (n = 4) randomized complete block design with five levels of N (0, 100, 200, 300, 400 kg ha^{-1}) applied as sulphate of ammonia. The N applications were broadcast over the plots and split into three equal applications given at 35, 62 and 120 DAP (days after planting) for the taro and at 30, 62 and 119 DAP for the sweet potato (see Fig. 1). Split applications of N fertilizer give generally higher yields in taro (de la Peña and Plucknett, 1972; Mohankumar *et al.*, 1990) and sweet potato (Mukhopadhyay *et al.*, 1992). In addition, 100 kg P ha^{-1} (triplesuperphosphate) was given at planting and 250 kg K ha^{-1} (muriate of potash) was given at 30 DAP for both the taro and sweet potato. The P and K fertilizers were also broadcasted which is commonly recommended for taro and sweet potato (de Geus, 1973).

Taro was planted at a spacing of 0.5 by 0.8 m (25,000 plants ha^{-1}) in plots of 4.0 by 3.2 m. Planting material consisted of corm apical portions taken from main plants from which the petioles had been cut 0.25 to 0.30 m above the corm removing the leaf laminae. The taro was planted on 12-11-1996 and harvested at 25-8-1997 (286 DAP). In the taro plots biocides were used to control hawkmoth (*Hippotion celerio* L.) and taro leaf blight (*Phytophtera colocasiae*). Sweet potato was planted at a spacing of 0.4 x 0.8 m (31,250 plants ha^{-1}) in plots of 4.0 x 3.2 m. Planting material consisted of 0.30 m vines with three to four nodes, and vines were planted at about 0.1 m depth. Planting date was 10-12-96 and the sweet potato was harvested at 10-6-97 (182 DAP). The taro and sweet potato plots were weeded manually at regular intervals as weeds may greatly affect the yield in root crops (Gurnah, 1985). Weeds were not removed from the plots to avoid nutrient removal. No mounds or ridges were constructed for the taro and sweet potato which is in accordance with normal farmers' practises in the area.

At harvest, taro main plants and suckers were separated and counted. For both main plants and suckers, the number of marketable corms (>100 g), non-marketable corms (<100 g) and the tops (i.e., above-ground biomass) were weighed. Three to five marketable and non-marketable corms were taken of each plot for dry matter determination and nutrient analysis. At harvest, sweet potato marketable tubers (>100 g), non-marketable tubers (<100 g) and vines were weighed. About one kg of vines per plot and three to five tubers were taken for dry matter determination and nutrient analysis. All plant samples were thoroughly rinsed with tapwater followed by distilled water whereafter they were dried for 72h at 65 °C in a forced air oven.

Plant samples were analyzed for nutrient content at the laboratories of the School of Land and Food of the University of Queensland. One subsample was digested in 5:1 nitric:perchloric acids and analyzed for P, K, Ca, Mg, S, B, Mn, Zn and Cu using ICP AES (Spectro Model P). A second subsample was digested according to the Kjeldahl procedure and analyzed for N on an Alpkem Rapid Flow Analyser Series 300.

Data analysis
Analysis of variance was conducted on marketable, non-marketable yield and above-ground biomass for both taro and sweet potato using Statistix 2.0 for Windows software. Standard error of the difference in means was calculated for each harvested portion and the nutrient uptake. For the yield data, the harvest index was calculated as marketable yield/ (total tuber yield + above-ground biomass) based on dry matter. Nitrogen uptake (in kg ha^{-1}) was calculated as the N content (in g kg^{-1}) multiplied with the yield (in Mg ha^{-1}).

8.3. Results

Crop yield and nitrogen uptake
The yield of marketable taro corms was not affected by increased N applications and average yields were below 8 Mg ha^{-1} (Table 2). The application of N increased, however, the yield of non-marketable corms by 0.5 to 0.9 Mg ha^{-1}. Above-ground biomass (tops) was not significantly increased up to 200 kg N ha^{-1} but higher applications yielded 8 to 11 Mg ha^{-1} more taro tops. As N rates increased, taro yield and biomass increased but the harvest index decreased (Table 2).

Marketable sweet potato yield was highest at 100 kg N ha^{-1} and lowest at 400 kg N ha^{-1} (Table 2). Non-marketable yield significantly decreased with increased N applications and the control treatment yielded about three times more non-marketable tubers compared to the 400 kg N ha^{-1} treatment. Above-ground biomass was not significantly increased up to 200 kg N ha^{-1}, but higher applications yielded two times more vines up to 45.3 Mg ha^{-1}. Sweet potato had a lower harvest index than taro, but the harvest index was significantly reduced to less than 10% with increased N fertilizer rates.

The harvest index for both taro and sweet potato was negatively correlated with N fertilizers (Table 3). Nitrogen fertilizer had a positive effect on non-marketable taro corms, but a negative and significant effect on sweet potato tubers. The amount of taro tops and sweet potato vines was positively correlated with N fertilizers.

Table 2. Taro and sweet potato yield (Mg ha^{-1}, fresh weight) at different N fertilizer rates

N application kg ha^{-1}	Taro				Sweet potato			
	Marketable yield	Non-marketable yield	Above-ground biomass	Harvest index[1]	Marketable yield	Non-marketable yield	Above-ground biomass	Harvest index[2]
0	5.8	0.6	8.5	0.57	4.4	5.4	19.1	0.20
100	5.4	1.1	9.9	0.51	6.5	4.9	26.1	0.25
200	6.4	1.0	10.9	0.49	3.3	3.8	45.0	0.10
300	6.9	1.5	16.5	0.43	3.7	3.8	36.8	0.13
400	7.8	1.4	20.0	0.43	1.5	1.8	45.3	0.06
SED[2]	1.15	0.26	1.71	0.051	1.46	0.49	4.23	0.047

[1] calculated as: marketable tuber yield/ (total tuber yield + above-ground biomass) based on dry matter
[2] Standard error of the difference in means (12 *d.f.*)

Table 3. Correlation coefficients between N fertilizer and yield components of taro and sweet potato

		N fertilizer	Marketable yield	Non-marketable yield	Above-ground biomass
Taro	Marketable yield	0.42 *			
	Non-marketable yield	0.63 **	0.22		
	Above-ground biomass	0.74 ***	0.78 ***	0.51 *	
	Harvest index	−0.65 **	−0.31	−0.52 **	−0.78 ***
Sweet potato	Marketable yield	−0.51 *			
	Non-marketable yield	−0.85 ***	0.62 **		
	Above-ground biomass	0.76 ***	−0.46 *	−0.62 **	
	Harvest index	−0.64 **	0.91 ***	0.59 **	−0.70 ***

*, **, *** indicates significant linear correlation at P<0.05, P <0.01 and P <0.001 respectively

When no fertilizer was applied, total N uptake of taro at harvest was 32.0 kg ha^{-1} of which 30% was taken up in the marketable corms (Table 4). At 400 kg N ha^{-1} the total N uptake by taro was 68 kg ha^{-1} of which 23% was found in the marketable corms. Most of the N was taken up by the taro tops and relatively little N in the non-marketable corms. Uptake of N in the marketable sweet potato was less than 11 kg ha^{-1}, and more N was taken up in the non-marketable tubers than in the marketable sweet potato yield. Up to 156 kg N ha^{-1} was taken up by the vines which was more than 90% of the total N taken up by the sweet potato (Table 4).

Per 10 Mg ha^{-1} of fresh marketable corms taro removed between 5.0 and6.8 kg N ha^{-1}. These values are much lower as reported in the literature (e.g. Manrique, 1995). Sweet potato removed per 10 Mg ha^{-1} marketable tubers between 13 and 31 kg N ha^{-1}. O'Sullivan *et al.* (1997) reported N removal of sweet potato tubers to be about 22 kg ha^{-1} per 10 Mg tubers ha^{-1}.

Table 4. Nitrogen uptake (kg ha^{-1}) at harvest of taro and sweet potato at different N fertilizer rates

N application kg ha^{-1}	Taro			Sweet potato		
	Marketable yield	Non-marketable yield	Above-ground biomass	Marketable yield	Non-marketable yield	Above-ground biomass
0	9.7	0.8	21.5	5.6	5.8	45.9
100	7.2	1.6	26.0	10.3	8.0	65.3
200	11.7	1.5	27.2	6.4	7.6	117.0
300	11.5	2.5	39.3	8.8	9.5	95.0
400	15.6	2.1	49.8	4.6	5.0	155.5
SED[1]	2.30	0.54	5.42	2.59	0.93	7.86

[1] Standard Error of the Difference in means (12 *d.f.*)

Nitrogen use efficiency

The relationship between inherent soil fertility, N fertilizer rates and yield is investigated with the help of the three-quadrant procedure. With this procedure, fertilizer application and yield relations (quadrant II) are split up into the relationships between N fertilizer rates and N uptake (quadrant IV in Fig. 2), and between N uptake and yield (quadrant I in Fig. 2). These relations have been plotted for the marketable yield of taro and sweet potato (left diagram in Fig. 2) and for the total biomass including non-marketable yield and above-ground biomass (right diagram in Fig. 2)

Yield response to N fertilizers is plotted in quadrant II. An almost linear response was obtained for the taro for both marketable yield and total biomass. The sweet potato marketable yield responded negatively to N application whereas the total biomass shows a plateau at 200 kg N ha^{-1}.

Quadrant I in the left diagram of Fig. 2 shows the N use efficiency (NUE) i.e., kg marketable yield per kg N taken up. Nitrogen use efficiency increases with increased N application for both taro and sweet potato. The NUE is about 600 kg marketable tubers per kg N taken up for sweet potato, and about 300 marketable corms per kg N taken up for taro. Nitrogen use efficiency of the total biomass was, however, larger for taro ($\approx$ 400 kg biomass kg^{-1} N) than for sweet potato ($\approx$ 300 kg biomass kg^{-1} N). As the figure shows, this is due to a decrease in N uptake of the sweet potato with increasing N applications. The initial slope of the lines (i.e., up to 60 kg N taken up) is the same for both root crops. It indicates that under the given growing conditions the same amount of N is needed to produce 1 Mg of taro or sweet potato biomass.

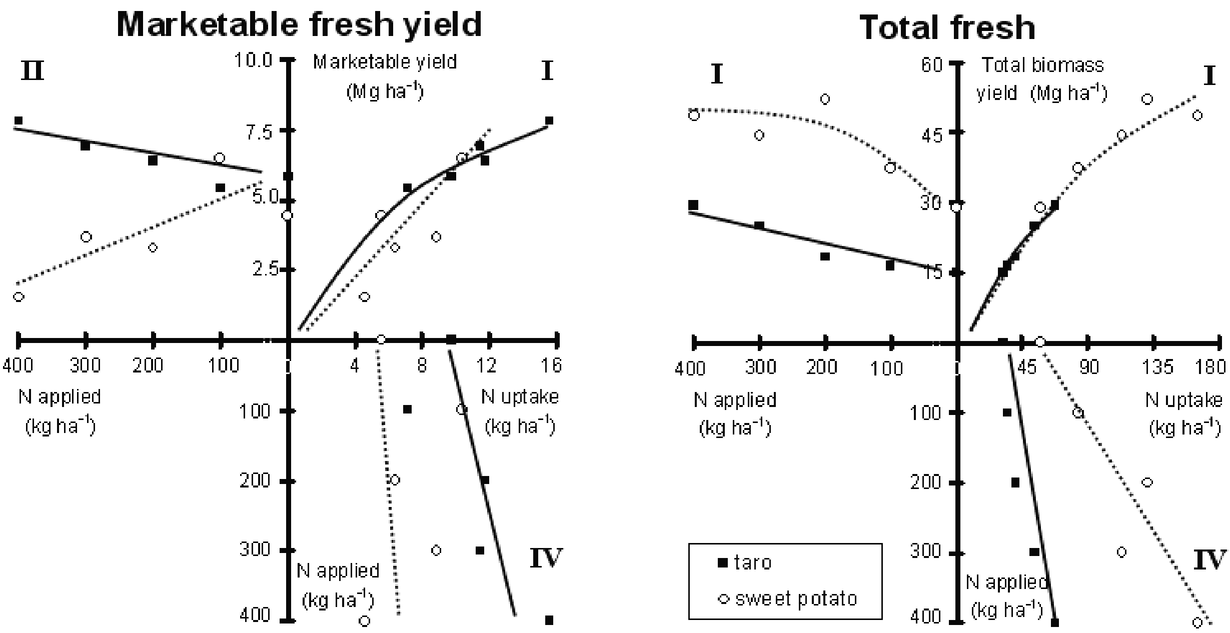

Fig. 2. Three-quadrant diagram linking N application, N uptake and marketable yield (left diagram) and total fresh biomass yield (right diagram); I. Yield against uptake (Nitrogen Use Efficiency), II. Yield against N rate (Fertilizer Use Efficiency), IV. N uptake against N application rate (Fertilizer Recovery)

Table 5. Efficiency ratios of marketable yield and total biomass yield for taro and sweet potato (data from Fig. 2)

	Marketable yield		Total biomass	
	Taro	Sweet potato	Taro	Sweet potato
Nitrogen use efficiency (kg kg N_{uptake}^{-1})	300	600	400	300 [1]
Fertilizer use efficiency (kg kg $N_{applied}^{-1}$)	5.5	−8.5	3.7	11.6 [2]
Fertilizer recovery (N_{uptake} $N_{applied}^{-1}$)	2%	<1%	9%	25%

[1] only linear part of the curve taken i.e. up to 300 kg N ha^{-1}
[2] id. up to 200 kg N ha^{-1}

From the relation between N uptake and N fertilizer application, the N recovery can be calculated (quadrant IV). There was a low N fertilizer recovery for the marketable yield of taro. Sweet potato showed an irregular N fertilizer recovery pattern. The amounts of N taken up from the soil in the marketable portion when no fertilizer was applied was 9.7 kg ha^{-1} for taro and 5.6 kg ha^{-1} for sweet potato. The total amount of native soil N taken up by the crops when no N fertilizer was applied was 32.5 kg ha^{-1} for taro and 57.3 kg ha^{-1} for sweet potato. It hence appears that sweet potato makes better use of the native soil N than the taro. The recovery fraction which is the slope of the line in quadrant IV, was 9% for taro and 25% for the total fresh biomass of the sweet potato. Table 5 presents the calculated efficiency ratios from Fig. 2.

8.4. Discussion

Marketable taro corm yields were below 8 Mg ha^{-1} which are low yields but not exceptionally low. Moles *et al.* (1984) conducted a series of fertilizer experiments at rich volcanic soils in the Papua New Guinea province of East New Britain and obtained taro corm yields between 1 and 18 Mg ha^{-1}. Taro yields on a high base status Inceptisol close to the University of Technology were slightly higher than reported in this experiment (Hartemink, unpubl. data). Marketable sweet potato yields were below 7 Mg ha^{-1} which are low yields for Papua New Guinea (Bourke, 1985b). This may be partly due to the Markham cultivar which is known to give inconsistent tubers yields (P. van Wijmeersch, DAL-Keravat, pers. comm., 1998). Both taro and sweet potato yields are within the average yield range reported for the Pacific (de la Peña, 1996).

The soil at the experimental site was moderately fertile but contained low amounts of total N and yield increases were therefore expected. Nitrogen fertilizer only increased marketable taro yield but decreased marketable sweet potato yield. Apparently, taro is less sensitive to high N whereas high N rates on sweet potato results in more vine biomass production at the cost of tubers (Bourke, 1985a; Hill and Bacon, 1984). Yield decline at higher N levels are possibly due to inadequate supply of other nutrients or an imbalance brought about by high levels of N fertilizer (de la Peña and Plucknett, 1972).

The efficiency by which the applied N was used (NUE) was low and fertilizer recovery was only 10% for taro and 25% for sweet potato. Since nutrients in the fibrous roots were not measured in the total plant uptake, the actual NUE and fertilizer recovery is higher (Janssen, 1998). Hartemink and Johnston (1998) found that fibrous roots account for 5% and 11% of the total N uptake of fertilized and unfertilized taro respectively. Taking these figures in account for the taro, total NUE would only increase with 1%. The low N fertilizer recovery could be due to other nutrients limiting growth, the loss of N through leaching, the genetic potential of the cultivars used, or the unfavourable weather conditions.

Since N rarely accumulates in the soil, the difference between N applied and N taken up by the biomass is probably lost. For taro the losses are on average more than 90% of the N applied whereas about 75% of the N applied to the sweet potato was lost. Although the N was given in split applications, considerable amounts of N may have been lost by leaching which is likely as rainfall is high and the soils are coarse textured. Within one week after the first N application on sweet potato, 181 mm rain fell and this may have leached the first N fertilizer application. The amount of rain following N fertilizer application at the taro was much lower. Such high N losses have environmental implications causing off-site effects including increased nitrate levels affecting water quality in ground water, streams, rivers and coastal environments. Although this problem is generally well recognised in agriculture of the temperate regions (Rodriguez-Barrueco, 1996), it has received little attention in tropical regions where the focus of attention has been predominantly on sustained and increased crop production and not so much on the environmental effects. The results also suggest that it is uneconomical to apply inorganic N fertilizers to taro and sweet potato on coarse textured soils in high rainfall environments.

8.5. Conclusions

Fertilizer N failed to substantially increase the yield of taro and sweet potato on coarse textured soils with low native N levels. Sweet potato made better use of the low native soil N levels than taro but data analysis through the use of a three-quadrant diagram showed a low N recovery for both root crops, which may be due to leaching losses of applied N, other nutrients limiting growth or the weather conditions. The results indicate that the addition of N is uneconomical and is likely to have adverse environmental implications. Although the data were limited it is tentatively concluded that inputs other than inorganic N fertilizer are required for substantial yield increases of taro and sweet potato in the humid lowlands of Papua New Guinea.

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9. Sweet potato yields and nutrient dynamics after short-term fallows in the humid lowlands of Papua New Guinea *

Abstract

Shifting cultivation is common in the humid lowlands in Papua New Guinea but little is known about the effect of different fallows on sweet potato (*Ipomoea batatas*) yield and nutrient flows and pools in these systems. An experiment was conducted whereby two woody fallows (*Piper aduncum* and *Gliricidia sepium*) and a non-woody fallow (*Imperata cylindrica*) were planted and slashed after one year. Sweet potato was planted for two consecutive seasons (1 year) after the fallows and yields were compared to continuously cultivated plots. The experiment was conducted on a high base status soil (Typic Eutropepts). In the first season, marketable sweet potato yield after piper and imperata fallow was about 11 Mg ha^{-1} but yields after gliricidia fallow and under continuous cultivation were significantly lower. Vine yield was similar for the continuously cultivated plots and for the sweet potato after piper and gliricidia, but significantly lower after imperata fallow. The effects of the fallows on sweet potato yield lasted only one season. Sweet potato yields were higher in the second season after the fallow as there was less rainfall. Nutrient budgets showed that the three fallows (piper, gliricidia, imperata) added insufficient amounts of N, P and K for the removal of these nutrients by two consecutive seasons of sweet potato. From a yield point of view there seems no benefit of having an N-fixing fallow species like gliricidia in sweet potato based systems on high base status soils.

9.1. Introduction

Shifting cultivation is an important land use system in many parts of the humid tropics. With the reduction in the length of the fallow period, there is a need to introduce fallow species that improve the soil fertility more rapidly than under natural fallows because shorter fallow periods often result in subsequent lower crop yields (Buresh and Cooper, 1999). Improved fallows are rapidly spreading in several regions of the tropics and some of the comparative advantage of woody versus herbaceous fallows

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include fuelwood production, weed suppression and improved soil physical properties (Sanchez, 1999). Many of the beneficial effects of fallows as well as the underlying mechanisms remain to be quantified (Sanchez *et al.*, 1997).

Shifting cultivation is common in the humid lowlands of Papua New Guinea. About 75% of the country is still under forest and only 13% is used for agriculture at significant levels of land use intensity, the remaining 12% is used at low intensity (Bellamy and McAlpine, 1995). The doubling of the human population in Papua New Guinea between the mid-1960s and mid-1990s, has not led to a significant increase in land under cultivation. Instead, the length of the fallow period has been reduced due to increased food and cash crop production to keep up with the growing population (Allen *et al.*, 1995; Hartemink and Bourke, 2000).

The secondary fallow vegetation in parts of the humid lowlands of Papua New Guinea is dominated by *Piper aduncum*, which is a shrub indigenous to tropical America. *Piper aduncum* (hereafter referred to as piper) was first observed in Papua New Guinea in the 1930s and was not widespread in the 1970s. However, by the mid-1990s it is very common in the humid lowlands but also can be found in the highlands (Hartemink, 2001). Short-term (< 2 years) piper fallows are followed by food crops including sweet potato (*Ipomoea batatas*), taro (*Colocasia esculenta*), sugarcane (*Saccharum* sp.) and bananas (*Musa* sp.). Sweet potato is the main staple crop and the tubers are used for human consumption but the smallest tubers are used as pig feed. Vines and leaves are occasionally eaten as green vegetable but their main use is also pig feed. Sweet potato production is increasing in the lowlands below 600 m altitude where it has displaced traditional taro to a large degree (Bourke, 1985b).

Although the aggressive invasion of piper has been described including its possible effect on Papua New Guinea's rich biodiversity (Rogers and Hartemink, 2000; Saulei and Swaine, 1988), there is no information available on the effect of piper fallows on soil and crop productivity. It is not known whether piper fallows are more productive than other natural fallows like *Imperata cylindrica* grasslands (hereafter referred to as imperata). Imperata fallows are also common in the lowlands of Papua New Guinea and as in other parts of the world imperata in Papua New Guinea is not confined to the poorest soils (Santoso *et al.*, 1997).

In Papua New Guinea some alley-cropping (hedgerow-intercropping) experiments have been conducted but as elsewhere in the humid tropics, results have been mixed (Brook, 1999; Louman and Hartemink, 1998; Sayok and Hartemink, 1998). Improved fallows may be more efficient than alley-cropping or traditional fallows in restoring soil fertility (Buresh and Cooper, 1999). Fallows with *Gliricidia sepium* (hereafter referred to as gliricidia) are planted in some parts of the world as an improved fallow and gliricidia is one of the most widely cultivated, leguminous multipurpose trees (Simons and Stewart, 1994). Gliricidia is common in Papua New Guinea where it is used as shadetree in cocoa plantations. From a soil N point of view it is a suitable species as it grows fast and thus takes up and recycles N within the soil-plant system and gliricidia also fixes atmospheric N (Young, 1997).

Field experiments were conducted to investigate the effects of piper, imperata and gliricidia fallows on sweet potato yields. The experiments were conducted in a farming area where the secondary fallow vegetation is dominated by piper, but in which imperata grasslands are also common. The fallows were grown for one year, slashed whereafter two crops of sweet potato were grown. The overall aim of the experiment was to quantify nutrient dynamics and productivity of short-term fallows including effects on soil chemical and physical properties and nutrient budgets.

9.2. Methods

Site

The experiment was conducted near Hobu village (6°34'S, 147°02'E) which is located about 25 km North of the city of Lae in the Morobe Province of Papua New Guinea. Rainfall records for the site were only available since the start of the experiments (November 1996). In 1997, there was a total rainfall of 1,897 mm, which is well below the long-term average, due to the El Niño/Southern Oscillation climatic event which hit the Pacific severely in 1997-98. In the first six months of 1998 more rain fell than in the whole of 1997. March 1998 was a particularly wet month with 725 mm of rain. At the University of Technology, which is about 15 km S of the experimental site, total rainfall in 1997 was only 2,594 mm compared to the long-term (20 y) annual mean of 3,789 mm. Daily rainfall during the experimental period is presented in Fig. 1, and shows the relatively dry period in the second half of 1997 due to El Niño. Temperature data are not available for the site but average daily temperatures at the University of Technology are 26.3°C. Since the University is at a lower altitude (65 m a.s.l.) temperatures at Hobu are probably on average slightly lower.

Soils

The experimental site is at the footslopes of the Saruwaged mountain range which from the major landmass of the Huon peninsula. The site is located on an uplifted alluvial terrace at an altitude of 405 m a.s.l. with slopes of less than 2%. Soils are derived from a mixture of alluvial and colluvial deposits dominated by sedimentary rocks and coarse to medium- grained, basic, igneous rocks. The soils are layered with water-worn gravelly and stony layers below 0.2 m depth. Many of the gravels and stones are rotten and effective rooting depth is over 0.7 m. Air-dried and sieved (< 2 mm) soil had the following properties in the top 0.12 m: pH H_2O (1:5 w/v) = 6.2, organic C (dry combustion) = 55 g kg^{-1}, available P (Olsen) = 9 mg kg^{-1}, CEC (NH_4Oac, pH7) = 400 $mmol_c$ kg^{-1}, exchangeable Ca = 248 $mmol_c$ kg^{-1}, exchangeable Mg = 78 $mmol_c$ kg^{-1}, exchangeable K = 16.9 $mmol_c$ kg^{-1}, clay = 480 g kg^{-1} and sand = 360 g kg^{-1}, bulk density = 0.82 Mg m^{-3}. Soils in the area are not enriched by volcanic ashes, which has occurred in many parts of Papua New Guinea (Bleeker, 1983). The low bulk density is probably related to the high soil organic C contents and these are often negatively correlated. The soils are classified as mixed, isohyperthermic, Typic Eutropepts (USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base). Inceptisols are the commonest soils in Papua New Guinea and are estimated to cover approximately 40% of the country (Bleeker, 1983). Inceptisols are widely used for agriculture (Freyne and McAlpine, 1987).

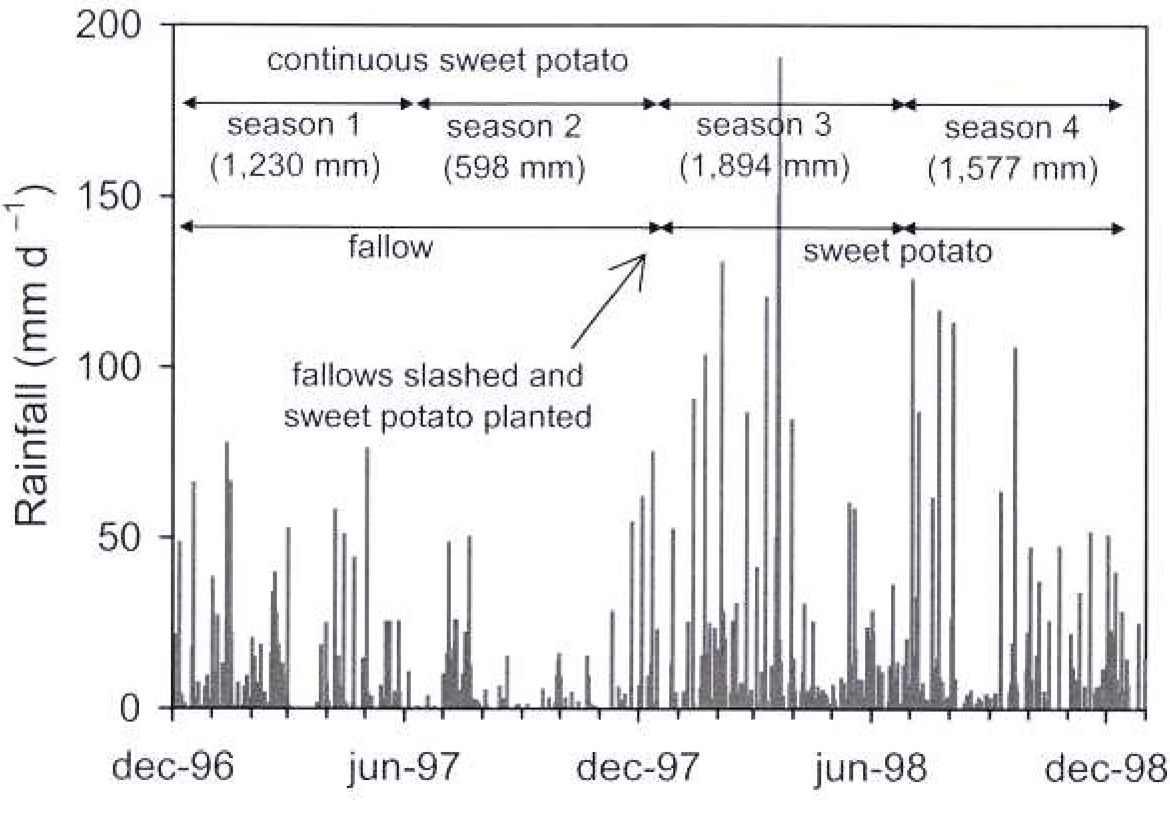

Fig. 1. Daily rainfall (mm) during the four seasons (December 1996 - November 1998) at the experimental site (Hobu village) in the humid lowlands of Papua New Guinea

The experiment

An area of about 0.5 ha secondary vegetation was slashed manually at the beginning of November 1996. The vegetation consisted mainly of *Piper aduncum* and to a lesser extent by *Homolanthus* sp., *Macaranga* sp., *Trichospermum* sp. and *Trema orientalis* (Hartemink and O'Sullivan, 2001). The site was intensively used for growing foodcrops but had been fallow since 1992. All vegetation debris was removed and no burning was practiced, which follows the landclearing practices of local farmers.

Sixteen plots of 6.0 by 6.0 m each were laid out and four treatments were assigned to the plots in a randomised complete block design. Blocks were separated by paths of 2 to 3 m. At the end of November 1996 the fallow plots were planted. Four plots were planted with seedlings (0.4 m) of *Piper aduncum* and four plots were planted with *Gliricidia sepium* cuttings (0.4 m). Piper and gliricidia were planted at distances of 0.75 by 0.75 m (17,778 plants ha^{-1}). In four plots the vegetation consisted of natural regrowth which was immediately dominated by *Imperata cylindrica*.

In the remaining four plots, sweet potato was planted with the local cultivar Hobu1. It is a widely grown cultivar with red skin tubers and white flesh. Hobu1 appears not to be very susceptible to sweet potato weevils, which is an important pest of sweet potato in Papua New Guinea (Powell *et al.*, 2001). Sweet potato plots were continuously cultivated for four seasons (see Fig. 1). Planting material was obtained from local gardens and consisted of vine cuttings that were planted almost vertically in the soils using a stick. One cutting of about 0.4 m length with 4 to 6 nodes was planted per hole which generally gives the highest tuber yield (Levett, 1993). Planting distance was 0.75 by 0.75 m (17,778 plants ha^{-1}).

After one year (20-24 November 1997), all fallow vegetation was cut at ground level. From the piper and gliricidia plots the inner 36 of the 64 plants per plots were harvested to avoid possible edge effects. Piper and gliricidia stems were removed from the plots; all other plant parts were applied as surface mulch. On 26th November 1997, the previous fallow plots were planted with sweet potato similar to the continuously cultivated plots. The previous fallow plots were not tilled when planted, and cropped with sweet potato for two seasons. The sweet potato cropping seasons lasted about 170 days whereafter the plots were harvested. Vines were cut at ground level, weighed, and removed from the plot. In each plots the inner 36 of the 64 sweet potato plants were taken to avoid possible edge effects. Vines are also removed in gardens of farmers, which may be related to its allelopathic effects that alter nutrient uptake (Walker *et al.*, 1989). Tubers were manually dug, counted and separated into marketable tubers (> 100 g) and non-marketable tubers (< 100 g) which were also removed from the plot. All plots were replanted directly after the harvest. Weeds were pulled out manually and not removed from the plot to avoid nutrient removal. No mounds or ridges were constructed for the sweet potato which is in accordance with normal farmers' practices in the area. No biocides or other inputs were used in the experiments. Rainfall in the first cropping season of the continuously cultivated plot was 1,230 mm and 598 mm rain fell in the second season. Total rainfall during the fallow period was hence 1,828 mm. In the first and second season after the fallow rainfall was 1,894 mm and 1,577 mm, respectively (Fig. 1).

Plant sampling and analysis

The sweet potato marketable tubers, non-marketable tubers and vines were weighed at harvest, and about one kg of vines per plot and three to five tubers were taken for dry matter determination and nutrient analysis. The plant samples from the fallow and sweet potato harvests were taken to the laboratory where they were rinsed with distilled water and ovendried at 70°C for 72 h. Samples were ground (mesh 0.2 mm) before being sent for nutrient analysis. Nutrient analysis of the plant samples was conducted at the laboratories of the School of Land and Food of the University of Queensland. Australia. One subsample was digested in 5:1 nitric:perchloric acids and analysed for P, K, Ca and Mg using ICP (Spectro Model P). A second subsample was analysed for C and N using a Leco combustion analyser. The analytical data were multiplied with the dry matter yield to obtain nutrient uptake in kg ha^{-1}.

Soil sampling and analysis

Soil samples for chemical analysis were taken prior to the planting of the fallows, after the fallows were slashed and after two seasons of sweet potato. In the continuously cultivated plots, soil samples were taken prior to the first planting, after two seasons, and after four seasons. Soil samples were collected with an Edelman auger (diameter 0.05 m) at 12 random locations in a plot, mixed in a 20 L bucket and a subsample of about 1 kg was taken. Airdried samples were ground and sieved (2 mm) before being sent for analysis to the National Analytical Chemistry Laboratories in Port Moresby. The procedures for soil analysis were as follows: pH H_2O (1:5 w/v); organic C and total N by Leco dry combustion; available P by Olsen; exchangeable cations and CEC by 1*M* NH_4OAc percolation (pH 7.0); particle size analysis by hydrometer. Bulk density was measured at the same time as soil samples for chemical analysis were taken. In each plot the 0-0.05 and 0.10-0.15 m soil horizons were sampled using two 100 mL cores per horizon. Cores were ovendried at 105°C for 72 h. Soil moisture measurements using 150 mL tins were taken one week before the fallows were slashed and 12 and 24 weeks after sweet potato was planted. Measurements were duplicated in each plot. The soil samples were ovendried at 105°C for 72h, and gravimetric soil moisture contents were calculated. Gravimetric values were multiplied with the bulk density to obtain volumetric water contents (m^3 m^{-3}). Topsoil chemical properties (C, N, P, K, Ca, Mg) were multiplied with average bulk density values of the 0-0.05 and 0.10-0.15 m soil horizons to obtain nutrient pools in kg ha^{-1}.

Statistical analysis

For the above ground biomass, nutrient content and nutrient removal, standard deviations were calculated. An ANOVA was conducted to investigate statistical differences in sweet potato yields, changes in soil chemical properties and in the soil bulk density. Standard error of the difference in means were calculated and in the discussion of the results the statistically significant difference was set at 5% (P<0.05). All statistical analysis has been conducted with Statistix 8 for Windows.

9.3. Results

Nutrient input by the fallows

There were significant differences in above ground biomass production and nutrient accumulation of the three fallows. One year old piper had produced 13.7 Mg dry matter (DM) ha^{-1}, compared to 23.3 Mg DM ha^{-1} produced by gliricidia and 14.9 Mg DM ha^{-1} of imperata (Table 1). The stems of piper and gliricidia were removed from the plots and total biomass returned was about 8 Mg DM ha^{-1} for piper and gliricidia and 14.9 Mg DM ha^{-1} for imperata. The largest amounts of nutrients were returned by the gliricidia fallow and 192 kg N ha^{-1} was present in the leaf mulch. Piper fallows returned the largest amounts of K (206 kg ha^{-1}). Imperata had accumulated the least nutrients of all three fallows. The P input by the above ground biomass was similar for the three fallows (~13 kg ha^{-1}).

Sweet potato yield after fallows

In the first cropping season after the fallow, marketable sweet potato yield after piper and imperata was about 11 Mg ha^{-1} and significantly higher than yield under continuous sweet potato or after gliricidia (Table 2). Marketable yield under continuous sweet potato cultivation was only 7.8 Mg ha^{-1}. Variation in non-marketable tuber yield was large and differences were not statistically significant. Total tuber yield (marketable plus non-marketable tubers) was highest after piper fallows (14.4 Mg ha^{-1}) and significantly lower after gliricidia fallow (9.9 Mg ha^{-1}). Vine yield was similar under continuous sweet potato cultivation and after piper and gliricidia fallow. Vine yield was about 10 Mg ha^{-1} less after the imperata fallow and the difference with the other fallows was highly significant.

Table 1. Above-ground biomass (Mg dry matter ha^{-1} ± 1 SD[1]), carbon and nutrient content (kg ha^{-1} ± 1 SD), of one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* fallows in the humid lowlands of Papua New Guinea

		Piper aduncum	*Gliricidia sepium*	*Imperata cylindrica*
Biomass	Total produced	13.7 ±1.3	23.3 ±1.6	14.9 ±2
(Mg ha⁻¹)	Returned to the soil [2]	7.8 ±0.3	8.1 ±0.6	All
C	Total produced	5.8 ±0.6	10.4 ±0.7	6.7 ±0.9
(Mg ha⁻¹)	Returned to the soil	3.1 ±0.2	3.5 ±0.4	All
N	Total produced	120 ±12	356 ±11	76 ±24
(kg ha⁻¹)	Returned to the soil	97 ±9	192 ±21	All
P	Total produced	22 ±2	36 ±4	12 ±4
(kg ha⁻¹)	Returned to the soil	14 ±2	12 ±2	All
K	Total produced	299 ±25	248 ±15	89 ±16
(kg ha⁻¹)	Returned to the soil	206 ±18	89 ±12	All
Ca	Total produced	157 ±20	312 ±38	56 ±18
(kg ha⁻¹)	Returned to the soil	147 ±19	222 ±30	All
Mg	Total produced	45 ±8	64 ±12	29 ±9
(kg ha⁻¹)	Returned to the soil	40 ±7	41 ±13	All
S	Total produced	11 ±1	25 ±2	4 ±2
(kg ha⁻¹)	Returned to the soil	10 ±1	12 ±2	All

[1] SD = standard deviation

[2] Returned to the soil when the fallows were slashed. *Piper aduncum* and *Gliricidia sepium* stems were removed from the field; leaves, small branches and litter were returned to the soil

Table 2. Sweet potato yield (Mg fresh weight ha^{-1}) for two seasons after one-year *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* fallows, and under continuous sweet potato cultivation

	Yield in Mg fresh weight ha⁻¹					
	Marketable tubers (> 100 g)		Non-marketable tubers (< 100 g)		Vines	
	First season	Second season	First season	Second season	First season	Second Season
Piper aduncum	11.2	13.4	3.1	2.1	30.4	22.9
Gliricidia sepium	8.4	14.3	1.6	1.8	31.6	26.1
Imperata cylindrica	11.3	15.2	1.5	1.1	20.7	18.9
Continuous sweet potato [1]	7.8	12.8	2.4	2.0	32.3	27.4
SED [2]	1.3	ns	ns	0.3	3.9	4.1

[1] Yields from the third and fourth season under continuous cultivation.

[2] Standard error of the difference between means (9 *d.f.*); ns = not significant ($P>0.05$)

In the second season after the fallow tuber yield was on average higher. There were no more fallow effects on marketable sweet potato yield in the second season. Non-marketable tuber yield was, however, significantly lower in the previous imperata plots but no differences were found in the other treatments. Vine yield in imperata plots was lower but statistically comparable to the other previous fallow treatments. Total tuber yield in the second season was similar for all treatments and no difference was found between yields from previous fallow plots and continuous sweet potato plots.

Cumulative total tuber yield over the two cropping seasons was about 29 Mg ha^{-1} for piper and imperata, 26 Mg ha^{-1} for gliricidia and less than 25 Mg ha^{-1} in the continuous sweet potato plots. The cumulative vine yield over the two seasons was between 53 and 60 Mg ha^{-1} for continuous sweet potato and the sweet potato after gliricidia and piper fallow, but total vine yield was less than 40 Mg ha^{-1} after imperata fallow.

Biomass production of the fallow and sweet potato

The total productivity of the fallow and continuous sweet potato systems can be assessed by the total dry matter that is removed from the field (i.e. tubers and vines from the sweet potato, and wood from the piper and gliricidia fallow). Table 3 presents the dry matter production of the four treatments. Continuous sweet potato had the highest dry matter production but more than 40% consisted of vines. Although gliricidia had a lower tuber production, it yielded almost three times more wood. Gliricidia and imperata systems yielded comparable amounts of tuber dry matter but imperata had no additional useful products like wood.

Table 3. Dry matter production (Mg ha^{-1}) under continuous sweet potato (four seasons) and after one year fallow with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* followed by two seasons of sweet potato. Amounts are the dry matter that is removed from the plots (wood; tubers and vines) in the two years experimental period

	Continuous sweet potato	Piper fallow and sweet potato	Gliricidia fallow and sweet potato	Imperata fallow and sweet potato
Marketable tubers	16.2	7.9	7.1	8.0
Non-marketable tubers	4.9	1.6	1.2	0.8
Vines	15.5	7.6	8.3	5.9
Wood (stem)	0	5.9	15.2	0

Table 4. Soil chemical properties under continuous sweet potato cultivation, and before and after one-year fallow with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* followed by two seasons of sweet potato. Sampling depth is 0-0.15 m

	Sampling time	pH H_2O 1:5 w/v	Organic C g kg^{-1}	Total N g kg^{-1}	Olsen P mg kg^{-1}	CEC pH7 $mmol_c$ kg^{-1}	Exchangeable cations $mmol_c$ kg^{-1}			Base Saturation %
							Ca	Mg	K	
Continuous sweet potato	Before first	6.2	69.9	6.0	10	405	268	61	12.2	84
	After two seasons	5.8	76.8	7.3	8	433	238	69	10.2	74
	After four seasons	5.8	71.3	5.9	6	466	227	59	8.4	63
	SED[1]	0.12	1.55	0.37	1.1	11.8	15.4	1.8	1.5	3.3
Piper aduncum fallow followed by two seasons sweet potato (1 year)	Before the fallow	6.2	68.4	6.2	8	407	242	60	12.5	77
	After the fallow	5.8	71.0	7.2	6	440	219	63	8.4	67
	After sweet potato	5.6	72.3	5.6	5	421	209	62	10.2	67
	SED	0.07	ns	0.59	ns	ns	ns	ns	0.51	ns
Gliricidia sepium fallow followed by two seasons sweet potato (1 year)	Before the fallow	6.2	67.8	6.2	6	393	252	63	9.5	83
	After the fallow	5.9	82.2	7.7	5	416	220	68	7.9	71
	After sweet potato	5.7	77.6	6.1	4	488	233	62	7.2	63
	SED	0.13	3.42	0.35	ns	35.5	ns	ns	ns	6.4
Imperata cylindrica fallow followed by two seasons sweet potato (1 year)	Before the fallow	6.3	70.1	6.7	7	409	279	60	11.6	86
	After the fallow	5.7	76.9	7.5	5	450	239	65	11.6	71
	After sweet potato	5.8	72.4	5.9	5	485	234	63	12.2	64
	SED	0.08	2.17	ns	0.7	ns	14.5	ns	ns	4.8

[1] SED = Standard error of the difference between means (6 *d.f.*); ns = not significant ($P>0.05$)

Changes in soil chemical properties
Under continuous sweet potato cultivation, the topsoil pH significantly declined with about 0.4 units and the change occurred in the first two seasons (Table 4). The soil acidification trend was accompanied by a significant decrease in exchangeable Ca, K and base saturation. Soil organic C and total N slightly increased during the first year of cultivation but both significantly decreased during the subsequent two seasons of sweet potato cultivation. Available P decreased by 4 mg kg^{-1} after two years of sweet potato cultivation.

Changes in soil chemical properties under the three different fallows followed by two seasons of sweet potato showed a similar pattern. The soils acidified significantly during the fallow period and the decrease in soil reaction was highest during the imperata fallow (–0.6 pH units). The pH change during the one-year piper and gliricidia fallow was about –0.4 units and the pH further decreased after two seasons of sweet potato. Overall, the pH decreased by 0.5 to 0.6 units in the fallow plots followed by two seasons of sweet potato.

Organic C increased during the fallow period which was accompanied by an increase in total N. The increase was largest under gliricidia. During the subsequent sweet potato seasons, organic C contents decreased in the previous fallow plots. Available P decreased under all fallows although the decrease was only statistically significant under the imperata fallow. Levels of exchangeable Ca decreased significantly during the imperata fallow but changes under the other fallows were not statistically significant. No changes were found in the exchangeable Mg of the soils under fallow followed by sweet potato. Exchangeable K decreased significantly during the piper fallow (–4.1 mmolc kg^{-1}) and slightly increased after the piper fallow was slashed. Base saturation decreased significantly under gliricidia and imperata fallows (Table 4).

Changes in soil physical properties
Soil bulk density was measured prior to the planting of all plots, after one year when the fallows were slashed and after two seasons with sweet potato (Table 5). There were slight changes in the soil bulk density and the pattern was the same under all three fallows: the bulk density in the 0-0.05 soil horizon was about 0.60 Mg m^{-3} prior to the planting and the bulk density had increased by about 0.08 Mg m^{-3} after the fallows. After two crops of sweet potato, bulk density decreased in the 0-0.05 soil horizons of the previous fallow plots. In the 0.10-0.15 m soil horizon this pattern was also depicted although bulk density values were slightly higher. Under continuous sweet potato cultivation, a slight decrease in bulk density was found in the 0-0.05 soil horizon but an increase in the 0.10-0.15 m soil horizon.

After one year of fallow, moisture contents in the 0-0.05 soil horizon was significantly lower under piper compared to gliricidia and imperata fallow (Table 6). The difference with the moisture content of the soils under gliricidia was 0.06 m^3 m^{-3}. This is remarkable as gliricidia had produced nearly 10 Mg DM ha^{-1} more biomass than piper (Table 2). Moisture contents in the 0.10-0.15 m soil horizon were also significantly lower under one-year old piper compared to gliricidia. Soil moisture contents under imperata were closest to those under piper. Twelve weeks after the fallows were slashed moisture contents in the 0-0.05 m soil horizon were highest in the previous imperata plots. There were no significant differences in soil moisture contents between plots at 24 weeks after the fallows were slashed.

Table 5. Bulk density (Mg m^{-3} ± 1 SD[1]) for two soil depths under continuous sweet potato cultivation and before and after one-year fallow with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* followed by two seasons of sweet potato cultivation

	Sampling time	Bulk density			
		0-0.05 m		0.10-0.15 m	
Continuous sweet potato	Before first planting	0.67	±0.10	0.62	±0.06
	After two seasons (one year)	0.68	±0.08	0.77	±0.08
	After four seasons (two years)	0.64	±0.06	0.75	±0.08
Piper aduncum fallow followed by	Before the fallow	0.61	±0.07	0.71	±0.08
two seasons sweet potato (1 year)	After the fallow (one year)	0.70	±0.10	0.81	±0.06
	After two seasons sweet potato (one year)	0.60	±0.05	0.71	±0.04
Gliricidia sepium fallow followed by	Before the fallow	0.57	±0.05	0.64	±0.05
two seasons sweet potato (1 year)	After the fallow (one year)	0.64	±0.06	0.75	±0.03
	After two seasons sweet potato (one year)	0.61	±0.03	0.66	±0.01
Imperata cylindrica fallow followed	Before the fallow	0.59	nd	0.74	nd
by two seasons sweet potato	After the fallow (one year)	0.67	±0.04	0.81	±0.06
(1 year)	After two seasons sweet potato (one year)	0.62	±0.09	0.56	±0.10

[1] SD = standard deviation
nd = insufficient data for calculating a standard deviation

Table 6. Volumetric soil moisture contents ($m^3\ m^{-3}$) under continuous sweet potato, and in sweet potato plots preceded by *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* fallow

Sampling time [1] Weeks	Sampling depth (m)	Continuous sweet potato	Sweet potato after one year of fallow with: *Piper aduncum*	*Gliricidia sepium*	*Imperata cylindrica*	SED [2]
–1	0-0.05	0.35	0.27	0.33	0.31	0.01
	0.10-0.15	0.37	0.30	0.39	0.33	0.03
12	0-0.05	0.42	0.43	0.44	0.47	0.01
	0.10-0.15	0.42	0.42	0.46	0.46	0.02
24	0-0.05	0.39	0.40	0.42	0.42	0.03
	0.10-0.15	0.41	0.40	0.38	0.41	0.03

[1] Weeks after fallow vegetation was slashed and sweet potato was planted
[2] Standard error of the difference between means (9 *d.f.*)

Table 7. Nutrient removal (kg ha^{-1} ±1 SD[1]) under continuous sweet potato and under *Piper aduncum*, *Gliricidia sepium and Imperata cylindrica* fallows followed by two seasons of sweet potato. Removal includes nutrients in the marketable, non-marketable tubers and vine biomass

	Season	Nutrients N	P	K	Ca	Mg	S
Continuous sweet Potato	1997 1st season	117 ±10.4	33 ±3.3	298 ±46.2	66 ±11.9	26 ±2.4	9 ±0.4
	1997 2nd season	69 ±3.8	13 ±3.7	120 ±29.4	35 ±8.3	14 ±1.6	4 ±0.6
	1998 3rd season	95 ±10.4	25 ±3.9	164 ±55.6	47 ±12.0	18 ±0.6	8 ±1.4
	1998 4th season	84 ±20.5	22 ±5.6	174 ±64.6	46 ±11.0	19 ±3.7	9 ±2.0
Piper aduncum fallow followed by two	Fallow [2]	23 ±2.8	7 ±0.6	92 ±7.9	10 ±1.6	5 ±1.4	1 ±0.1
seasons sweet potato (1 year)	1998 1st season	90 ±10.2	26 ±2.0	202 ±47.0	38 ±9.7	16 ±2.6	8 ±0.8
	1998 2nd season	69 ±8.4	19 ±1.8	159 ±23.3	39 ±5.5	16 ±2.2	7 ±0.3
Gliricidia sepium fallow followed by	Fallow [2]	164 ±24.0	24 ±4.5	159 ±11.3	90 ±22.4	23 ±3.5	13 ±2.7
two seasons sweet potato (1 year)	1998 1st season	83 ±14.8	22 ±4.7	195 ±55.3	40 ±18.0	16 ±5.0	7 ±1.7
	1998 2nd season	84 ±19.4	18 ±1.5	159 ±30.6	45 ±11.9	19 ±4.9	8 ±1.4
Imperata cylindrica fallow followed by	Fallow [3]	0	0	0	0	0	0
two seasons sweet potato (1 year)	1998 1st season	60 ±7.9	20 ±2.9	137 ±19.0	34 ±1.3	14 ±2.3	5 ±0.7
	1998 2nd season	61 ±8.0	18 ±1.1	156 ±18.6	32 ±4.7	14 ±2.5	6 ±0.2

[1] SD = standard deviation
[2] Nutrient removed in the woody biomass (stems) when the fallows were slashed
[3] No nutrients removed: all nutrients returned to the soil

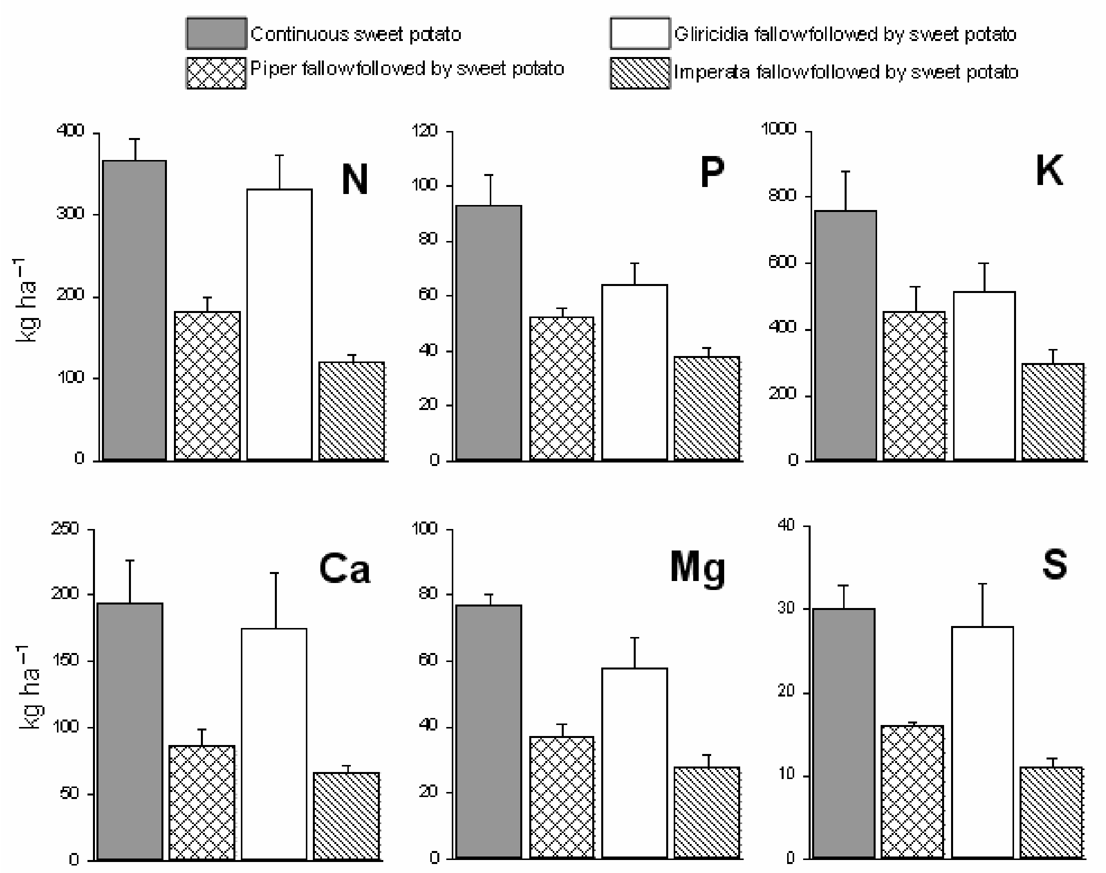

Fig. 2. Total nutrient removal (kg ha^{-1}) with fallow and sweet potato biomass after two years (error bar = 1 standard deviation)

Nutrient removal

Nutrient removal was calculated for each of the fallow and sweet potato seasons (Table 7). The removal was particularly high for the first season in the continuous sweet potato plots and for the gliricidia. Nutrient removal of sweet potato after the different fallows matches the tuber yield levels, more yield: more removal. From the imperata fallow the least nutrients were removed because no nutrients were removed when the fallows were slashed and the subsequent sweet potato crop produced significantly less vines (Table 2). Fig. 2 shows that total nutrient removal was very high for continuous sweet potato, but that also the gliricidia fallow followed by two sweet potato crops removed large amount of nutrients, particularly Ca and Mg.

Nutrient input and output and change in soil contents

No nutrient input was made in the continuous sweet potato plots and as result the difference between input and output was largest for all major nutrients (Table 8). The difference was particularly large for N (–365 kg ha^{-1}) and K (–756 kg ha^{-1}). Differences between the input and output of N, P, K and S was negative for all treatments but for Ca the difference was positive for piper and gliricidia fallow followed by two crops of sweet potato. This was due to the high input of Ca by the piper and gliricidia biomass and the relatively low output (removal) by the sweet potato tubers and vines. Also the Mg budget was positive for piper.

Table 8. Nutrient transfer and output (kg ha^{-1}) under continuous sweet potato (four seasons) and after one year of *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* fallows followed by two seasons of sweet potato. Total period: two years

Nutrient		Continuous sweet potato	Piper fallow and sweet potato	Gliricidia fallow and sweet potato	Imperata fallow and sweet potato
N	Transfer [1]	0	97	192	76
	Output [2]	365	182	331	121
	Difference	–365	–85	–139	–45
	Change topsoil content[3]	–209	–708	–211	–833
P	Transfer	0	14	12	12
	Output	93	52	64	38
	Difference	–93	–38	–52	–26
	Change topsoil content	–4.3	–2.6	–1.8	–1.9
K	Transfer	0	206	89	89
	Output	756	453	513	293
	Difference	–756	–247	–424	–204
	Change topsoil content	–148	–94	–90	–33
Ca	Transfer	0	147	222	56
	Output	194	87	175	66
	Difference	–194	60	47	–10
	Change topsoil content	–843	–698	–426	–950
Mg	Transfer	0	40	41	29
	Output	77	37	58	28
	Difference	–77	3	–17	1
	Change topsoil content	–26	15	–28	16
S	Transfer	0	9	12	4
	Output	30	16	28	11
	Difference	–30	–7	–16	–7
	Change topsoil content	nd [4]	nd	nd	nd

[1] Transfer = Nutrients returned with the *Piper aduncum* leaves, branches and litter; with the *Gliricidia sepium* leaves, branches and litter and nutrients returned with *Imperata cylindrica* leaves (from Table 1)

[2] Output = Nutrients removed with sweet potato tubers and vines (4 seasons for continuous; 2 seasons for previous fallow plots); Nutrients removed with *Piper aduncum* stems and with sweet potato tubers and vines; Nutrients removed with *Gliricidia sepium* stems and with sweet potato tubers and vines (Table 7)

[3] Change in topsoil content = Calculated from difference in soil nutrient contents (0-0.15 m) prior to the experiment and after two years (from Table 4 and 5)

[4] nd = no data

Changes in soil nutrient contents were calculated as the difference in nutrient concentration of the topsoil (0-0.15 m) at the beginning of the experiment and two years later (Table 8). Topsoil N contents decreased greatly under piper and imperata fallow followed by sweet potato. The decrease was much smaller under gliricidia fallow followed by sweet potato and under continuous sweet potato. Changes in soil P contents were only small and ranged from –1.8 to –4.3 kg P ha^{-1} over the two-years period; the largest change in P was found under continuous sweet potato and the smallest in the gliricidia and imperata fallow followed by sweet potato. The decrease in total soil K contents was largest in the soils under continuous sweet potato and lowest under imperata fallow and sweet potato. The decrease in soil K contents under piper and gliricidia fallow was similar. Piper biomass returned enough K for about one season of sweet potato whereas the K in the gliricidia and imperata was highly insufficient for one or more crops of sweet potato. Calcium contents decreased considerably in all four treatments but the decrease was highest in the imperata fallow and sweet potato plots.

The relation between nutrient budgets and changes in topsoil contents differs considerably for different nutrients. It appears that much more N was lost from the topsoils under piper and imperata fallow followed by sweet potato than could be explained by the nutrient budget. On the other hand, the P and K budget was much more negative for all treatments than the difference in soil P and K contents. Changes in topsoil Ca contents were much larger than could be explained by the nutrient budget. The positive Mg budg*et* also resulted in net increases in soil Mg contents in the piper and imperata fallow followed by two seasons of sweet potato.

9.4. Discussion

Considerable differences were found in the nutrient input by the fallows, the effects of the fallows on sweet potato, and in changes in soil chemical and physical properties. Several of these factors interact and this discussion focuses on differences and similarities in these factors. Although there is a growing body of literature on the effects of (improved) fallows in the tropics including gliricidia, most studies have focussed on grain crops (e.g. Hartemink *et al.*, 2000c; Juo *et al.*, 1995; Silva-Forsberg and Fearnside, 1997; Zaharah *et al.*, 1999) or with nutrient recovery from fallow mulch under laboratory conditions (e.g. Cadisch *et al.*, 1998) which hampers comparisons with the present study in which the fallow effects on a tuber crop under field conditions were studied.

Nutrient input and sweet potato yields

Nutrient input by above ground biomass of the woody fallows (piper and gliricidia) was large compared to other studies on high base status soils in the humid tropics (Szott *et al.*, 1999). In the first cropping season, the fallows had a significant effect on sweet potato tuber and vine yield. Sweet potato yields were significantly higher after piper than after gliricidia. This is likely caused by the high K input of the piper biomass of which 112 kg ha^{-1} was released within eight weeks (Hartemink and O'Sullivan, 2001). Sweet potato has a high demand for K (George *et al.*, 2002; Nicholaides *et al.*, 1985) and K influences tuber yield via increased dry matter diverting to the tubers and a increase in tubers per plant (Bourke, 1985a).

Sweet potato has generally a low demand for P (Hanh and Hozyo, 1984) and as the soils had fair amounts of available P, the recycling of P by the fallow had possibly little effects on sweet potato yield. Hartemink *et al.* (2000b) sampled sweet potato leaves under continuous sweet potato for four seasons at the same site and found that P levels were at least 50% above the critical level and no decreasing trend occurred over time. Also pottrials with soils from the same site showed no response to P. This suggests that P is not limiting sweet potato production.

Gliricidia fallows added large amounts of N and the N input was two times larger than that of piper and imperata fallows. Nitrogen influences sweet potato yield by increasing leaf area duration which in turn increase mean tuber weight and thus tuber yield (Bourke, 1985a) but too much N reduces tuber yields (Hill *et al.*, 1990; Marti and Mills, 2002). The high N input by the gliricidia resulted in high vine production and a lower harvest index which may explain the lower yields after gliricidia fallow compared to the other fallows. The lower yield may also be related to the allelopathic compounds of the gliricidia leaves. Ramakoorthy and Paliwal (1993) have shown that applications of 4 to 12 Mg ha^{-1} of gliricidia leaf mulch effectively control weeds whereas Alan and Barrantes (1998) showed that extracts from gliricidia leaves drastically reduced the germination of weed species including *Ipomoea* sp. It is hard to quantify whether allelopathic effects affected the sweet potato yield although the polyphenolic contents of the gliricidia leaves were indeed significantly higher than in piper or imperata (Hartemink and O'Sullivan, 2001). Phenolic compounds have been reported to possess allelopathic activities (Inderjit and Keating, 1999).

Sweet potato after imperata fallows produced significantly less vine biomass because of the thick layer of imperata leaves on the soil hindering the spreading of vines. Imperata leaves had high C/N ratios and decomposed slowly which kept the soils more moist and also immobilised about 18 kg N ha^{-1} during the first cropping season after the fallow (Hartemink and O'Sullivan, 2001). The reduced vine biomass production had no significant effect on sweet potato tuber yield despite the fact that vine and tuber yields are often inversely related (Enyi, 1977). In many parts of the humid tropics, imperata is known to reduce crop yields (Chikoye *et al.*, 2000; Santoso *et al.*, 1997) and Kamara and Lahai (1997) found a significant yield reduction of sweet potato when more than 10 Mg ha^{-1} imperata biomass was applied. It was attributed to the high C/N ratio of the mulch and the phytotoxic properties of the imperata biomass (Kamara and Lahai, 1997). Ngiumbo and Balasubramanian (1992) found that burning of the imperata biomass gave better yield. Farmers in the experimental area do not burn the fallow debris but burning enhances the bioavailability of nutrients (Giardina *et al.*, 2000) and the burned mulch dries the soil, which could be an advantage under the prevailing wet conditions.

In the second season after the fallow, there was no difference between the treatments. Residual benefits of fallows on crop yields usually last for one or two cropping seasons only (Buresh and Cooper, 1999; Szott *et al.*, 1999) and the absence of a response in the second season of this experiment may be related to the rapid mineralisation of nutrients in the fallow mulch during the first season (Hartemink and O'Sullivan, 2001). Overall, sweet potato yields were higher in second season and this is likely due to the fact that there was 317 mm less rain (Fig. 1). In the experimental area, it was found that sweet potato yields are significantly reduced in wetter seasons regardless of the cropping history of the soil, more rain: less yield (Hartemink *et al.*, 2000b). Although high rainfall is very beneficial for the biomass and nutrient accumulation of *Piper aduncum* (Hartemink, 2001), it is detrimental during tuber initiation of sweet potato (Gollifer, 1980; Hahn and Hozyo, 1984). Piper fallows significantly reduced soil moisture (Table 7) and this effect lasted for some time after the piper fallow was slashed and sweet potato was planted. It is probably favourable for tuber initiation after piper fallows. The exact relation between soil moisture contents and tuber initiation and yields remain to be quantified but this experiment has shown that there may be linkages.

Fallow and sweet potato effects on the soil

Both the fallow and sweet potato crop affected soil chemical and physical properties. During the fallow period a small increase was found in the soil organic C content and total N. It is often found, however, that organic C decrease in the first years of a fallow and increases thereafter (Szott *et al.*, 1999). During sweet potato cropping, organic C slightly decreased which is commonly found on high-base status soils with short-term fallows (Juo *et al.*, 1995; Roder *et al.*, 1997). The soils acidified significantly during the fallow period and the pH further decreased during sweet potato cropping. Although the total changes in pH are considerable, the high-base status of these soils and the fact that sweet potato tolerates a wide range of soil reactions (O'Sullivan *et al.*, 1997) implies little effect on sweet potato production. Exchangeable K significantly decreased during the piper fallow and slightly increased after the piper fallow was slashed which is in accordance with the high uptake of K by piper and the rapid release of K in the piper biomass.

Changes in the soil bulk density were the same under all three fallows: an increase of about 13% during the one-year fallow period. After two crops of sweet potato, bulk density decreased in the previous fallow plots due to forking required to harvest the tubers. Under continuous sweet potato cultivation, bulk density gradually decreased due to the forking. The soils at the experimental site have low bulk densities and the slight increase during the fallow and decrease during sweet potato cropping have probably no effect on root or tuber root growth. However, bulk density affects mass nutrient balances (Table 9) and also affects soil water storage. Differences in volumetric soil moisture contents differed between the fallows. Soil moisture contents under sweet potato after imperata fallows were highest due to the undecomposed imperata mulch layer. Stephens (1967) also found higher soil moisture contents after imperata fallows compared to continuously cultivated plots because the rainfall was accepted more readily in the imperata plots.

Nutrient budgets

The long-term sustainability of fallow systems on high base status soils depends on the size of nutrient stocks and the magnitude of net nutrient loss during each crop-fallow cycle (Szott *et al.*, 1999). The nutrient budgets (Table 8) showed that continuous sweet potato had the most negative nutrient budget because there was no input. These budgets have some limitations as only nutrients in the 0-0.15 m soil horizon were measured and extractable P and cations were measured. Organic C and total N are the total figures but P is extracted by bicarbonate and Ca, Mg and K by an NH_4-acetate so P and cations are a fraction of the total amounts present in the soil. On the other hand, the data give a fair quantification of the amounts of nutrients that are potentially available for crop production. As soil depth is limited at the experimental site and most roots were found in the top 0.2 m, deep capture of nutrients which is important in many fallow systems (Hartemink *et al.*, 2000c) is not relevant for this study site. Therefore, nutrient stocks reported for the topsoil are more or less equal to the amount of nutrients available.

None of the three fallows (piper, gliricidia, imperata) added sufficient amounts of N, P and K for the removal of these nutrients by two consecutive seasons of sweet potato. Although there is some difference between the fallows, the high nutrient demand of sweet potato seems to allow for only one crop after the fallow. The woody fallows had more favourable Ca and Mg budgets than the imperata fallow. As the soils are high in exchangeable Ca and Mg and sweet potato has a relatively low demand for these nutrients the favourable Ca and Mg budgets of woody fallow has limited value.

The major function of fallows is to recycle and conserve nutrients rather than to cause net increases in ecosystem nutrient stocks (Buresh and Cooper, 1999). Gliricidia and piper fallow recycled larger amounts of nutrients than the imperata fallow. More biomass is produced by these fallows when compared to imperata fallows (Table 4). The larger amounts of nutrients recycled in the fallow-crop system may induce greater losses and some idea on the amount of losses can be obtained by comparing the nutrient budgets with the changes in soil nutrient contents. More N and Ca were lost from the soil than could be explained by the input-output budgets. In the budgets, only input by the above ground fallow biomass and output by sweet potato vines and tubers and piper and gliricidia wood were considered. Nutrient output by leaching, volatilisation, denitrification or soil erosion were not quantified. At a nearby site, Sayok and Hartemink (1998) showed that soil erosion under sweet potato on a 58% slope was less than 4 Mg soil ha^{-1} y^{-1} which are very low erosion rates. As the experiment described in this paper was at a slope of site less than 2%, nutrient losses by soil erosion are therefore negligible. It is likely that leaching losses were high and this has been reported for other experiments with sweet potato in the humid tropics (Islam *et al.*, 1994) which explains the low N use efficiency that is often found in sweet potato field experiments (Hartemink *et al.*, 2000a).

9.5. Conclusions

The long-term sustainability of the different fallow systems can be appraised in different ways; for the farmers tuber yield and useful products of the fallow (wood) are important factors whereas nutrient budgets and changes in soil nutrient contents determine the long-term productivity of the land. Short-term fallows of piper give higher sweet potato yields than gliricidia fallows but the effects lasted only one season. Gliricidia fallows produced three times more wood, which is an advantage in areas where fuelwood is scarce. These short-term fallow systems are insufficiently capable to compensate for the high nutrient removal during the consecutive cropping season and possibly the high nutrient losses during the cropping period.

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10. Integrated nutrient management research with sweet potato in Papua New Guinea *

Abstract

This paper summarises a series of field experiments that investigated the effects of organic and inorganic nutrients on sweet potato tuber yield in the humid lowlands of Papua New Guinea. In the first experiment, plots were planted with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* which were slashed after one year whereafter sweet potato was planted. Sweet potato yield was lowest after gliricidia fallow but no yield differences were found after piper and imperata fallow. In the second season, there was no significant difference in sweet potato yields. The second experiment consisted of a factorial fertiliser trial with four levels of N (0, 50, 100, 150 kg ha^{-1}) and two levels of K (0, 50 kg ha^{-1}). Nitrogen fertilisers increased yield in the first season but depressed tuber yields in the second and third season. Potassium fertiliser had no effect on marketable tuber yield. The third experiment consisted of a comparison between N from inorganic fertiliser and poultry litter at four rates (0, 50, 100, 150 kg ha^{-1}). No difference was found between the inorganic fertiliser and poultry litter and highest yields were found at 100 kg N ha^{-1}. In the second season no significant response was observed. Although yield variation was considerable this series of experiments has shown that sweet potato yield can be significantly increased by inorganic or organic N applications. Sweet potato yields after fallows were less variable than after inorganic nutrient inputs. Inputs through inorganic fertiliser or poultry litter may strongly increase or decrease tuber yields.

10.1. Introduction

Up to the 1980s it was widely perceived that inorganic fertilisers would be a viable option to increase land productivity in the low fertility soils of the humid tropics. Organic fertilisers (e.g. compost, farm yard manure) were regarded as important but it was realised that organic fertilisers would not be available in sufficient amounts to drastically increase food production. In the early 1980s, various reports showed stagnated use of inorganic fertilisers in the tropics and this was explained by poor marketing and

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* Hartemink, A.E., 2003. Integrated nutrient management research with sweet potato in Papua New Guinea. Outlook on Agriculture, 32: 173-182. © IP Publication; reprinted with permission.

inadequate profitability from inorganic fertiliser use (Hartemink, 2002). From then on integrated nutrient management was advocated which essentially means the combination of both inorganic and organic fertilisers to increase crop production (Janssen, 1993).

This paper reviews integrated nutrient management research with sweet potato (*Ipomoea batatas* L.) in the humid lowlands of Papua New Guinea. Sweet potato is the main staple crop in many parts of Papua New Guinea but the number of detailed integrated nutrient management experiments with sweet potato is limited (Hartemink and Bourke, 2000). Most nutrient management experiments have been conducted on experimental stations and little work has been done in farmers' fields. This is particularly unfortunate as poor crop nutrition contributes to the low yield of root crops of many farmers in Papua New Guinea and throughout the Pacific region (Halavatau *et al.*, 1998).

The research reported in this paper took place on-farm at Hobu (6°34'S, 147°02'E), which is about 15 km north of the Papua New Guinea University of Technology in Lae. The experimental site was in farmers' fields but all field operations (planting, weeding, harvesting etc.) were managed by the researchers. The experiments were conducted between November 1996 and December 1998. Three sets of experiments were conducted: (i) fallow experiment with both natural and improved fallows, (ii) inorganic fertiliser experiments with N and K, (iii) poultry litter experiments. The main aim of the experiments was to assess the effects of different nutrient inputs on sweet potato yield.

10.2. Environmental conditions at the experimental site

Hobu is at the footslopes of the Saruwaged mountain range which forms the major landmass of the Huon Peninsula. The experimental site is located on an uplifted alluvial terrace at an altitude of 405 m a.s.l. with slopes of less than 2%. Soils are derived from a mixture of alluvial and colluvial deposits dominated by sedimentary rocks and coarse to medium grained, basic, igneous rocks. The soils are layered with water-worn gravelly and stony horizons below 0.2 m depth; effective rooting depth is over 0.7 m. Air-dried and sieved (< 2 mm) soil from the top 0.12m had the following properties: pH = 6.2, organic C = 55 g kg^{-1}, available P (Olsen) = 9 mg kg^{-1}, CEC = 400 $mmol_c$ kg^{-1}, exchangeable Ca = 248 $mmol_c$ kg^{-1}, exchangeable Mg = 78 $mmol_c$ kg^{-1}, exchangeable K = 16.9 $mmol_c$ kg^{-1}, clay = 480 g kg^{-1} and sand = 360 g kg^{-1}, bulk density = 0.82 Mg m^{-3}. Further details can be found in Hartemink *et al.* (2000b). The soils are classified as mixed, isohyperthermic, Typic Eutropepts (USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base). Inceptisols (Eutropepts) are the commonest soils in Papua New Guinea and are estimated to cover approximately 40% of the country (Bleeker, 1983). In the Hobu area, Sayok and Hartemink (1998) showed that erosion under sweet potato on a 58% slope was less than 4 Mg ha^{-1} $year^{-1}$, which are very low erosion rates. The site for the experiments described in this paper had a slope of less than 2% and erosion is therefore not a problem.

In 1997, there was a total rainfall of 1,897 mm which is below the long-term average, due to the El Niño/Southern Oscillation climatic event, which hit the Pacific severely in 1997-98. In the first six months of 1998, more rain fell than in the whole of 1997. March 1998 was a particularly wet month with 725 mm of rain. At the University of Technology total rainfall in 1997 was only 2,594 mm compared to the long-term (20 y) annual mean of 3,789 mm. Temperature data are not available for the site but average daily temperatures at the University of Technology are 26.3°C. Since the University is at a lower altitude (65 m a.s.l.) temperatures at the experimental site are probably on average slightly lower.

An area of about 0.5 ha secondary vegetation was slashed manually at the beginning of November 1996. The vegetation consisted mainly of *Piper aduncum* L. and to a lesser extent by *Homolanthus* sp., *Macaranga* sp., *Trichospermum* sp. and *Trema orientalis* (Rogers and Hartemink, 2000). The site had been intensively used for growing foodcrops but had been fallow since 1992. All vegetation debris was removed and no burning was practised, which follows the land-clearing practices of local farmers.

10.3. Experiments with natural and improved fallows

Shifting cultivation systems with cropping periods alternating with short fallow periods is still widely practised in the humid lowlands of Papua New Guinea. Very little is known about nutrient cycling in those shifting cultivation systems. The particular effects of the addition of nutrients by the secondary fallow vegetation and subsequently on sweet potato yield are largely unknown.

The secondary fallow vegetation in many parts of the lowlands is dominated by *Piper aduncum* (L.), which is a shrub indigenous to tropical America (Hartemink, 2001). It is not known how and when *Piper aduncum* arrived in Papua New Guinea, but it was first described in the Morobe Province in 1935. In the standard work on New Guinea vegetation by Paijmans (1976), *Piper aduncum* (hereafter referred to as piper) is not mentioned as a separate species. This is hard to imagine nowadays as in many parts of the humid lowlands piper forms monospecific stands. In the Morobe Province of Papua New Guinea it occurs at altitudes up to 600 m a.s.l., but is also found in the highlands up to altitudes of 1900 m a.s.l. It grows very fast but there is virtually no undergrowth of weeds or shade tolerant tree species. Despite this lack of undergrowth severe erosion under piper has not been observed in Papua New Guinea.

Farmers in the Hobu area usually have short term piper fallows (< 2 years) followed by one crop of taro, gradually intercropped with sweet potato, sugarcane (*Saccharaum* sp.) and bananas (*Musa* sp.). The length of the fallow period has, however, reduced due to the need for increased food and cash crop production to keep up with the growing population (Allen *et al.*, 1995; Freyne and McAlpine, 1987). Farmers claim that the piper arrived in the Hobu area in the early 1970s. In this area, the secondary fallow vegetation is dominated by piper, but *Imperata cylindrica* grassland is also common.

Although the aggressive invasion of piper has been described, including its possible effect on Papua New Guinea's rich biodiversity (Rogers and Hartemink, 2000), there is no information available on the effect of piper fallows on soil and crop productivity. For example it is not know whether piper fallows are more productive than other natural fallows like *Imperata cylindrica* grasslands (hereafter referred to as imperata). With the reduction in the length of the fallow period there may be a need to introduce fallow species which improve soil fertility more rapidly than natural fallows (Young, 1997). *Gliricidia sepium* (hereafter referred to as gliricidia) is in some parts of the world planted as an 'improved fallow' and it is one of the most widely cultivated multipurpose trees (Simons and Stewart, 1994) and in the Papua New Guinea lowlands it is used as a shade tree in cocoa plantations.

Experimental set-up

Sixteen plots 6.0 by 6.0 m each were laid out and four treatments were assigned to the plots in a randomised complete block design. At the end of November 1996 the fallow plots were planted. Four plots were planted with seedlings (0.4 m) of piper obtained from a nearby road-side and four with gliricidia cuttings (0.4 m) obtained from a nearby cocoa plantation. Piper and gliricidia fallows were planted at distances of 0.75 by 0.75 m (17,778 plants ha^{-1}). These spacings are often observed in natural piper fallows (Hartemink and O'Sullivan, 2001). In four plots the vegetation consisted of natural regrowth which was immediately dominated by *Imperata cylindrica*. Some minor weeds in the imperata fallow were *Ageratum conyzoides, Sphaerostepanos unitus*, *Rottboellia exalta*, *Sida rhombifolia*, *Polygala paniculata*, *Euphorbia hirta* and *Emilia sonchifolia*.

Sweet potato local cultivar Hobu1 (E. Guaf, *pers. comm.*, 1997) was planted in the remaining four plots. Hobul is a widely grown cultivar with red skin tubers and white flesh. It appears not to be very susceptible to sweet potato weevils, an important pest of sweet potato in Papua New

Guinea (Bourke, 1985b; Powell *et al.*, 2001). Planting material was obtained from local gardens and consisted of vine cuttings which were planted almost vertically in the soils using a stick. One cutting of about 0.4 m length with 4 to 6 nodes was planted per hole which generally gives the highest tuber yield (Levett, 1993). Planting distance was 0.75 by 0.75 m (17,778 plants ha^{-1}). The plots were continuously cultivated for four seasons.

After one year (20-24 November 1997), all fallow vegetation was cut at ground level. Piper plants were separated into stems, branches, leaves and litter, gliricidia plants into stems, leaves and litter, and for the imperata fallow total biomass was taken as there was virtually no litter. In each plot, the total fresh matter was weighed for each of the different plant parts and samples were taken for dry matter determination and nutrient analysis. Piper and gliricidia stems were removed from the plots; all other plant parts were applied as surface mulch after weighing. On 26th November 1997, the previously fallow plots were planted with sweet potato as for the continuously cultivated plots. The previously fallow plots were not tilled when planted, and they were cropped with sweet potato for two seasons.

The sweet potato cropping seasons lasted about 170 days whereafter the plots were harvested. Vines were cut at ground level, weighed, and removed from the plot. Vines are also removed in farmers' gardens (perhaps to avoid allelopathic effects), which alters nutrient uptake (Walker *et al.*, 1989). Tubers were manually dug, counted and separated into marketable tubers (>100 g) and non-marketable tubers (<100 g) which were also removed from the plot. All plots were replanted directly after harvest. Weeds were pulled out manually but not removed from the plot. No pesticides were used in the experiments. Fig. 1 shows the daily rainfall during the experimental period and during each of the four seasons.

Nutrient input and sweet potato yield after the fallows

The nutrient return from the one-year old fallows is presented in the left columns of Table 1. Nitrogen returned to the field with gliricidia leaves and litter was 192 kg ha^{-1} compared to 97 kg N ha^{-1} for piper and 76 kg N ha^{-1} for imperata. The amount of P returned with the fallow vegetation was similar for all three fallows and around 12 to 14 kg ha^{-1}. Piper returned 206 kg K ha^{-1} compared to 89 kg K ha^{-1} with gliricidia and imperata.

In the first season after the fallow, marketable sweet potato yield after piper and imperata was about 11 Mg ha^{-1} and it was significantly higher than under continuous sweet potato or after gliricidia fallow (Table 1). Marketable yield under continuous sweet potato cultivation was 7.8 Mg ha^{-1}. Variation in non-marketable tuber yield after the fallows was large and differences were not statistically significant. Total tuber yield (marketable plus non-marketable tubers) was highest after piper (14.4 Mg ha^{-1}) and significantly lower after gliricidia fallow (9.9 Mg ha^{-1}). Vine yield was similar under continuous sweet potato cultivation and after piper and gliricidia fallow, but significantly lower after the imperata fallow, which produced about 10 Mg ha^{-1} sweet potato vines less.

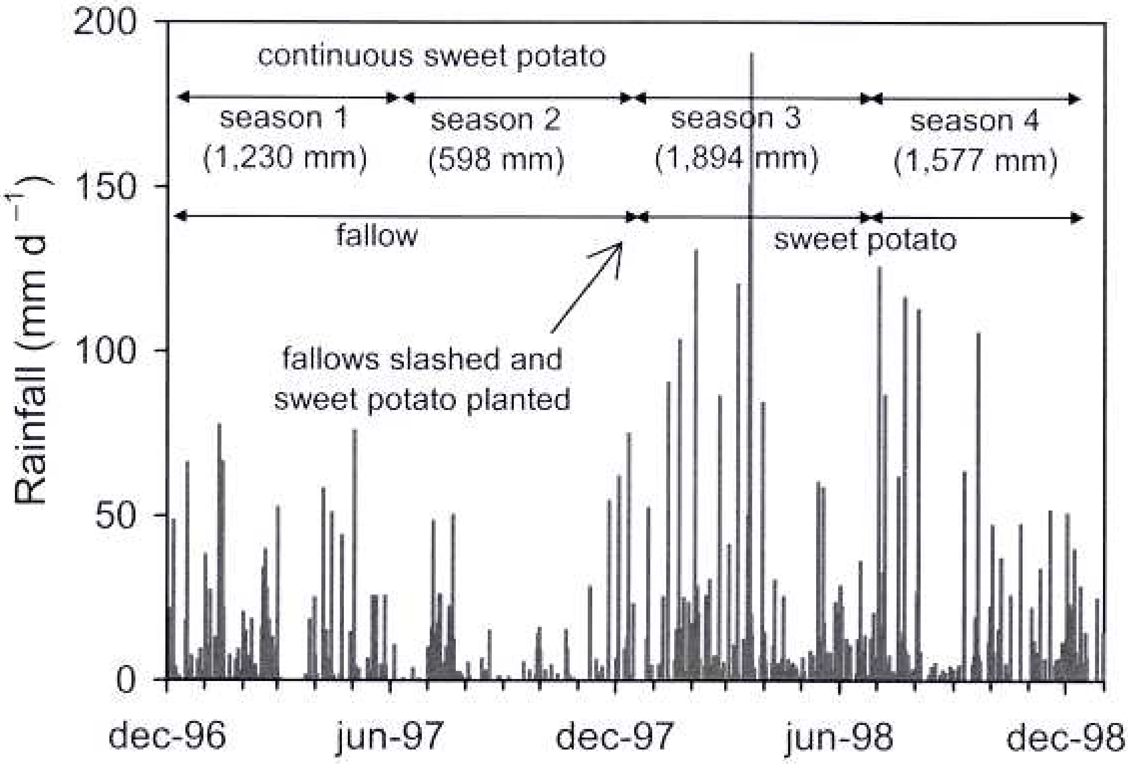

Fig. 1. Daily rainfall (mm) during fallow experiment at the experimental site. Total rainfall during each of the four seasons is given in parentheses

Table 1. Sweet potato yield for two seasons after one year piper, gliricidia and imperata fallows, and under continuous cultivation

Fallow species	Nutrient input [1] kg ha^{-1} N	P	K	Yield in Mg ha^{-1} fresh weight: Marketable tubers first season	second season	Non marketable tubers first season	second season	Vines first season	second season
Piper aduncum	97	14	209	11.2	13.4	3.1	2.1	30.4	22.9
Gliricidia sepium	192	12	89	8.4	14.3	1.6	1.8	31.6	26.1
Imperata cylindrica	76	12	89	11.3	15.2	1.5	1.1	20.7	18.9
Continuous sweet potato [2]	0	0	0	7.8	12.8	2.4	2.0	32.3	27.4
SED [3]				1.3	ns	ns	0.3	3.9	4.1

[1] Nutrients returned with the above-ground biomass when the fallows were slashed and the first season of sweet potato was planted
[2] Yields from the third and fourth season under continuous cultivation
[3] Standard error of the difference in means (9 *d.f.*); ns = not significant ($P>0.05$)

In the second season, there was no fallow effect on marketable sweet potato yield. Non-marketable tuber yield was, however, significantly lower in the previous imperata plots but no differences were found in the other treatments. Vine yield in imperata plots was statistically comparable to the other previous fallow treatments. Total tuber yield in the second season was similar for all treatments. Cumulative tuber yield over the two seasons was about 29 Mg ha^{-1} for piper and imperata but less than 25 Mg ha^{-1} in the continuous sweet potato plots. Cumulative vine yield over the two seasons was between 53 and 60 Mg ha^{-1} for continuous sweet potato and previous gliricidia and piper plots, but it was less than 40 Mg ha^{-1} in the previous imperata plots.

10.4. Inorganic fertilizer experiments

There is fair a body of literature on the use of inorganic fertilisers on sweet potato although the information is limited compared to that for other staple crops in the tropics like rice and maize. Sweet potato consumes considerable amounts of K and responses to K fertilisers are generally recorded (de Geus, 1973). Sweet potato has high N requirements but can produce reasonable yields in soils of poor fertility (Hill *et al.*, 1990). This may be partly caused by its capacity to fix atmospheric N through association with symbiotic, non-nodulating bacteria. Estimates have shown that as much as 40% of the N uptake of sweet potato may be derived from di-nitrogen (Yoneyama *et al.*, 1998), although cultivar differences are large. A very wide range of N fertiliser requirements has been reported for sweet potato (Hill, 1984) but much depends on the cultivar, soil type and climatic conditions (O'Sullivan *et al.*, 1997).

In Papua New Guinea, various inorganic fertiliser experiments have been conducted from the 1950s onwards. Bourke (1977) summarised 17 field trials and 6 pot trials conducted on volcanic ash soils in Keravat and found that N and K were mostly needed. Nitrogen increased vine yield but N responses to tuber yield were inconsistent. Potassium fertiliser had no effect on vine yield but K increased tuber yield and the number of tubers. Somewhat similar findings have been reported by Hartemink *et al.* (2000a) working on alluvial soils near Lae. Floyd *et al.* (1988) also working on volcanic ash soils showed that P and K applied as organic manure gave better responses than inorganic fertilisers. Overall the literature seems to suggest that sweet potato in Papua New Guinea responds inconsistently to inorganic fertilisers.

Experimental set-up
The inorganic fertiliser experiment at Hobu was laid out as a randomised block design with four levels of N (0, 50, 100, 150 kg ha^{-1}) and two levels of K (0, 50 kg ha^{-1}) in a factorial combination. Each treatment was replicated four times and plot size was 4.5 by 4.5 m. The experiment lasted for three consecutive seasons. Throughout this experiment the sweet potato cv Hobu1 was again used. During the experiment weeds were pulled out manually and not removed from the plot. No pesticides were used.

Potassium fertiliser was broadcasted directly after planting. Nitrogen fertiliser was given in split application: 50 kg ha^{-1} was given at planting, 50 kg ha^{-1} was given 59 days after planting (DAP) to the 100 kg ha^{-1} treatment. The 150 kg N ha^{-1} treatment received another 50 kg ha^{-1} at 80 DAP. At harvest, vines were cut at ground level, weighed, and removed from the plot. Tubers were manually dug, counted and separated into marketable tubers (>100 g) and non-marketable tubers (<100 g) which were also removed from the plot. Total rainfall received during the first crop was 1,028 mm. All plots were replanted directly after the harvest. Rainfall in the second season was 1,034 mm and total rainfall received in the third season was 2,214 mm. Fig. 2 shows the daily rainfall during the experimental period, and for each of the three seasons.

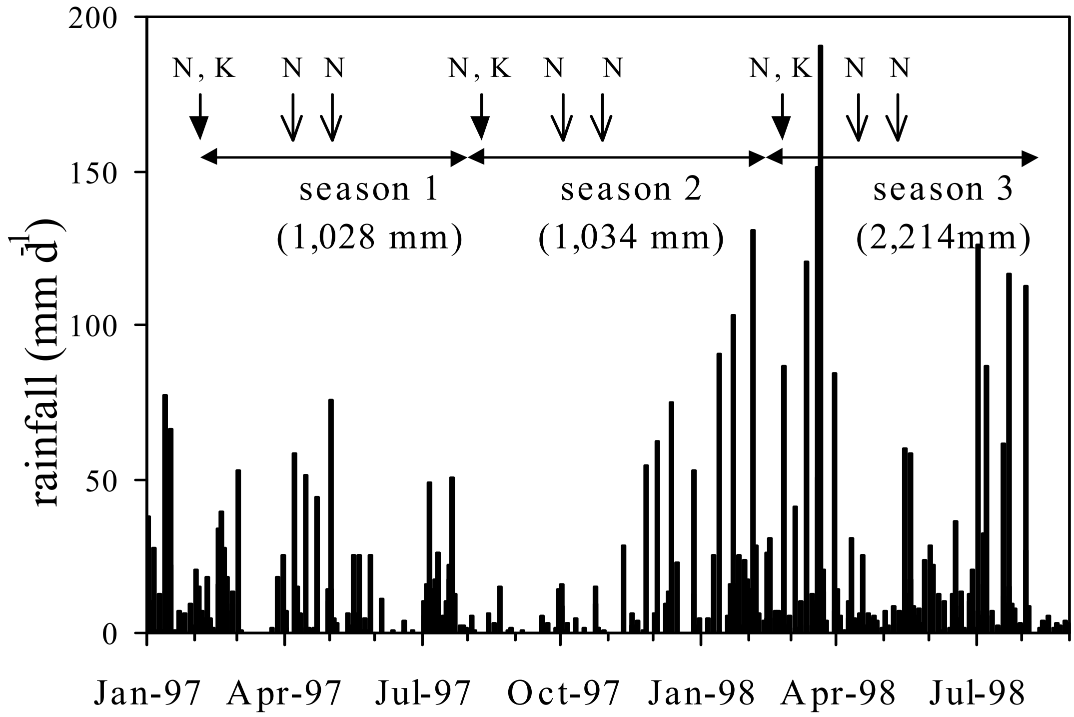

Fig. 2. Daily rainfall (mm) during inorganic fertiliser experiment. Vertical arrows indicate timing of N and K fertiliser application. Total rainfall during each of the three seasons in parentheses

Sweet potato yield

Sweet potato tuber yields of the three seasons are presented in Fig. 3. Marketable tuber yield in the first season ranged from 18.3 to 23. 8 Mg ha^{-1} but it was not affected by K fertiliser. Nitrogen fertiliser increased marketable tuber yields (P=0.10) and the highest yield was obtained with 100 kg N ha^{-1}. Non-marketable tubers were significantly increased by about 1 Mg ha^{-1} due to the K fertiliser.

In the second season, N fertiliser significantly reduced marketable tuber yields. The reduction was almost linear from about 25 Mg ha^{-1} when no fertiliser was applied to 17 Mg ha^{-1} at 150 kg N ha^{-1}. Potassium fertiliser had no significant effect on the marketable tuber yield but increased non-marketable tuber yield.

In the third season, yield levels dramatically dropped in all treatments. Marketable tuber yield in the control plots was only 7 Mg ha^{-1} and N fertiliser significantly reduced yield by about 3 Mg ha^{-1}.

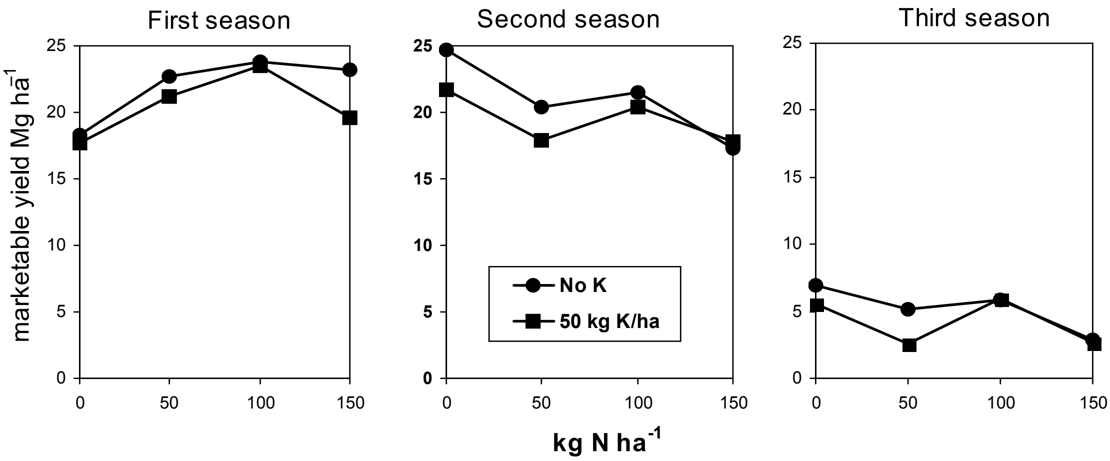

Fig. 3. Marketable sweet potato tuber yields for three consecutive seasons at different rates of inorganic N and K application

10.5. Poultry litter experiments

In Papua New Guinea, various field trials with sweet potato have shown that inorganic fertilisers produce higher and more consistent yields than inorganic inputs, e.g. (D'Souza and Bourke, 1986; Floyd *et al.*, 1988; Preston, 1990). Various factors could be involved like, for example, the addition of beneficial nutrients within the organic manure which are not found in the inorganic fertilisers, or the improvement of the soil physical or biological properties.

In the highlands of Papua New Guinea compost and coffee pulp are available as organic nutrient sources for the sweet potato. In the lowlands of the Morobe Province poultry litter is widely available because of the many smallholders raising chickens for large commercial companies. The poultry litter (manure plus sawdust) is usually removed from the shed when the chickens are slaughtered and dumped near the shed. It is rarely used in food gardens despite its containing many nutrients.

Igua (1985) conducted an experiment near Port Moresby with poultry litter and sweet potato and found that highest yields when 10 Mg poultry litter ha^{-1} was applied. Higher application rates depressed sweet potato yield. No other reports are available on the effect of poultry litter on sweet potato yield in Papua New Guinea.

Experimental set-up

The poultry litter experiment consisted of 4 levels of N (0, 50, 100, 150 kg ha^{-1}) given as poultry litter or as inorganic fertiliser (NPK). The equivalent amount of K and P given in the poultry litter plots was given to the inorganic fertiliser plots. The experiment was laid out as a randomised complete block design with four replicates per treatment. The experiment lasted for two seasons. Directly after planting the poultry litter and inorganic fertiliser (NPK) was applied. The application of inorganic N fertiliser (sulphate of ammonia) was split. Harvesting techniques was similar to those used in the fallow and inorganic fertiliser experiments. Fig. 4 shows the daily rainfall during the experiment and for the two seasons. During the first season total rainfall was 1,203 mm and 2,091 of rain fell in the second season.

Nutrient concentration of the poultry litter in the first season was 24.6 g N kg^{-1}, 15.7 g P kg^{-1}, 22.5 g K kg^{-1}, 30.2 g Ca kg^{-1}, and 6.4 g Mg kg^{-1}. The poultry litter contained about 84% dry matter and 362 g C kg^{-1}. Application of 50 kg N ha^{-1} corresponded to 2.4 Mg ha^{-1} fresh poultry litter. In the second season the poultry litter contained less nutrients: 13.0 g N kg^{-1}, 12.5 g P kg^{-1}, 10.3 g K kg^{-1}, 30.2 g Ca kg^{-1}, and 6.4 g Mg kg^{-1}. Dry matter content was 59% and application of 50 kg N ha^{-1} corresponded to 6.5 Mg ha^{-1} fresh poultry litter.

Sweet potato yield

In the first season, marketable sweet potato yield was significantly increased by poultry litter and inorganic N fertiliser. The yield pattern was about the same for both N sources (quadratic response) and highest yields were recorded when 100 kg N ha^{-1} was applied. In the second season, marketable tuber yield was significantly reduced by both poultry litter and inorganic N fertiliser. Marketable tuber yields in the control plots were similar to the yields in the first season but non-marketable tuber yield was about 10 times higher. No effect of poultry litter or inorganic fertiliser was recorded in the second season (Fig. 5).

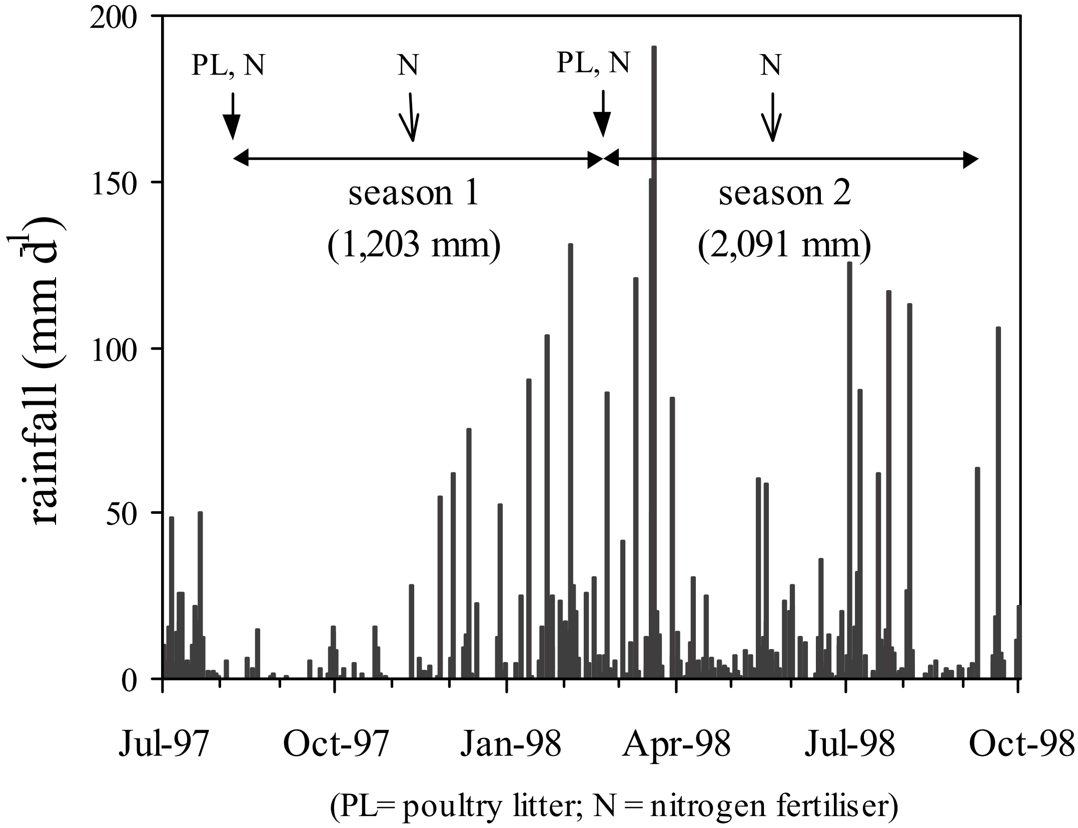

Fig. 4. Daily rainfall (mm) during the poultry litter experiment. Vertical arrows indicate timing of poultry litter and fertiliser application. Total rainfall during the two seasons in parentheses

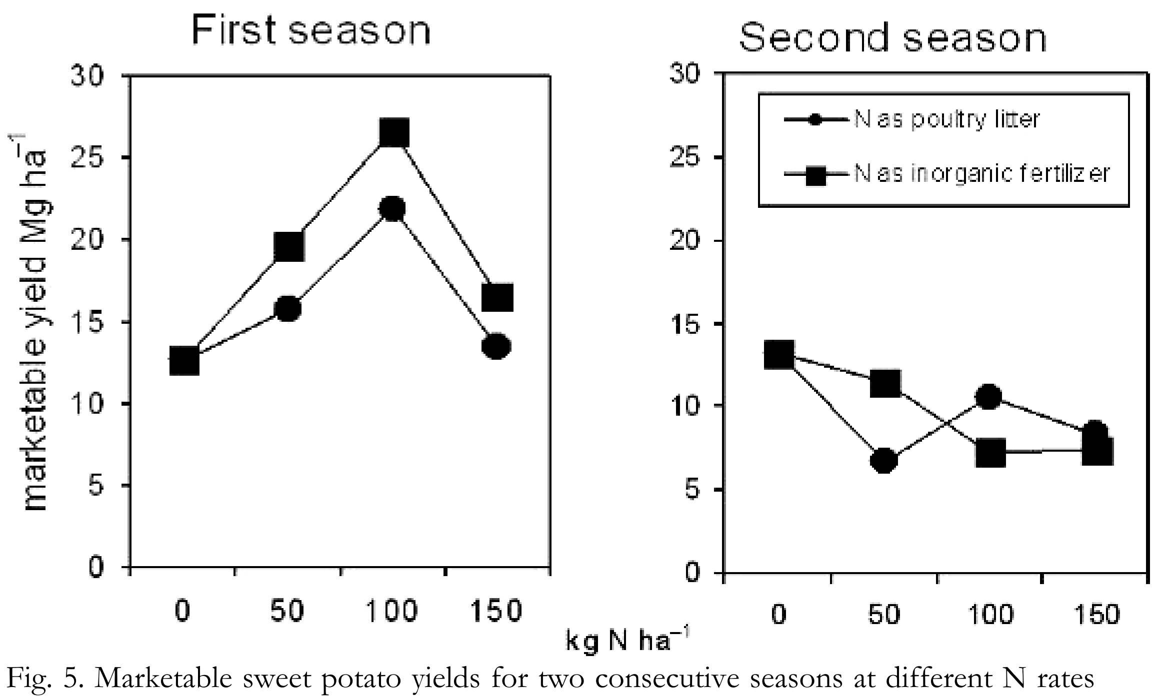

Fig. 5. Marketable sweet potato yields for two consecutive seasons at different N rates given as poultry litter

10.6. Yield variation and yield trends

Considerable yield variation was noticed in all experiments which is generally found in field experiments with sweet potato (Hartemink *et al.*, 2000b; Martin *et al.*, 1988). Several factors contributed to this variation: rainfall, soil changes and the build-up of pests and diseases.

During the experiments the impression was formed that yields were generally higher in seasons with lower rainfall. Sweet potato is reported to be very sensitive to excess soil water during the first 20 days after planting when tubers are formed (Hahn and Hozyo, 1984) and a regression analysis between marketable yield and rainfall received during the first 20 days of growth was conducted (analysis not shown). No obvious relation was found, and instead correlation coefficients were calculated for the tuber yield, vine yield and total rainfall received in the season (Table 2). It was found that rainfall at Hobu was significantly correlated with the marketable and non-marketable tuber yield, as follows: the higher the rainfall the lower the tuber yield. Vine yield was positively correlated with rainfall which suggests that the reduction in tuber yield in wetter seasons favours the growth of vine biomass. The number of cropping seasons at Hobu was significantly correlated with both marketable and non-marketable tuber yield, but not to the vine biomass: tuber yield declined under continuous cultivation but vine yield was not affected. At the University of Technology (Unitech) correlations among yield, rainfall and cropping seasons were weaker. The number of cropping seasons was not correlated with tuber yield. Marketable yield was also negatively correlated with the rainfall received during the cropping season.

Table 2. Correlation between rainfall, number of cropping seasons, sweet potato tuber yield and vine yield (Hartemink *et al.*, 2000)

Site [1]		Marketable yield	Non-marketable yield	Vine yield
Hobu	rainfall during the growing season [2]	– 0.601 **	– 0.814 ***	0.866 ***
	number of cropping seasons [3]	– 0.556 *	– 0.622 **	0.274
Unitech	rainfall during the growing season [2]	– 0.558 **	0.085	– 0.167
	number of cropping seasons [3]	– 0.202	0.018	– 0.628 **

***, **, * indicates significant correlation at $P<0.001$, $P<0.01$ and $P<0.05$ respectively

[1] results from experiments at Hobu and the farm of the University of Technology in Lae

[2] covariate = number of cropping seasons (i.e. 4 at Hobu and 5 at Unitech)

[3] covariate = rainfall received in the season

Another major factor which may explain the variation and trends observed is changes in soil chemical properties as a result of continuous sweet potato cultivation. Table 3 shows soil chemical properties before the first planting and after four seasons (± 2 years) of continuous sweet potato cultivation. The topsoil pH had decreased by 0.4 units accompanied by a decrease in base saturation. Bulk density was not altered in soils under continuous sweet potato cultivation. This can be expected as harvesting sweet potato involves topsoil digging with a fork to about 0.2 m depth. No obvious pattern of decline was found in the leaf nutrient concentrations, but the highest concentration of all major nutrients was found in the first cropping season at Hobu (Hartemink *et al.*, 2000b). A decrease in leaf nutrient concentration was expected because large amounts of nutrient are removed with the sweet potato harvest. Considerable amounts of K are removed with the tubers and vines. For Hobu it was found that sweet potato removed about 16 kg N, 7 kg P and 51 kg K ha^{-1} per 10 Mg ha^{-1} of fresh marketable tubers (Hartemink *et al.*, 2000b).

Table 3. Changes in soil chemical properties under continuous sweet potato cultivation (sampling depth 0-0.15m); partly after Hartemink *et al.*, (2000)

Sampling time	pH H_2O	Organic C g kg^{-1}	Total N g kg^{-1}	Olsen P mg kg^{-1}	CEC pH7 $mmol_c$ kg^{-1}	Exchangeable cations $mmol_c$ kg^{-1}			Base saturation %
						Ca	Mg	K	
Before planting	6.2	69.9	6.0	10	405	268	61	12.2	84
After four seasons	5.8	71.3	5.9	6	466	227	59	8.4	63
Difference	$P<0.01$	ns	ns	ns	$P<0.01$	ns	ns	ns	$P<0.001$

Data from fallow experiment; values are the arithmetic mean of four plots

In the fallow and inorganic fertiliser experiment observations were made on nematodes and sweet potato weevils. Nematode counts in soil extracts from the fallow experiment showed that the juvenile population of *Meloidogyne* sp. increased with increasing number of cropping seasons (Table 4). The increase in number of nematodes was significant between the first and second seasons but the number of nematodes in soils did not differ significantly over three or four seasons. Although the species of Meloidogyne could not be identified with certainty common root-knot species under sweet potato in Papua New Guinea are *Meloidogyne incognita* and *Meloidogyne javanica* (Bridge and Page, 1984).

Table 4. Nematode counts (number per 200 mL ±1 SD) in soils under sweet potato (Hartemink *et al.*, 2000b)

Hobu			Unitech		
Cropping season	Sampled plots	Nematodes [1]	Cropping season	Sampled plots	Nematodes [2]
1	12	65 ±52	4	4	1795 ±329
3	4	211 ±73	5	4	1208 ±250
4	4	157 ±52			

[1] root knot nematodes (*Meloidogyne* sp.)
[2] reniform nematodes (*Rotylenchulus reniformis*)

In the fallow experiment, the aboveground population of weevils at harvest was very low for both seasons but a considerable portion of the marketable tubers and vines was damaged (Table 5). Damaged tubers over both seasons were predominantly described as category 1, i.e., only superficial damage to the periderm (Sutherland, 1986). The high level of vine damage was not reflected in tuber damage.

Table 5. Weevil counts and vine and tuber damage in unfertilised sweet potato plots of different age (Hartemink *et al.*, 2000b)

			Tubers		Vines	
Site	Cropping season	Weevil counts no. m^{-2}	Damage %	Life stages per tuber no.	Damage %	Life stages per vine no.
Hobu	3	0.0	78	0.25	52	1.5
	4	0.5	35	5.25	55	0.5
Unitech	4	12.8	0	0	100	3.5
	5	1.1	0	0	100	5.3

values are the average of 4 sampled plots

10.7. Discussion

Sweet potato yields were higher after piper fallows than after gliricidia fallows so there is no yield advantage of employing an improved N-fixing fallow species like gliricidia. The low yield response after the gliricidia fallow is puzzling and yields could have been affected by the high input of N which may decrease yield (Hill *et al.*, 1990; Marti and Mills, 2002). Yields may also be affected by the allelopathic compounds found in gliricidia leaves. Reports from India have shown that applications of 4 to 12 Mg leaf mulch ha^{-1} effectively control weeds (thought to be attributable to phenolic compounds in the gliricidia mulch) (Ramakoorthy and Paliwal, 1993). Alan and Barrantes (1998) showed that extracts from gliricidia leaves drastically reduced the germination of weed species including *Ipomoea* sp. in Costa Rica. It is hard to estimate whether allelopathic effects influenced the sweet potato yield in our experiment although the polyphenolic content of gliricidia leaves was indeed much higher than those in piper or imperata (Hartemink and O'Sullivan, 2001).

The gliricidia fallow produced three times more wood, which is of advantage in the lowland areas where firewood is scarce. The greater biomass of gliricidia could be because gliricidia is better in scavenging the limited nutrients than piper. It is likely that piper suffered from too little water due to the El Niño drought (see Fig. 1) as piper grows faster in wetter periods (Hartemink, 2001). Piper significantly reduced soil moisture which is of advantage in wet seasons as Hartemink *et al.* (2000b) have shown for sweet potato yields which were significantly reduced in wetter seasons regardless of the cropping history of the soil (see also Table 5).

Sweet potato tuber yields after imperata fallow were comparable to those after the woody fallows i.e. piper, gliricidia. However, imperata biomass returned less N to the soil and vine biomass was lower due to the slow decomposition of the biomass and the N immobilisation (Hartemink and O'Sullivan, 2001). The reduced vine yield after the imperata fallow did not result in higher tuber yield even though vine and tuber yields are often inversely related (Enyi, 1977). A significant yield reduction of sweet potato when more than 10 Mg ha^{-1} was applied was found by Kamara and Lahai (1997). The yield reduction was attributed to the low C/N ratio of the mulch resulting in poor mineralisation and immobilisation of N. It has been suggested that imperata biomass has phytotoxic properties (Kamara and Lahai, 1997).

The experiment has shown that short term fallows with piper and imperata gave slightly higher sweet potato yields than with gliricidia. From a nutrient perspective, however, gliricidia fallows are probably more effective but additional research in nutrient budgets is required before a final assessment can be made on the sustainability of short term fallows.

The inorganic fertiliser and poultry litter experiments have shown that sweet potato responded to N fertiliser, which confirms other research in Papua New Guinea (Bourke, 1985a; Bourke, 1985b; O'Sullivan *et al.*, 1997). The highest yields are obtained with applications of when 100 kg N ha^{-1}. However, the response was mostly recorded in the first season after the fallow and subsequent seasons gave inconsistent results. The response to nutrient inputs is, however, much affected by other factors like rainfall, number of cropping seasons and pests and diseases.

Table 6. Ranking of 10 highest and lowest marketable sweet potato yields observed in all nutrient management experiments at Hobu

Rank	Yield Mg ha^{-1}	Experiment	Treatment	Season	Rainfall during season in mm
10 highest	26.7	Pl	100 kg N ha^{-1} as inorganic fertiliser	First	1,203
yields	24.7	If	Unfertilised	Second	1,034
	23.8	If	100 kg N ha^{-1} no K	First	1,028
	23.5	If	100 kg N ha^{-1} 50 kg K ha^{-1}	First	1,028
	23.3	If	150 kg N ha^{-1} no K	First	1,028
	22.7	If	50 kg N ha^{-1} no K	First	1,028
	21.9	Pl	100 kg N ha^{-1} as poultry litter	First	1,203
	21.7	If	no N 50 kg K ha^{-1}	Second	1,034
	21.5	If	100 kg N ha^{-1} no K	Second	1,034
	21.3	If	50 kg N ha^{-1} 50 kg K ha^{-1}	First	1,028
10 lowest	2.6	If	150 kg N ha^{-1} no K	Third	2,214
yields	2.7	If	150 kg N ha^{-1} 50 kg K ha^{-1}	Third	2,214
	2.9	If	50 kg N ha^{-1} 50 kg K ha^{-1}	Third	2,214
	5.2	If	50 kg N ha^{-1} no K	Third	2,214
	5.6	If	100 kg N ha^{-1} 50 kg K ha^{-1}	Third	2,214
	5.8	If	100 kg N ha^{-1} no K	Third	2,214
	6.0	If	no N 50 kg K ha^{-1}	Third	2,214
	6.8	Pl	50 kg N ha^{-1} as poultry litter	Second	2,091
	6.9	If	Unfertilised	Third	2,214
	7.3	Pl	100 kg N ha^{-1} as inorganic fertiliser	Second	2,091

Pl - Poultry litter; If - Inorganic fertiliser

The question arises as to the best treatment to sustain and improve sweet potato yield in the Hobu area. Table 6 presents the 10 highest and lowest yields from all the experiments. These are average yields for a treatment since variation between plots was large. Some plots had very high marketable tuber yields (up to 39 Mg ha^{-1}) whereas some plots yielded below 20 Mg marketable tubers ha^{-1}. The table clearly shows that most of the highest yields are found in the first and second season after the fallow and when seasonal rainfall was about 1,000 to 1,200 mm. The lowest yields were recorded in the third season after the fallow when the seasonal rainfall exceeded 2,000 mm. Most importantly the table shows that none of the fallow treatments occur in either the highest or lowest yield ranking. Apparently using fallows is the safest way to obtain steady sweet potato yields whereas with extra inputs through inorganic fertiliser or poultry litter yields may be strongly increased or decreased.

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Part IV
Socio-economic effects

Chapter 11

Siges, T.H., A.E. Hartemink, P. Hebinck and B.J. Allen, 2005. The invasive shrub *Piper aduncum* and rural livelihoods in the Finschhafen area of Papua New Guinea. Human Ecology, 33: 875-893.

11. The invasive shrub *Piper aduncum* and rural livelihoods in the Finschhafen area of Papua New Guinea *

Abstract

In many parts of the world exotic plants have invaded natural ecosystems and are regarded as a threat for global biodiversity. Several studies have focussed on the effects of invasive plants on ecosystem functioning or eradication and control programmes. Virtually no studies have looked at the socio-economic effects. The effects of *Piper aduncum* invasion on rural livelihoods was investigated in three villages in Papua New Guinea. In the study area, *Piper aduncum* was first described in the 1930s but it now dominates the secondary fallow vegetation and has locally formed monospecific stands. In total, 27 in-depth interviews were held on how the villagers perceive and use *Piper aduncum*. In combination with detailed field observations a comprehensive picture emerged about the effect of *Piper aduncum* on people's ways of life. The tree and its products (stems, leaves, mulch, ashes) are used in farm practices, in the household and the plant is used for medicinal applications. The invasion and dominance of piper has also some negative effects but that is mainly related to the destruction of the natural forest and the loss of natural secondary fallow vegetation. In conclusion, villagers found several new uses for piper and its products so it became both a resource to which they were forced - but which they also chose to use. It is suggested that control programmes for invasive plants should take into account the adaptation of the plants and its effects on rural livelihood strategies.

11.1. Introduction

Bioinvasion is recognised as an important component of the global biodiversity crisis, which contains, amongst other things, a loss of species and habitats. Some have argued that bioinvasion is a greater threat than the greenhouse effect, industrial pollution or ozone depletion (Mack *et al.*, 2001). An understanding of the causes and spread of bioinvasive species is needed to assess the economic and ecological impacts.

In Papua New Guinea, which is regarded as hot spot of biodiversity, several aquatic and terrestrial plants have invaded (Orapa, 2001). The shrub

* Siges, T.H., A.E. Hartemink, P. Hebinck and B.J. Allen, 2005. The invasive shrub *Piper aduncum* and rural livelihoods in the Finschhafen area of Papua New Guinea. Human Ecology, 33: 875-893.

Piper aduncum (L) has invaded the humid lowlands and locally dominates the fallow vegetation, mainly in the Morobe and Madang Provinces. It is not known when and how *Piper aduncum* arrived in Papua New Guinea but it is likely that seeds were introduced by accident from Papua (Irian Jaya) or perhaps from Fiji where it was introduced in the 1920s (Hartemink, 2001). The botanist Mary Clemens first observed *Piper aduncum* (hereafter referred to as piper) in 1935 in the Morobe Province. It was not very widespread in the early 1970s and is not listed in the standard text on New Guinea vegetation (Paijmans, 1976). However, by the late 1990s piper was very common in the lowlands of the Morobe and Madang Provinces, and was observed in the Central Highlands above 2,000 m a.s.l. (Rogers and Hartemink, 2000) and in Bougainville a large island (Waterhouse, 2003). Causes for its rapid spread remain unclear but evidence is being accumulated that areas of high native plant species richness and cover, like many areas in Papua New Guinea, and areas high in soil fertility, may be highly invasible (Stohlgren *et al.*, 1999). Leps *et al.* (2002) explains the successful invasion of *Piper aduncum* in Papua New Guinea as being caused by piper having a large native geographic range, the ability to aggressively colonize disturbed habitats such as fallow gardens, a short juvenile period and relatively small seeds that are produced in large quantities every year. Recent research has also shown that the aggressive invasion of *Piper aduncum* in early fallow successions vegetation is not explained by a competitive advantage resulting from a low herbivore load (Novotny, 2003).

The invasion of piper appears to be similar to the spread of *Chromolaena odorata* in Asia and parts of West Africa (McFadyen and Skarratt, 1996) or to the invasion of *Miconia calvescens,* in the Society Islands of the Pacific where it was introduced as an ornamental but is now a major pest (Meyer, 1996) and is nicknamed the "green cancer" (Stone, 1999).

Piper is a low tree with alternate leaves and spiky flowers and fruits. It occasionally reaches a height of 7 to 8 m, and has very small seeds, which are mostly dispersed by the wind, fruit bats and birds (Bonaccorso *et al.*, 2002; Kidd, 1997). Piper is common throughout Central America where it occurs between sea level and 2,000 m a.s.l. along roadsides and in forest clearance areas, on well-drained soils. It occurs in Mexico, Central America, Surinam, Cuba, Southern Florida, Trinidad and Tobago, and Jamaica and is very common in Costa Rica on open or partly shaded sites (Burger, 1971).

In Papua New Guinea, research on piper has focussed on biomass and nutrient accumulation (Hartemink, 2001; Hartemink, 2004), leaf litter dynamics (Hartemink and O'Sullivan, 2001) and the effects on soils and crops (Hartemink, 2003; Hartemink, 2003). Virtual nothing is known of the socio-economic effects of the invasion and how it affects the livelihoods of rural people. Studies in South America have shown that extracts of piper are used as folk medicine. The species is mentioned in several ethnopharmalogical databases, and has antifungal and antibacterial compounds (Nair and Burke, 1990). In their survey of the Morobe Province of Papua New Guinea, Holdsworth and Damas (1986) noted that new *Piper aduncum* leaves are crushed and rubbed into fresh cuts and the treatment was repeated daily.

This study explores how piper affects rural livelihoods in the Finschhafen area in Papua New Guinea. In this area, which is close to the place where piper was first observed in the 1930s, it is common (Bourke *et al.*, 2002). The study combined qualitative fieldwork in three villages with some existing literature on *Piper aduncum*. Observations in people's fields and interviews with men and women were used to analyse the relationship between the spread of piper and people's livelihoods. In total 27 in-depth interviews were held, combined with a similar number of field observations. The studies aims were to (1) find out how people use piper; and (2) find out what implications piper has on their livelihood. Fieldwork was conducted between July and November 2003 by Thomas Siges who originates from the area. The research was undertaken as part of Siges' graduate study at Wageningen University; The Netherlands Alfred Hartemink initiated the research and supervised it jointly with Paul Hebinck whereas Bryant Allen was involved in the write-up of the results and discussion.

11.2. Study area

The fieldwork for this study was conducted in three villages in Pindiu area in the Finschhafen District of Papua New Guinea. The villages were Sanangac (147°31' E, 6°27'S), Sanzeng (147°31' E, 6°27'S) and Tongucboc (147°28' E, 6°28'S). These villages were chosen because piper is very common in the area (Bourke *et al.*, 2002), and it is an area where the first author could speak the indigenous language and as a local person himself, could quickly gain acceptance.

Sanangac and Sanzeng village (ca. 730 m a.s.l.) are about 2 km apart whereas Tongucboc village (995 m a.s.l.) is about 3 km south from Sanzeng. The topography in the study area includes the flat valley of Doi, which extends from the Sanzeng River to the periphery of the Sanangac village. Doi valley is viewed as ideal land for agriculture by Sanzeng and Sanangac people. Tongucboc village is in hillier terrain. The three villages have reasonable access to the district centre Finschhafen. The three villages are located in the same agro-ecological zone and have very similar agricultural systems. Construction of soil retention barriers on cultivated slopes is characteristic for the Pindiu area (Bourke *et al.*, 2002).The region has a population density of about 26 people km^{-2} on land used for agriculture, including land in fallow.

The villages

The three villages are described with a view to contextualising rural people's lives and their livelihoods. The villages differ only slightly from each other in terms of rural livelihoods, and the timing and the degree of the spread of piper is not exactly known. Piper is very common in the area. Because the three villages are in a similar agro-ecological zone it is possible to carry out a comparative analysis of the use of and reactions to piper and to make an assessment of the factors that may account for differences between the villages in these matters.

The farmers in the three villages live at different distances from the primary forest. Common to the three villages is that land belongs to kin-based groups, known as a 'clans'. Families are given usufruct rights to land for individual use and clan leaders, who are also the family heads, administer these rights. Piper, and its by-products, is considered as both a private and an open-access resource. If piper grows in people's fields (cultivated and fallow) it belongs to them; if it grows in the forest, then anyone can access and use it. Local councillors and clan leaders are not involved in the decision making in relation to piper.

Land use intensity in the area is low (Ruthenberg's R=25) (Ruthenberg, 1980) and slightly differs between the three villages. Two agricultural subsystems were observed in this area. In the first, which occupied most of the area; new gardens are cleared annually from low woody regrowth fallows, between 4 and 6 years old. All vegetation is cut down and burned. The most important crop is sweet potato (*Ipomoea batatas*) but sometimes taro (*Colocasia esculenta*) is planted first and sweet potato is a second planting. Chinese taro (*Xanthosoma sagittifolium*) is cultivated around the edges of gardens. Land is tilled and sweet potato is planted in 30 cm high mounds formed from topsoil. In the second subsystem, which occupies about 20% of the land area, gardens are cleared from tall woody regrowth fallows over 15 years old. Fallow vegetation is cut down and usually but not always burned. Chinese taro and bananas are planted. Although only one planting is made, Chinese taro and bananas continue to produce harvests for over 3 years. These gardens are not tilled (Bourke *et al.*, 2002). This pattern of land use means that about 80% of the cultivated land is cleared, burned and cultivated every six years and about 20% every 15 to 20 years. The first subsystem is almost certainly gradually spreading at the expense of the longer cycle second subsystem. Fallow regrowth is largely a result of natural processes and is not deliberately interfered with by people.

Village houses are similar in all three villages and are constructed from local materials. Houses accommodate one family with five to six members. The houses are small, rectangular and single-roomed, and are built on wooden posts, about one meter above the ground. The walls are made from wooden planks or split bamboo woven artistically with intricate patterns, which are nailed to the light wooden frame of the building. Roofs are constructed from triangular frames of light wooden sticks, thatched Sanangac and Sanzeng villages with either bamboo leaves or sago palm (*Metroxylon* spp.) leaves and in Tongucboc village with grass (*Imperata cylindrica*). The floors of all the houses are constructed with long and straight wooden sticks, which are laid across and fastened with rattans. Split bamboos are laid on top of the wooden sticks. A fireplace is made in the centre of the room from a wooden box that is filled with stones and clay and smoke exits through the roof. The house normally has one or two small, shuttered windows. . In Sanangac and Sanzeng villages, except for the posts, most of the wood used for building houses is piper, but in Tongucboc wood from native species predominates.

Sanangac village

About 300 people live in Sanangac but only 150 people lived there permanently in 2003; the rest have migrated to work in urban areas or have moved to newly settled rural areas. The village had 30 houses, surrounding a central open space used for community gatherings. Bank, postal services and schools are about a one-hour walk distance from the village at Pindiu government station. The deteriorated gravel road that connects Pindiu to Finschhafen passes near the village enabling the government and other public passenger vehicles to provide goods and services to the village in dry weather. In wet weather, the village is difficult to reach by road.

People in Sanangac are farmers but most have other income generating activities such as marketing and casual labour in town. Most families cultivate 500 to 1,000 coffee (*Coffea arabica*) trees and up to 200 vanilla plants (*Vanilla fragrans*). Until recently, the sale of parchment coffee has been the main source of income with supplementary incomes from local sales of peanuts (*Arachis hypogaea*), fresh vegetables, livestock, betel nut (*Areca catechu*) and rice. Recently, vanilla briefly replaced coffee as the biggest income earner international prices boomed for 3 to 4 years, consequent on a failure of production in Madagascar.

People say piper first appeared in this area in the early 1950s. It gradually spread until today it has colonised much of the fallow garden areas. In some places piper completely dominates the fallow vegetation. It was estimated that only 30% of the village land remains in primary forest with the remaining 70% under secondary forest vegetation or cultivation. Of this 70% land in use, around three-quarters is cultivated one-quarter is fallow. On much of the land cultivated since the 1970s, fallow vegetation is dominated by piper. A vanilla farmer described the changes as follows:

"Our forefathers cut a lot of forest trees down to make gardens in the past. All the forest and its services are gone, together with the wild animals. We only see what forest is like from the pictures in the magazines or books. Piper has become our new environment."

Sanzeng village

About 250 people live and work in Sanzeng village permanently; others live and work in the urban areas or have migrated to other villages. Sanzeng, like Sanangac, lies close to poorly maintained gravel road that connects Pindiu to Finschhafen, but is closer to Pindiu than Sanangac. Access to services like banks, postal services and schools is similar to Sanangac village. In terms of livelihoods, Sanzeng is similar to Sanangac village except that piper *is* sold as firewood to government officers in Pindiu.

People say that piper was first brought to Sanzeng village Timbulim on the coast. Fifty years later, piper occupies almost the entire land area of Sanzeng. It has replaced almost all the previous secondary vegetation. At Sanzeng less than 10% of the land area is primary forest, which is restricted to the top of crest of highest hills. Of the 90 % of land area in use, about 70% of the area is fallow and 30% under cultivation.

Tongucboc village

The village is smaller than the other two villages and has a population of 100. The population structure appears to be younger. There are 20 houses. A number of people have migrated to other parts of the district. Within the village land, people are scattered in small hamlets leaving the main village with only eight houses. Banks, postal and health services and schools are about 2 hours walk from the village.

Like Sanangac and Sanzeng, people grow coffee and peanuts as cash crops. Families own around 500 coffee trees. Many have recently planted vanilla. A few people keep pigs for sale and some make money from selling wild fowl eggs and the sale fur, meat and skin from hunted game. Two men make handles of tools from forest hardwoods and sell them at the local market. Betel nut is another source of income.

According to the villagers piper was brought to this area in 1946 as an ornamental plant and as a source of firewood. Piper is currently seen in small patches as understory in gaps in the secondary forest. It was estimated that primary forest covers about 60% of the total land area, 30% is under fallow successions and about 10% is under cultivation. Fallow vegetation is dominated by piper. Clan leaders have imposed restrictions on felling primary forest and tall secondary forest; so all farmers cultivate lands in the secondary forest areas

11.3. Fieldwork and data collection

The selection of informants followed a purposeful sampling technique, a procedure that is often used in exploratory investigations (Poate and Daplyn, 1993). Snowball sampling was applied to select people within each village (Russel Bernard, 1994). In Sanangac, older men and women whom could speak about piper were interviewed. The men were interviewed separately from their wives. This was necessary because it is common that women are supposed to keep silent when men communicate with visitors. In Sanzeng village, an open village meeting was held first and then people were questioned individually. In Tongucboc, many villagers wanted to say something about piper so many spontaneously came and told stories and gave their opinions about piper.

In each village, 9 villagers were interviewed and some 6 to 7 detailed field observations were made. In this way, various accounts were collected that contain people's views on piper, its history in their village and whether and how they use it. Villagers are able to provide through these narratives, a map of the social consequences of the piper invasion and its present dominance. An interview guide was prepared to make sure that in all the three villages similar topics were covered. The interview guide was pre-tested in three other villages in Finschhafen District (Torecko, Heldsbach, and Siki) by randomly interviewing 12 people. This pre-testing phase also enabled us to trace part of the history of the introduction and spread of piper in Finschhafen and other districts. The interviews were conducted by the first author in the local language and Pidgin, which are nowadays used interchangeably in everyday conversation. A tape recorder was not used but handwritten notes were typed up after the interviews.

11.4. The use of *Piper aduncum*

The villagers use piper in three ways: (i) in agriculture (farm use), (ii) in and around the house, and (iii) in medicinal applications, and each of these uses is described in this section. Villagers in the area have found different uses for all parts of the piper plant and in general they favour it. However, the villagers also indicated there are negative aspects associated with the invasion of piper.

11.5. Farm use

The most valued parts of the piper tree for use in agriculture are the stems, the roots and the ashes from burned wood and leaves. There is a difference in the use of piper by men and women (Table I). Men mostly use piper stems and roots while women tend to use the ashes as pesticide in the food gardens. Older people and women prefer the tree for fence constructions or for other farms use because it is locally available and the wood is soft. Younger and more active men who are able to travel longer distances and carry heavier loads, fetch harder wood from the forests, because they longer than piper when used in fences. Each of the main uses is discussed briefly below.

Table 1. Summary of the main uses of *Piper aduncum* in the three villages of the Finschhafen area of Papua New Guinea

Plant part	Products or Services	Users
Live trees	Shade for the pig	-
	Windbreaks	All
	Weed control	All
Mature Stems	Used as digging stick	Men
Stems and branches	Build soil retention structures	Men
Stems, stumps and branches	Staking crops	Men
Stems	Making new fences	Men
	Maintain fences	*Men*
	Used as pegs	Men
	Build chicken houses	Men
	Coffee and Vanilla Platforms	Men
	Handles for tools	Men and Woman
Roots	Makes soil tillage easier	All
Ashes	Pesticides	Women
	Fertiliser for the soil	Women

Most villagers till the soil with hand tools before new crops are planted. Several steps usually precede tillage. A young farmer from Tongucboc explained the steps as follows:

"The first thing before I select the land for my farm, I survey the area to see if the vegetation is covered by piper. Everyone in the village does that because the vegetation under piper is light and so it is easy to clear the place quickly with fewer difficulties. After all the vegetation is slashed, the last task is to fell the piper trees. Not all trees are cut down. I leave few trees standing which can be used later for the staking of yams or sugar cane. I just pollard them. Leaves and branches from the felled trees are stripped off and spread out equally and evenly around the garden and the piper stems are either grouped in upright positions against any remaining unfelled stems to dry or piled at the sides of the cleared area. The cleared area is left to dry for about 3 or 4 weeks depending on the weather. When it is dry I burn the dry vegetation starting from one end of the garden. I then wait at least a day before I rake the debris together and burn the rubbish in small heaps, known as "qago". ("Qago" is made out where specific crops like banana and yams will be planted in the ashes. Dry piper branches or stems and bamboos make good materials for "qago". The soil is now ready for tillage, which is done with the help of my family members or by myself depending on the size of the clearing. I normally choose piper dominated areas for farming as the tree roots break up the soil and make it easier to till and also the roots of the trees are easier to remove than those trees from the jungle".

This account summarises what many farmers told us. People till the soil with hand tools like digging sticks, hoes, forks and spades, so areas where the soil is lighter are preferred and the deeper rooting systems of secondary forest areas are avoided. Tillage is unusual in PNG shifting cultivation systems and its practise here may be an important factor in the rapid spread of piper. Piper enables women to prepare land for cultivation because it does not require the heavier work that it takes to clear local woody fallow species.

Soil erosion control

The majority of the respondents use piper stems to build soil retention structures that take the form of narrow terraces. Felled dry branches are cut to a length of 1 to 2 m and pushed into the soils in a fence-like-pattern roughly along the contour in garden. The structures are fastened with ropes so that it can sustain the weight of the debris such as soil, stones, roots and branches. Men usually do this before the soil is tilled. Prior to the invasion of piper cane and other grasses were planted on the contour.

Allen *et al.* (2002) describe migrants from Finschhafen District using piper to make terraces for subsistence sweet potato growing on the Sogeri Plateau, inland of Port Moresby. At Sogeri, piper stems that had been pushed vertically into the soil along the front edge of the narrow terraces were striking, creating rows of piper trees across previously Imperata grass covered hillsides. Highlands's migrants living nearby had not adopted this practice.

Fences and stakes

More than half of the people in Sanangac and Sanzeng said that piper stems were very useful for constructing fences to keep feral and domesticated pigs out of gardens Both dry and newly cut piper stems were used. In Sanangac, farmers used dry stems in new and existing fences. On several occasions, it was observed that some piper plants would be left growing inside the fences. This was to provide shade for domestic pigs who are sometimes allowed into gardens post harvest; it was also mentioned that pigs eat piper. Piper stems were also used for staking sugar cane, pitpit (*Saccharum edule*) and bananas. Women and children collect the stakes for firewood after the crops have been harvested.

Digging sticks and tool handles

Mature stems of piper are used as digging sticks to plant root crops like *Xanthosoma sp*. They are also used in stony soils where farmers do not want to damage their iron tools. Fresh piper stems are used because they are heavier and stronger. Piper stems are used as handles for tools such as rakes, hoes and spades in Sanangac and Sanzeng, but not in Tongucboc where two specialist craftsmen make all types of tool handles from forest hardwoods.

Other uses
Piper stems are also used as pegs for marking out new fields. This was observed in a newly developed cocoa plot at Heldsbach, near Finschhafen, and at Sanzeng, where piper was used as pegs and then as support, for vanilla plants. Villagers near Heldsbach used piper stems to remove the husk from dry coconuts. They were also used in the construction of chicken houses and for building raised platforms for drying copra, vanilla and coffee. Live trees were used for windbreaks.

11.6. Household use

Various parts of the plants are used in and around the house particularly by women who now prefer piper to other tree species.

Construction of fences and boundary markers
Piper stems were used as small protective fences for flower gardens near houses and to keep village chickens and children from trampling the flowers. Piper stems laid lengthwise along the ground served as markers to indicate the field boundaries shared between clan members or neighbouring clans.

Poles and rafters for buildings
Stems of mature piper were widely used as framing for houses at Sanangac and Sanzeng but not at Tongucboc where very few people used piper for building. Straight and mature piper stems were selected and felled and the desired portions were cut off and the bark removed. The stems were placed in a vertical position for several days to dry, and were then transported to the construction sites. Men normally prepared the stems but woman and children helped to carry them to the building site. There were disparities in the views in Sanangac on the usefulness of piper stems as house frames. Some men argued that piper rots easily compared to hardwood from the forest. Its wide use as framing is possibly related to its ability to resist ants and termites.

Uses as fire wood/fire stick
Cooking food was done over an open fire, usually indoors. Firewood and its collection played an important role in daily life. Dry piper wood was preferred over indigenous trees by many people. A man summarised this as follows:

"We prefer piper as it does not produce as much smoke inside the house, it cooks our food quickly and also it is a soft tree which women and children can chop and carry home. It is not heavy like other trees in the forest. If you walk long distances to the bush or distant gardens, you can carry a fire stick that will burn until you reach that place. We prefer piper wood for such characteristics."

Another man from Sanzeng village said:
"Men and women like this tree as it is easy to chop with bush knives and to break with our hands. The trunk of the tree is usually straight and small and that is why women and children can easily chop and carry it. Once in a while, policemen and governments officials working at the station request us to bring firewood to them for cash, clothes or food."

Piper has become an important source for domestic firewood and as a source of cash or trade at Sanzeng, because of its proximity to the government station at Pindiu.

Other household uses
Young leaves of the piper were used for cleaning household utensils together with ashes from the fireplace. Young leaves of piper were also placed at pit toilet houses. The leaves were picked a few days previously because fresh leaves are uncomfortable to use. In the past the people used the leaves of a flowering plant for this purpose. These flowers were grown near the toilets and picked them when they were on their way to the toilet. Not many villagers were keen to talk about this.

Piper plant parts appear to have a number of medicinal properties (Table II below provides a summary of the uses in the three villages). Extracts from leaves, bark and roots were reported to heal some sicknesses and diseases. A few villagers also indicated that a preparation from piper leaves will kill leeches and that leeches have almost disappeared from areas where piper has become dominant in the secondary forest. Treatment of cuts with piper was widely used and a man explained this as follows:

"One day I was planting taro and a sharp bamboo cut my foot. It was a deep cut and I lost much blood. I scraped the bark of piper and squeezed the sap on to the cut. The blood clotted very quickly. Later I dressed the cut with piper leaves. I did not visit the hospital. I waited about a month before the sore healed to an extent where I could walk around. At that point, I realised that piper is a good medicine."

In the three villages, medicinal knowledge of the piper is usually shared only with close family members or associates. The villagers are not sure whether the piper medicine will work for others and that makes them reluctant to advocate its use to others. Due to the prestige accorded to modern medicine, discoveries such as medicinal uses of piper are regarded by villagers as relatively unimportant.

Most villagers have learned about the medicinal properties of piper by trial and error. A man from Sanangac used it for stomach ache and when asked why he took the risk and tried it, he replied:

"I have a dog and every time I passed through an area of piper she would eat the fallen fruits. When I first saw this I did not think about it but suddenly I witnessed some changes in my dog. You know when dogs are sick in the stomach they pass out bad smells from their anus. It is then that the dog ate the fallen piper fruits. After several observations on my dog, I got curious and tried it on myself by digging the roots of the plant and use its extracts to stop my stomach-ache. The relief was instant. I never have this problem anymore, but I have told nobody. I only told few family members about my discovery".

Table 2. Plants part and medicinal use of *Piper aduncum* in the three villages of the Finschhafen area of Papua New Guinea

Plant parts used	Maladies
Extracts from fresh leaves, bark and roots	New cuts to the body
Extracts from the bark and fruits	Tooth-ache
Extracts from fresh barks and roots	Diarrhoea, Dysentery ,Cough
Fresh bark extracts used with lime	Fungal infections (grille)
Extracts from fresh leaves	Insect bites (centipedes, Bees and leeches)
Extracts from the leaves	Dressing sore
Juice extracted from the fresh stem	Head-ache
Extracts from the fresh marks and leaves	Scabies
Extracts from the fresh roots	Stomach – ache (pain)

11.7. Other effects

There are several other aspects of the piper invasion that people reported during the interviews.

Loss of forest and timber products

Forest products refer to timber and non-timber products that are collected from the primary and secondary forest. Some people expressed concern that products they were able to collect from the forest in the past, are not available since the invasion of piper.

In Sanzeng and Sanangac villages, older people could compare the situation before and after the invasion of piper. They argue that the regeneration of the indigenous forest was disturbed by the fast growth of piper. As a result, useful trees for building houses disappeared. A particularly hard felt loss was trees used for making planks. Men also spoke of trees that were used for rafters, poles, posts and other smaller parts of houses, which have been replaced by piper stems. In Tongucboc, a clan leader has made a rule that no forest can be cut unnecessarily. Although Tongucboc land has a larger area of forest than the other two villages, people there still expressed their concern at the decreasing supply of forest products. In Sanangac and Sanzeng the loss of some species has forced villagers to adopt woven bamboo for walls instead of plank walls.

Loss of non-timber products from the forest

Wild fowl eggs are another product no longer harvested from the secondary forest. Rattans that men collected for fastening fences and houses are also no long easily found. Both fowl eggs and rattans are absent under piper and have become scarce, particularly in Sanzeng and Sanangac villages. Wild animals like cassowary, pigs and other small animals do not live in piper dominated fallows.

Older women reminisced about particular trees that produced mushrooms: An older woman told how they would go through the forest and collect the mushrooms:

"In the past Sanzeng was covered with secondary forest where we could harvest mushrooms like Kinge, Gulu and Siula. Siula is still collected today but the others have disappeared. Today lots of young people do not know about these mushrooms."

Effects on food production

There were conflicting views on the effect of piper on food production. According to people at Sanangac and Tongucboc, root crops like Chinese taro are less productive than before. But at Sanzeng, people said that Chinese taro will yield well if some piper trees are left in the middle of the fields and occasionally coppiced to generate mulch for the crop. Taro (*Colocasia esculenta*) yields are said to have decreased in areas where the piper has become dominant and some farmers have given up growing taro and local yam varieties.

Other men said that before the invasion and dominance of piper, their staple diet consisted of Chinese taro (*Xanthosoma sagittifolium*), taro (*Colocasia esculenta*), yam (*Dioscorea spp*) and to a lesser extent sweet potatoes (*Ipomoea batatas*). Gradually, they have switched to sweet potato as a staple crop because it grows so well after a piper fallow. This change from taro to sweet potato has also been observed in many other areas where piper is not dominant, so it may not be a consequent of the piper invasion at Finschhafen, but more a broader outcome of shorter fallows and lowered soil fertility (see for example Bourke, 1992).

Effects on social or community life

The dispersion of the large village into smaller and more isolated hamlets has been indirectly associated with the spread of piper. Piper makes it easy to clear new areas to construct settlements and the establishment of small hamlets in the three In Sanangac, there were three such hamlets, Sanzeng had two and Tongucboc two. These breakaway communities are usually made up of close family members. Elsewhere in PNG, fears of interfamily conflict and jealousies create pressures for large settlements to disperse and the introduction of piper appears to have facilitated a desire that was previously more difficult to satisfy because a small family unit did not have sufficient labour to clear well developed secondary forest.

Effects on social or community life

Several villagers expressed mixed feelings about the influence of piper on the existence of bush spirits. These often malicious spirits lived in small waterholes in difficult to access areas in the forest. They are commonly mythically associated with the origins of humans and many domesticated plants and animals. People believe that they will get sick and die they trespass on places where these spirits are said to live. . A villager from Tongucboc explained how the introduction of piper had affected these human-spirit relationships:

"That place called Wiri Sungurungu used to be a masalai [spirit] place. People would get sick and die if they went there. We would protect ourselves with magic and insert a piece of special vine in our hair when we went there. When piper took over, after people made gardens and disturbed the nearby forests, the spirits may have fled. Today even the children can go there without fear of being harm".

People have long forgotten the special protective charms but they can still identify the special protective vines. These bush spirit sites are integral part of the traditional knowledge systems In Sanzeng and Sanangac village, most bush spirit sites were reported to be rendered useless, but in Tongucboc, at least one such bush-spirit site still exists. The influence of mission teaching, which discourages such beliefs, on the continued existence of these creatures, is not known.

11.8. Discussion

The shrub *Piper aduncum* is not indigenous in Papua New. Although the exact period of introduction remains unknown the species was not very widespread in the 1970s, but currently it is the dominant fallow vegetation in Morobe and Madang Provinces. It is also important in part of the highlands, and in the island of Bougainville. In this study, it was found that although piper had been in the area less than 50 years, villagers used it in many different ways. In the three villages, the tree had significantly influenced livelihoods. Villagers appreciated the usefulness of piper although the uses differed slightly in the three villages (Table 3). It had also some unfavourable aspects. This discussion focuses on the main effects of piper on the livelihoods of rural people and how these effects were brought about. It should be stressed that there are particular aspects of the piper that raise concern, which makes it difficult to generalise about the generic usefulness of piper or other bioinvasive plants.

Table 3. The significance of *Piper aduncum* uses in three villages in the Finschhafen area in Papua New Guinea

	Sanangac	Sanzeng	Tongucboc
Farm uses			
Digging stick	XXX	X	-
making fences	XXX	XXX	XX
Stakes	XXX	XXX	XX
Pegs	XX	X	-
Tool handles	XX	XX	X
Soil retention structures	XXX	XXX	XXX
Shade	XX	XXX	X
Helps tillage	XXX	XXX	XX
Good fertilizer	XXX	XX	X
Burn debris	XXX	XXX	XXX
Weed control	XXX	X	X
Household uses			
Cleaning stains on cooking utensils	XXX	XXX	XXX
Temporary platforms for resting	X	X	X
Ashes used as insecticide	X	X	XX
Leaves used as toilet tissues	XXX	XXX	X
Walking stick	X	X	X
Fire stick	XXX	XXX	XXX
Fuel wood	XXX	XXX	XXX
Rafters for houses	XXX	XXX	X
Poles for buildings	XX	X	-
Cleaning stains on teeth	XX	X	XX
Plant support	XXX	XXX	XX
Sticks for flower bed fences	X	X	X
Making temporary ladders	XX	X	-
Services			
Attracts wild animals	XX	XXX	XX
Improves soil fertility	X	XX	X
Dries of waterlogged soils	X	X	X
Provides shades	XX	XXX	X
Chases away the leech	X	XX	X
Host to other useful plants	-	X	-
Good sweet potato yield in short fallow	XXX	XX	XX
Provides wind breaks	XX	XX	XX

X: Rarely used; XX: Often used; XXX: Very often used; (-): Not used

In part, villagers were forced to use piper because it had out- competed and replaced indigenous trees in the fallow vegetation successions. It had direct effects on the soil and on successive crops after a fallow, but had also some indirect effects. In field experiments, it was observed that piper had significantly higher growth rates than other common fallow species in lowland Papua New Guinea (Hartemink, 2001; Hartemink, 2004) and such characteristics influence its use. Several farmers mentioned that soils after piper fallows are easier to till and this is likely related to the fact that soils after piper fallows contain less moisture (Hartemink, 2003).

Some farmers indicated that crop yields are lower after piper fallows but that was not a universal observation and it is not supported by the limited data in the agronomic literature (Hartemink, 2003; Hartemink, 2003). Yield decline and changes in cropping patterns (e.g. from taro and yam to sweet potato) is related to a range of factors affected by the population increases and the higher yields per unit area of sweet potato systems (Allen, 2001; Allen *et al.*, 1995). Thus there is some mismatch between what farmers observe and what has been concluded from experimental data. Such differences in perceptions are not uncommon (Bouma, 1993). In this case the decline in yields (and crop switching) is caused by a shortening of fallow times, which has coincided with the invasion of piper and people have blamed the more obvious change of fallow species in the landscape, rather than the more insidious decline in soil fertility.

Villagers had also found several new uses for piper and its products so it became both a resource which they were to some extent forced to use, as well as one they chose to use. Examples that include new uses are processed leaves and stems used as medicines for various maladies. Although there is a small body of literature that indicates the usefulness of *Piper aduncum* for medicinal purposes (Maia *et al.*, 1998; Nair and Burke, 1990) and the species appears in various ethno-pharmacological databases, it is interesting how quickly people have discovered these uses, especially as they appear reluctant to tell non-family members about these properties of the plant.

Villagers have adapted quickly to the changes brought about by piper to their natural environment. Issues of governance, the nature of institutional relations defining access to natural resources, which in many parts of the world restrict both use and access, do not occur in Papua New Guinea with regard to piper. In the study area, the tree has been defined as a common property resource that is freely accessible in the fallow land. Nor do restrictive gender relations impinge on the use of piper. In some cases the piper provided alternative sources of cash for women. These institutional dimensions of piper have contributed to the positive evaluation of the plant made by the villagers. Such a conclusion warrants the observation that piper has brought new opportunities for rural people in Papua New Guinea. There was some difference in the use and the appreciation of piper by men and women and that is probably related to household task related issues. Women praise the applications of piper in and around the homes of people.

The invasion and dominance of piper has also had some negative effects on rural livelihoods in the study area. These are mainly related to the loss of primary forest and the replacement of indigenous secondary fallow vegetation successions with one dominated by piper. There is disintegration of social cohesion that people have associated with piper, the vanishing bush-spirit sites, the disappearance of certain forest products and the destruction of the natural forest. These changes would probably have occurred, with or without piper. It is unlikely that piper was the primary cause of cultivated land reaching bush-spirit sites that were once deep in the primary forest. But piper has become associated with fallows and is forming a monospecific single fallow succession, very different to the previous species rich, secondary forest successions that dominated these landscapes, so people associated with it the loss of the bush-spirit sites, rather than population pressure on land. The villagers in Sanangac and Sanzeng now have limited access to the products and services from the forest. Such vulnerability may have compelled them to accept and use piper as in its place.

Other studies have argued for a negative interpretation of the impact of bioinvaders on people's livelihoods. McWilliam (2000) found that the invasive shrub, *Chromolaena odorata,* challenged the ability of farmers in Timor to farm and ultimately prosper. Comparing the Timorese and Papua New Guinea cases highlights the difficulty of generalising meaningfully about socio-economic and agronomic impacts of bio-invasive plants. The effect of bioinvaders is clearly site-specific. Possible bioinvasive control programmes in their turn need to take into account locally specific conditions.

The long-term impact of piper may be different from the short-term adaptation people have made, which this research reports on. Careful monitoring of changes in the impact and the agronomic and livelihoods aspects of piper invasion and dominance is required. The specificity of the social and natural environment is important in assessing the impact of bioinvasive plants on people's lives and interdisciplinary research needs to explore the possible relations between the way the social and the natural interact and mutually transform each other. For such research, a situational perspective is required. The challenge for such interdisciplinary research is placing the human actor and the natural environment at the forefront of one's analysis.

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Summary and conclusions

Summary and Conclusions

Piper aduncum, a shrub native to Central America, arrived in Papua New Guinea before the mid-1930s possibly from West Papua. From the 1970s it started to dominate the secondary fallow vegetation in many parts of the humid lowlands. It invaded grassland areas and it also appeared in the highlands up to 2100 m a.s.l. As a result, it has affected the farming systems and livelihoods of many rural people. This book brings together the main findings of an agronomic research project that focused on the effects of *Piper aduncum* invasion in the shifting cultivation systems of the humid lowlands.

The invasion

Although the exact details on the introduction of *Piper aduncum* to Papua New Guinea are not known, it spread through many parts of the lowlands through seed dispersion by birds, bats and the wind, as well as by logging equipment, and in some localities by migrating people. The introduction into the highlands was possible by people as they planted *Piper aduncum* as hedge tree or an ornamental tree. The combination of its vigorous generative characteristics (small and abundant seeds), its high growth rates, and the accidental or intentional spreading has resulted in its presence in most provinces of Papua New Guinea. The spread will continue.

In Papua New Guinea's lowland forests, which are subjected to catastrophic natural disturbances, such as landslides or stand-devastating windthrow, *Piper aduncum* may pose a serious threat to the indigenous flora by out-competing other pioneer species. Moreover, anthropogenic factors contribute to the spreading of *Piper aduncum* through logging and shifting cultivation. Forest fires, which were particularly severe in the 1997/98 El Niño Southern Oscillation, may present new frontiers for *Piper aduncum* invasion (Rogers and Hartemink, 2000).

In none of the sources on *Piper aduncum* in South America is there any mention of the formation of monospecific stands or aggressive invasion. Only in Malaysia and in Kalimantan do such stands occur. In the Papua New Guinea lowlands monospecific stands - 'wheatfields' according to Waterhouse (2003) – are common. In the lowlands, *Piper aduncum* is able to outcompete and smother seedlings of other species. In the highlands above 1000 m a.s.l. such monospecific stands are not seen and *Piper aduncum* occurs only as single trees along roads, in gardens or in disturbed areas. Apparently, in the highlands it is unable to form such stands and cannot outcompete indigenous fallow trees and shrubs.

At sites near Lae, *Piper aduncum* has been reported to out compete another plant invader: *Chromolaena odorata* (Orapa, 2001). It also invades grasslands. Bourke *et al.* (2002) surveyed part of the Huon Peninsula and found that the fallow vegetation has changed from mainly cane grass to short woody regrowth, following the introduction of *Piper aduncum*, which is now the dominant fallow vegetation. In 2000, near Nadzab Airport in the Markham Valley of Morobe, individual *Piper aduncum* trees had begun to invade the *Imperata cylindrica* grasslands. Although it is too early to tell if such trees will survive the regular fires that sweep through such grasslands, this appears to be another case showing *Piper aduncum* able to outcompete other vegetation types.

The monospecific stands in the lowlands are temporary: the growth of the *Piper aduncum* eventually levels off. In the Morobe Province, it was observed that other species slowly invade the monospecific *Piper aduncum* stands after about five to ten years.

Characteristics and fallow effects

Two experiments were conducted that measured biomass and nutrient contents of *Piper aduncum*. In the first experiment, plots with *Piper aduncum* were planted and sampled every three months for 23 months. Above ground biomass of *Piper aduncum* increased linearly, and reached 48 Mg dry matter (DM) ha^{-1} at 23 months. Growth rates of piper were on average 69 kg DM ha^{-1} day^{-1}, and increased with higher rainfall. At 23 months, *Piper aduncum* had accumulated 222 kg N, 50 kg P, 686 kg K, 255 kg Ca, 75 kg Mg, and 24 kg S per ha. The large accumulation of K is particular important for sweet potato that dominates the cropping phase in the shifting cultivation systems of the humid lowlands (Hartemink, 2001).

In another experiment, nutrient stocks (soil, above ground biomass, litter) were assessed of one-year old fallows with *Piper aduncum*. Soil samples were taken prior to fallow establishment and after one year when the fallows were slashed and above ground biomass and nutrients measured. In this experiment, the above ground and litter biomass of *Piper aduncum* was 13.7 Mg DM ha^{-1}. The largest stocks of C, N, Ca and Mg were found in the soil, whereas the majority of P was found in the above ground biomass and litter. Almost half of the total K stock of *Piper aduncum* was in the biomass (Hartemink, 2004).

These two experiments have shown that *Piper aduncum* accumulates large amounts of biomass with high K content, and has high growth rates that are increasing with higher rainfall. These rates of accumulation are in the highest range found for secondary fallow in the tropics and may explain the dominance *Piper aduncum* over natural vegetation.

An experiment was conducted whereby one year of *Piper aduncum* fallows was followed by two seasons of sweet potato. In the first season, marketable sweet potato yield after was about 11 Mg ha^{-1}. The positive effects of the fallow on sweet potato yield lasted only one season. *Piper aduncum* fallows were better than natural grass fallows (e.g. *Imperata* *cylindrica*). Nutrient budgets showed that the *Piper aduncum* fallows added insufficient amounts of N and P for the removal of these nutrients by two consecutive seasons of sweet potato (Hartemink, 2003).

Socio economic effects

The effects of *Piper aduncum* invasion on rural livelihoods was investigated in three villages in the same Province as the on-farm experiments. In those villages, *Piper aduncum* was first described in the 1930s but now dominates the secondary fallow vegetation. In total, 27 in-depth interviews were held on how the villagers perceive and use *Piper aduncum*. The tree and its products (stems, leaves, mulch, ashes) are used in farm practices, in the household and the plant is used for medicinal applications. The invasion and dominance of piper has also some negative effects but that is mainly related to the destruction of the natural forest and the loss of natural secondary fallow vegetation. Villagers found several new uses for *Piper aduncum* and its products so it became both a resource to which they were forced - but which they also chose to use. This research has shown that eradication and control programmes for invasive plants should take into account the adaptation of the plants and its effects on rural livelihood strategies.

Future research

This book has described several aspects of *Piper aduncum* invasion in Papua New Guinea. Although there is research on this species in forestry (Saulei, 1989), pharmacology (Orjala *et al.*, 1994), mapping agricultural systems (Bourke *et al.*, 1998), entomology and ecology (Leps *et al.*, 2002; Novotny, 2003) the overall amount of research on *Piper aduncum* invasion is limited, particularly given the fact that it is so widespread and continues to spread. Most of the research lacks a multi-ecoregional focus (single location) and is short-term (snap shot data). There are four areas of research that in my view require attention:

Firstly, there is a need to map its current distribution and the patterns, and rates of its spread across the country. *Piper aduncum* occurs in most provinces of Papua New Guinea but current information is only qualitative, and no information on areal extent and impact is available. With current satellite imagery mapping different vegetation types is feasible and by using images from different periods it should be possible to map changes over time. Moreover, it may be possible to detect *Piper aduncum* areas in other locations where it has not been reported yet. This is an important quantitative step that would assist the planning of future policies on eradication or the setting of agronomic research priorities.

A second field that requires research attention is the concern for biodiversity. This issue is probably the least known. The loss or transformation of natural (secondary) vegetation as a consequence of the expansion of *Piper aduncum* has received little research attention including the loss of species or the changing composition of fallow vegetation.

Thirdly, research efforts on growth rates, biomass and nutrient accumulation or the modes of invasion have been mostly concentrated in the humid lowlands of the Morobe and Madang province. No ecological or agronomic research has been conducted in other parts of the country where *Piper aduncum* is increasingly important such as parts of East Sepik, Central and Northern provinces. In these provinces it already may have significantly altered ecosystems and farming systems.

Finally, research has shown that farmers rapidly adapt to the invasion of *Piper aduncum* and that the replacement of natural secondary vegetation or grasslands to *Piper aduncum* dominated fallows is not necessarily perceived as negative. Additional socio-economic surveys on how *Piper aduncum* is used by farmers are needed. These aspects are neglected in most of the literature on plant invaders at the expense of other aspects like loss of biodiversity, and eradication programmes.

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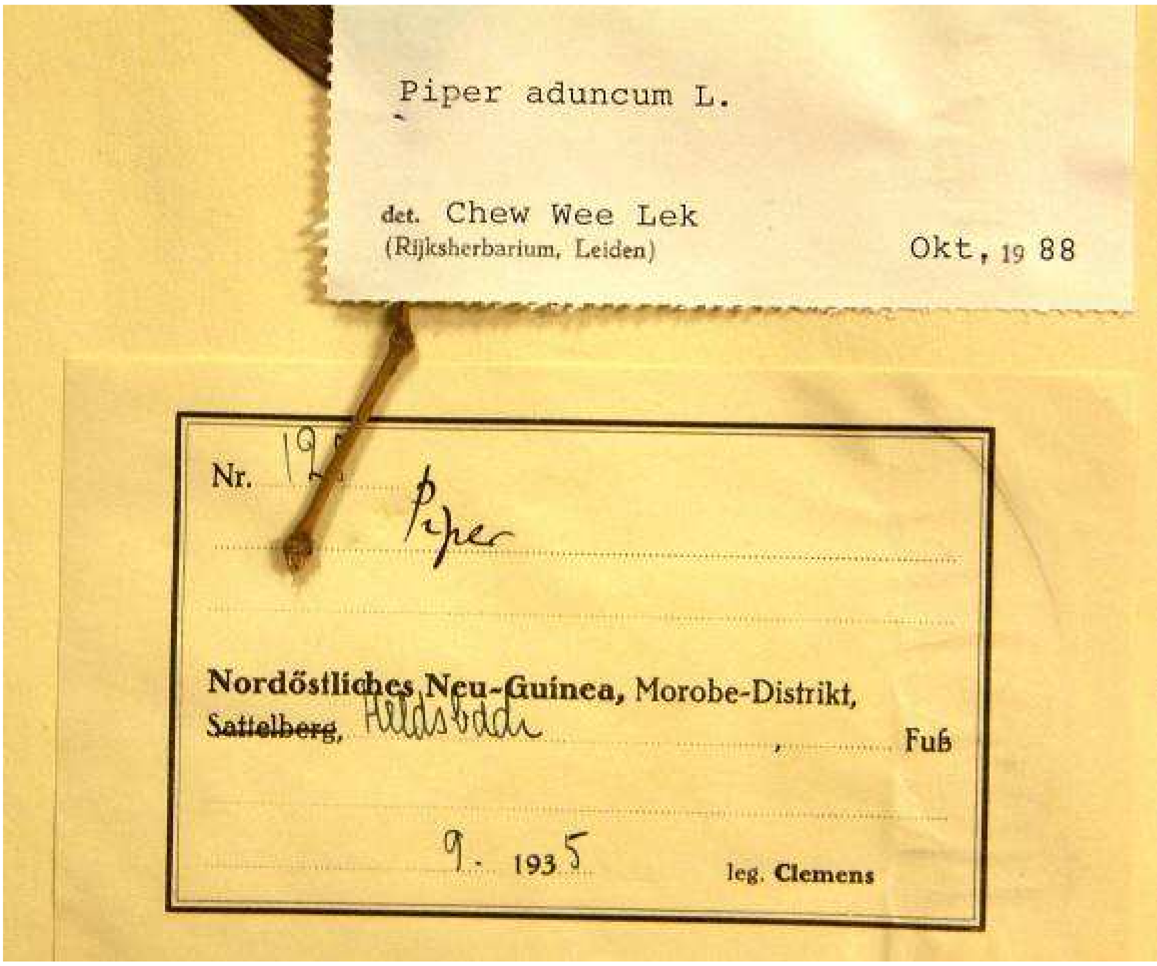
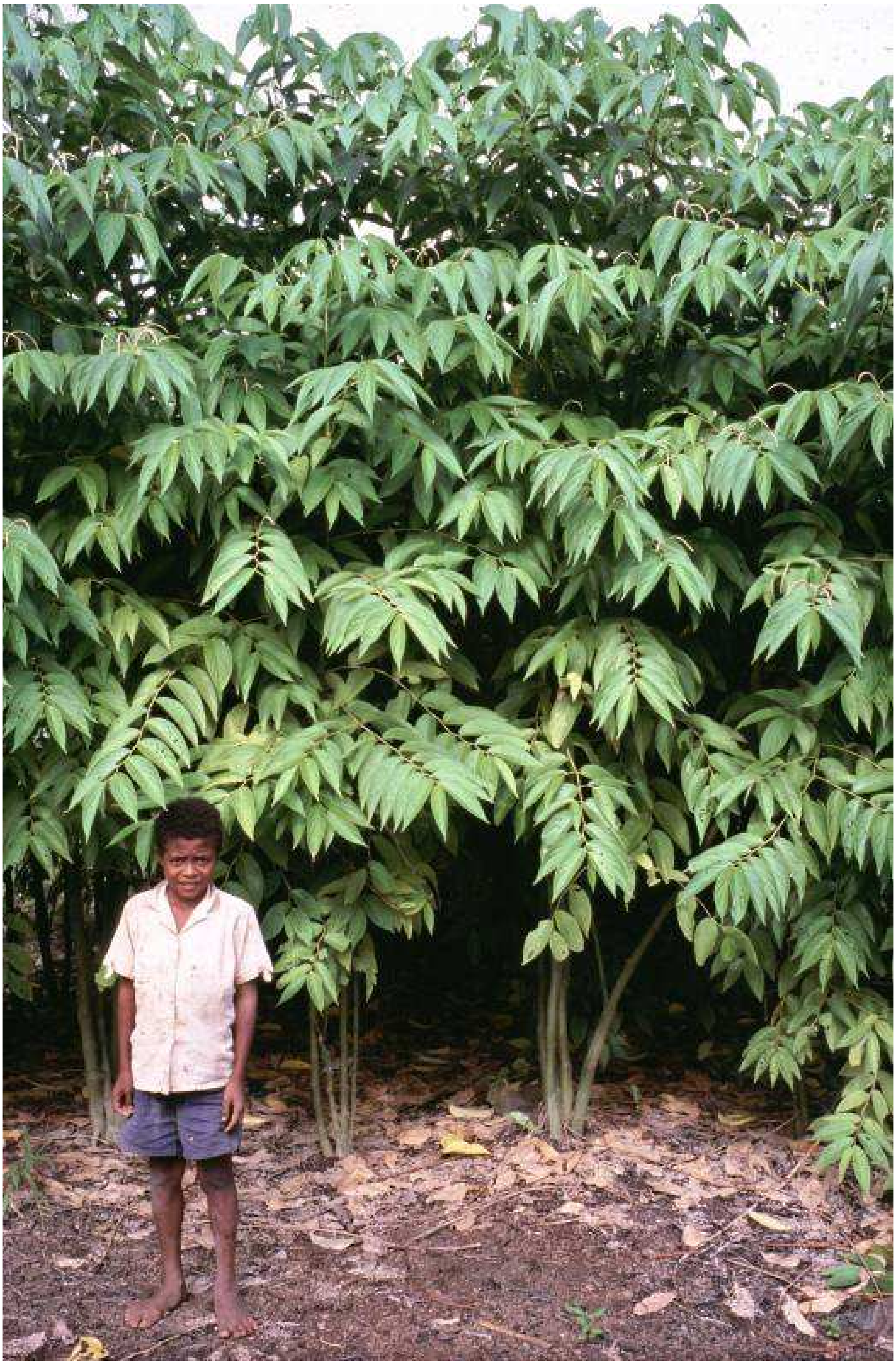


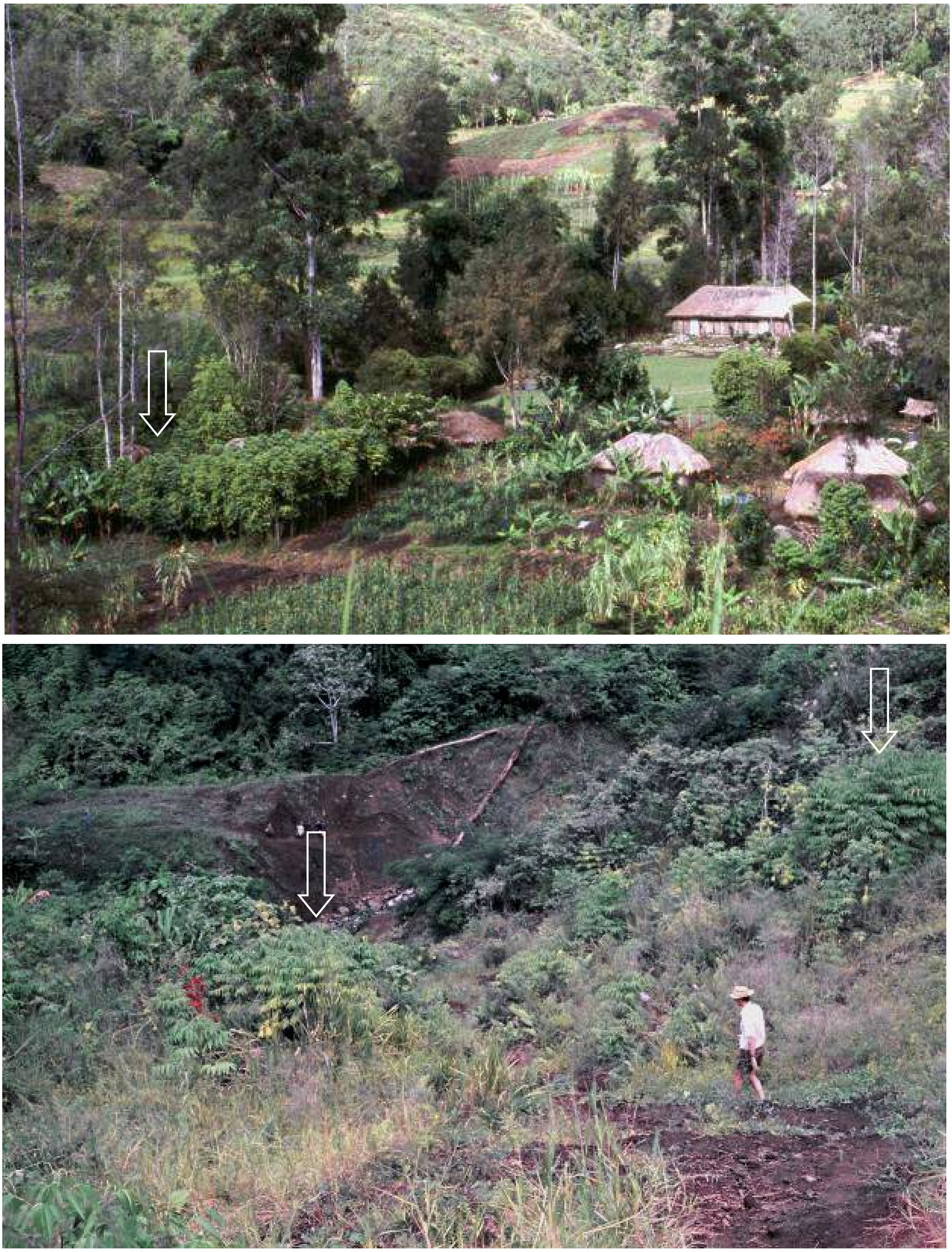
National Herbarium Leiden with specimen of *Piper aduncum* collected by Mary Clemens in 1935

Piper aduncum leaves (top); cleared garden in the forest near Hobu in 1996 with, amongst others, bananas and sago (bottom picture)

Landslide in the Hobu area (1995) with *Piper aduncum* as pioneer vegetation: the light green in the top picture; *Imperata cylindrica* grasslands in the Markham valley invaded with *Piper aduncum* in 2000 (bottom picture)



18 months old *Piper aduncum* at the experimental site near Hobu village (with Morobe mangi Zenga). Total aboveground biomass was about 30 Mg dry matter ha^{-1} and the trees were about 3.5 m. Trees had formed first flowers and fruits. Note absence of undergrowth



Between Mt Hagen and Tambul *Piper aduncum* hedges (arrow in top picture); *Piper aduncum* abundance on fallow land and landslide areas near Musom in 1995 (bottom picture)

Cleared garden in the Hobu area (1996) with *Piper aduncum* (top); Shallow rooting pattern of *Piper aduncum* in experimental fields at Hobu (bottom picture)

Smallholder farmer in the Musom area near Hobu in 1995 (top); dense two-year old *Piper aduncum* fallows at Hobu in 1996 (bottom picture)

Experimental site at Hobu in May 1997 with *Piper aduncum* and other fallow plots as well as sweet potato plots (top); harvesting one-year old *Piper aduncum* plots for assessing biomass and nutrients in 1997 (bottom picture)

Experimental plots at Hobu with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in 1997 (top); cleared plots which were successively planted with sweet potato (bottom picture)

Harvesting sweet potato in plots previous under *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* fallow (top); farmers field day at the Hobu experimental site in 1997 (bottom picture)

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Invasion of *Piper aduncum* in the shifting cultivation systems of Papua new Guinea

Alfred E. Hartemink
ISRIC – World Soil Information, Wageningen, The Netherlands

With a Foreword by Prof. David Pimentel

Piper aduncum, a shrub native to Central America, arrived in Papua New Guinea before the mid-1930s possibly from West Papua. From the 1970s it started to dominate the secondary fallow vegetation in many parts of the humid lowlands. It invaded grassland areas and it also appeared in the highlands up to 2100 m. The combination of its small and abundant seeds, its high growth rates, and the accidental or intentional spreading has resulted in its presence in most provinces of Papua New Guinea. The spread will continue.

Its growth rates are in the highest range found for secondary fallow in the tropics. *Piper aduncum* dries the soil out and takes up very large amounts of nutrients. The fallow has important effects on the soil and sweet potato, which is the main staple crop in Papua New Guinea. The invasion of *Piper aduncum* affects the rich biodiversity. People found several new uses for *Piper aduncum* and its products so it became both a resource to which they were forced - but which they also chose to use.

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www.piperaduncum.net

ISRIC – World Soil Information
PO Box 353, 6700 AJ Wageningen
The Netherlands

Cover*: Piper aduncum drawing from Icones plantarum rariorum (1781-1793, 3 volumes) by the Dutch botanist and chemist Nicolaus Joseph Jacquin (1727-1817).*