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Final report

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1.1 Abbreviations and currency units

APSIM	Agricultural Production Systems Simulator
AQIS	Australian Quarantine Inspection Service
AUD*	Australian dollar
CSPO	Certified sustainable palm oil
CIRAD	Centre Internationale de Recherche Agronomique pour le Developpement
DM	Dry mass
DO	Dissolved oxygen
ECEC	Effective cation exchange capacity
EFB	Empty fruit bunches (palm oil mill by-product)
FFB	Fresh fruit bunches
FM	Fresh mass
FP	Frond pile
GHG	Greenhouse gas
GIS	Geographic Information System
GPS	Global positioning system
HOPL	Hargy Oil Palms Ltd.
HP	Harvest path
JCU	James Cook University
LSS	land settlement scheme
NAAR	Net acid addition rate
NARI	National Agricultural Research Institute
NBPOL	New Britain palm Oil Ltd.
NTU	Nephelometric turbidity unit
OH&S	Occupational health and safety
OM	Organic matter
OPIC	Oil Palm Industry Corporation (Smallholder extension service)
PGK*	Papua New Guinean Kina
PNG	Papua New Guinea
PNGOPRA	Papua New Guinea Oil Palm Research Association
POME	Palm oil mill effluent
RSPO	Roundtable on Sustainable Palm Oil
SOC	Soil organic carbon
TDS	Total dissolved solids
VOP	Village oil palm
WC	Weeded circle
WNB	West New Britain

*1 PGK ≈ 0.42 AUD (August 2014)

2 Executive summary

PNG's palm oil industry produces the country's most valuable agricultural export (over PGK 1,200 million in 2013), is the largest non-government employer, and directly supports approximately 20,000 registered smallholder grower families and an estimated 200,000 people. It underpins the cash economies of the main provinces in which it is grown; West New Britain, Oro, Milne Bay and New Ireland. In those provinces, future productivity of oil palm and other crops, future food security, integrity of surrounding ecosystems, and community well-being all rely on environmentally sustainable management of oil palm.

The aims of this project were: a) To identify the main risks to environmental sustainability in and around oil palm fields, with particular reference to soil and water resources, and b) To establish and implement management practices that ensure environmental sustainability. These activities were designed to support environmental accreditation according to the Principles and Criteria of the Roundtable on Sustainable Palm Oil (RSPO), in which all PNG palm oil producers participate.

Indicators of soil condition, nutrient balance, and aquatic ecosystem condition were designed, in consultation with the industry, underpinned by a range of research activities. The indicators are aimed at maintaining and improving environmental condition, especially with regard to biodiversity of the streams and organic matter content and pH of the soils. They operate at scales appropriate to management and to the processes involved. The plantation-based indicators can be calculated at block or management unit scale (corporate plantations) or division scale (smallholder blocks). The aquatic ecosystem indicators operate at the scale of stream reaches. The indicators require data inputs that are to a large extent already collected routinely by growers. Several new routine monitoring activities will be desirable, and requirements for these new activities have been minimised. The indicators were designed using research carried out in this project and also the large database of research that exists in the PNG oil palm industry, particularly in the form of large, long-term PNGOPRA fertiliser trials. Data from those trials were critical for development of the crop system model (APSIM Oil Palm) that was carried out in this project. The model was used to help develop the indicators and can be used to operate them and evaluate changed management scenarios.

Several research activities were necessary to obtain information necessary for development of the indicators and to ensure that future monitoring can be carried out simply and meaningfully. Field trials were instigated to measure fluxes of carbon, nutrients and soil in key locations and crop management phases. Stream and riparian condition was measured throughout the Dagi catchment, one of the most heavily impacted parts of the industry. Soil fertility and stream physical health are generally good in the oil palm growing areas of PNG, with few physical, chemical or biological constraints. However, the streams are heavily impacted by over-fishing and degradation of riparian vegetation, water quality is impacted at mill outfalls, and the soils face potential threats, such as acidification.

The project has already had positive impacts on the industry, mainly by raising awareness about the issues that need to be managed to ensure sustainability. Capacity has also been raised in the industry organisations involved. Adoption of the indicators will help ensure that long term benefits to growers and other members of the community are maintained through environmental sustainability and scientifically-based demonstration of that sustainability to the consumer.

3 Background

This project directly addressed one of the ACIAR research priorities for PNG under Sub-program 3 (Improving smallholder returns from export tree crop production and marketing): “Assessment of natural resource sustainability indicators for tree crop industries”. For rural communities in PNG to benefit from a sustainable and economically viable oil palm industry, the industry must focus on practices that enable smallholders to achieve maximum productivity, profitability, and livelihood standards in an ecologically and socially sustainable manner. This proposal grew out of workshops held with PNG oil palm industry stakeholders and Australian sustainability scientists in 2009.

The PNG oil palm industry is small by international standards, comprising approximately 1% of the global area under oil palm (144,000 ha in 2012), 1.7% of global palm oil production, 10% of oil palm seed production and 17% of certified sustainable palm oil (CSPO). The industry is also growing much more slowly in PNG than in the higher producing countries. However, palm oil is the largest agricultural export earner for PNG (over PGK 1,200 million in 2013). Oil palm is grown in plantations owned by the two companies New Britain Palm Oil Ltd (NBPOL) and Hargy Oil Palms Ltd. (HOPL) and in 19,777 smallholder blocks. The smallholder blocks directly support more than 200,000 people and the industry underpins the cash economies of the five provinces in which it is grown; West New Britain (WNB), Oro, Milne Bay, New Ireland and to a smaller extent, Morobe. The beneficiaries of the project will be those who depend directly on the oil palm industry for income, plus the people employed by and served by associated businesses, and people relying on downstream aquatic ecosystems. Rapid population growth throughout the country is being accompanied by an increase and unplanned change from shifting agriculture to permanent agriculture. In order to maintain livelihoods and food security it is crucial to ensure that management regimes maintain soil fertility and aquatic ecosystem health.

Maintenance of soil fertility and the health of surrounding aquatic ecosystems is critical for sustainability of the PNG oil palm industry and the activities of surrounding communities. Oil palm is a highly productive system requiring large and balanced inputs of nutrients. Potential soil degradation issues for oil palm smallholders have been identified as acidification, erosion and organic matter decline. Degradation can be rapid in the wet tropics if management is poor. The main effect of these processes is to reduce the ability of soil to retain and supply nutrients, and nutrient deficiencies are the major limitation to oil palm production. Research is necessary to determine which degradation processes may be occurring, and what management approaches would be most effective in preventing them. Water quality may be impacted by agricultural management. Research is required to determine the impact on ecology of streams and estuaries and what management approaches will be most effective in reducing impacts.

The oil palm industry in PNG has been pro-active in the establishment of the international Roundtable on Sustainable Palm Oil (RSPO). The PNG palm oil industry is unique in that all oil palm growers in the country (plantations and smallholders) are participants in the RSPO. The RSPO focuses on OH&S, legal, economically viable, environmentally responsible, socially beneficial and transparent management practices and operations. Many of the principles of the RSPO can be directly applied by smallholders, whereas others will require new information, novel approaches to extension, a very good knowledge of social behaviour in PNG rural societies and excellent planning. While the RSPO has principles and criteria for sustainability (RSPO 2013), there is a need to develop measurable indicators that can underpin certification. The challenge is to produce meaningful, scientifically-based and practical indicators of sustainability that are applicable and beneficial to smallholders and plantation estates, and can be audited in a quantifiable manner. It is worth clarifying the definition of the term ‘indicator’, because the RSPO definition is different from the one used here. For the RSPO auditing process, management performance is already assessed against ‘indicators’. The RSPO indicators are plans, practices or monitoring programs to achieve a particular criterion. The PNG oil palm industry has identified a need to underpin the RSPO indicators, particularly those to do with soil and water, with indicators as defined in this report: a measurable value of a rate or quality used to define trend in or state of land/water/system properties (Nelson et al. 2010)

The results of the project will be relevant to tree crops other than oil palm. For example, cocoa and coffee markets are increasingly demanding environmental certification. The cocoa industry in particular may benefit from results of the project as cocoa is grown in similar environments to oil palm.

PNG is a small and relatively high cost palm oil producer, so maintaining competitiveness is critical for the long-term viability of smallholder oil palm growers, the oil palm industry as a whole, and associated businesses. Environmental certification under the RSPO has the potential to produce premiums, which the PNG palm oil producers have committed themselves to pass directly to smallholder fruit suppliers. More important than premiums is continued market access. PNG currently sells almost all of its oil to the discerning European market, where there is a great deal of anti-palm oil sentiment. Continued access to that market will be best guaranteed if the whole PNG industry can continue to demonstrate it is environmentally sustainable. PNG has a unique opportunity in this regard as it is the only palm oil-producing country in which all producers are participating in an environmental certification scheme. Even in the absence of RSPO, the benefits of compliance to an environmental standard will live on.

One critical problem for large-scale agriculture is how to minimise collateral impacts to adjacent ecosystems. Human induced degradation of Papua New Guinea’s coral reef ecosystems has been raised as a concern (Munday 2004). Unfortunately, it is impossible to determine the exact source of damage given a) the limitations of current technology, b) because the impacts are spatially separated from specific terrestrial sources of potential impact, and c) because of the difficulty of differentiating local level impacts from the broad-scale effects of climate change (P. Munday pers. com.). Impacts on Papua New Guinea’s other coastal aquatic ecosystems (estuaries and freshwater streams) are also reported regularly but are generally anecdotal rather than being based on hard data. Consequently, definitive studies of these coastal ecosystems are urgently needed, and provide multiple benefits in the context of sustainability of the oil palm industry. Not only does the proximity of coastal streams and oil palm plantations allow direct evaluation of impacts and confer the ability to attribute impacts to specific sources, but these coastal streams are the primary conduits through which stressors likely to impact coastal reefs are transported. As a result, studying estuaries and freshwater streams provides the joint benefits of safeguarding those systems themselves and at the same time making a real contribution to evaluating the likelihood of impacts from specific terrestrial sources being transmitted to offshore habitats, providing a sound basis for monitoring, management and mitigation.

This proposal addresses the Australian National Research Priority: “An environmentally sustainable Australia: overcoming soil loss, salinity and acidity”. Many of the principles of sustainable management of plantation crops in PNG, such as oil palm, also apply to plantation tropical horticultural crops in Australia. In addition, a quantitative modelling capability for plantation crops has previously not received significant attention in PNG or Australia and will be directly relevant to management of tree crops in northern Australia. The exchange of expertise and capabilities in landscape modelling in tropical systems, including the development of environmentally sustainable tropical agricultural practices and management will benefit both countries in terms of increased production and skills. Furthermore, biodiversity in managed agricultural systems in the tropics is a common issue for both PNG and Australia. Given the commonalities, further collaborative projects can be developed in the future capitalising on the unique set of skills and knowledge in the partner organisations.

4 Objectives

The aims of the project were to improve the environmental sustainability and long-term viability of the PNG oil palm industry by establishing the use of environmental sustainability indicators that facilitate continuous improvements in management practices.

The project has 6 objectives:

- Objective 1. To develop indicators of soil health.
- Objective 2. To develop indicators of nutrient balances.
- Objective 3. To develop indicators of C sequestration.
- Objective 4. To develop indicators of aquatic ecosystem health.
- Objective 5: To develop a crop system model that enables prediction of management effects on soil health, C sequestration, greenhouse gas emissions and nutrient balances.
- Objective 6: To test and implement an integrated monitoring & recommendation package, and build institutional capability to maintain it.

Objectives 1-4 were aimed at understanding of processes and production of indicators while Objectives 5 and 6 were aimed at integration and application of the results. Activities under the first 4 objectives aimed to: i) assess vulnerabilities and produce models of the main processes leading to environmental risks, ii) quantify the main processes in representative and suitable study sites in the main oil palm growing areas, and iii) propose and evaluate indicators of those processes. Objective 5 aimed to integrate, as far as possible, research results from Objectives 1, 2 and 3. Additional aims of the model developed in Objective 5 were to predict productivity, and provide a tool for further knowledge generation and capacity building. Finally, the understanding and indicators produced were put into practice in Objective 6. Activities in Objective 6 revolved around trialling the indicator package, transferring knowledge of key measurements and assessments, and building institutional capability and staff skills to facilitate the maintenance and further development of the monitoring program, with the overall aim of maintaining or improving environmental sustainability.

5 Methodology

5.1 Production of indicators

Workshops and desk-top research were carried out to formulate a conceptual basis for indicators that take into account: the requirement for a practical product; spatial and temporal scale and complexities; and the principal processes involved. Necessary research activities were identified and are described below. Indicators fell into two categories: block-based indicators and stream-based indicators. The block-based indicators quantify soil condition, soil erosion, nutrient balances and greenhouse gas emissions. The stream-based indicators quantify condition of the stream and riparian zone.

For indicators of soil condition, soil must be sampled and analysed. Existing routine sampling methods were not adequate to detect trends over time, so we evaluated sampling designs (Sections 5.2 and 7.2). However, even if soil sampling and analysis is carried out in a rigorous manner, able to detect trends over time, it still has the drawback that it can detect changes only after they have happened. A minimum of approximately 5-10 years is normally needed to detect trends. If managers want to predict trends, then the processes that cause soil condition to change must be monitored. To enable such monitoring, we developed an approach described in Section 7.1. To underpin the approach, we carried out research to measure and model the driving processes (Sections 5.2-5.9 and 7.2-7.9). Soil acidification and soil organic matter inputs were chosen as key indicators of soil condition, as they determine many physical, chemical and biological processes. Soil physical condition was also considered as an indicator, but as it is primarily influenced by one factor, the use of in-field machinery, it was not examined further.

For indicators of nutrient balance we decided on two related indicators. Nutrients are essential for palm productivity, but an excess can cause undesirable environmental impacts and an insufficient supply may lead to depletion of the soil resource. Therefore there is one indicator for palm nutrient status and another for change in nutrient stocks in the palm-soil system.

For indicators of aquatic ecosystem health, existing monitoring methods were inadequate to detect trends in ecosystem condition, and large variability in space and time must be considered. Existing monitoring methods focussed on measuring water quality parameters. A number of potential indicators were identified and trialled before arriving at 4 key indicators that would: inform managers about water quality; be robust and simple measures that were easily applied under field conditions and therefore; provide consistent and reliable monitoring data. The indicators are turbidity, sludge, aquatic vegetation and riparian inventories (Section 7.2). Their choice was based on assessment of the state of the aquatic ecosystems and the main drivers of change in ecosystem processes (Sections 5.9-5.12 and 7.9-7.12).

5.2 Soil sampling designs

Soil must be analysed to determine its condition. However, existing practice was not adequate to reliably detect trends over time. Existing good practice involves taking samples separately from the weeded circle and frond pile, but there are several drawbacks to the approach; the areal proportion of the sampled zones is not taken into account, and their size and location changes when plantations are felled and replanted. Therefore, to quantify trends in soil properties over time, a sampling design is needed, that better takes into account lateral tree-scale variability. We started by defining and evaluating all sampling designs that can account for lateral variability at the tree scale. Details are given by Nelson et al. (2014).

A tree-scale sampling grid could be used to produce soil samples that account for tree-scale variability. A grid approach is useful for research but is too onerous for routine sampling by managers. We therefore evaluated simpler transect sampling designs for their ability to account for tree scale variation. The evaluation was carried out based on the known geometry of tree-scale variability, and using measured data (soil respiration, bulk density, pH and effective cation exchange capacity (ECEC) from grid sampling exercises.

5.3 Palm carbon and nutrient stocks over the growth cycle

Biomass, carbon and nutrient stocks in palms were measured in commercial plantations at 3 palm ages (6, 10 and 20 years). These measurements were used to estimate nutrient and carbon balances as well as providing information for the modelling component. Carbon and nutrients balances are the fundamental processes determining the trajectory of soil condition and inputs of nutrients to aquatic ecosystems and greenhouse gases to the atmosphere. The measurements also enabled the development of allometric relationships so that amounts of biomass and nutrients can be estimated from simple routine measurements.

Estimating biomass, area and nutrient content of fronds

The details of the procedures and calculations for estimating frond dry mass and leaflet area are detailed in PNGOPRA (2012). Briefly, fronds of various ages from 6-, 10-, and 20-year-old palms were sampled and fresh matter (FM) measured. FM and dry matter (DM) of subsamples of leaflets and rachis were measured and DM for the total frond calculated from FM/DM ratios. Relationships were developed between frond DM and other easily measured parameters such as petiole cross section and frond length so that estimates of total biomass could be made from these simple measures. Frond area is used in the calculation of light interception by the canopy and thus important for the model. Total area of leaflets in a palm was calculated from the area of leaflets along a frond and then aggregated up to the whole palm. A relationship was developed to relate the routine measurement of the standard frond 17 leaflet length by width measurement to the total frond area depending on the number of fronds.

Nutrient concentrations were measured in some of the frond samples. We combined these concentrations with the allometric relations we developed for biomass, to estimate total nutrient content of fronds in the canopy and that which are returned to the soil through pruned fronds.

Estimating mass and nutrient content of FFB, roots, trunk and cabbage

FFB mass can be derived from company records and FM/DM ratios. The nutrient concentration in FFB was measured and this is converted to a nutrient content being removed for the plantation by multiplying by the DM of FFB removed.

Root mass was estimated for a ‘half hexagon’ by intensively sampling to 2 m depth. The procedure is explained in detail by Nelson et al. (2014).

Trunk samples were taken at four depth increments and at five heights along the length of the stem with near-constant diameter (1.5 m to base of frond 41; including the standard height at 1.5 m above the ground). Samples were also collected for the base of the stem and the stem above frond 41; both of which had changing diameters. Samples were taken with a standard increment corer (12-mm diameter) commonly used in forestry studies and trunk density determined and nutrient content measured (N and C to be done). With standard measures (trunk height and diameter) and the density distribution, equations for trunk biomass are being developed. Together with nutrient analysis, the amount of nutrients sequestered by the trunk are being calculated. Similarly, samples of the cabbage were taken, mass determined, and nutrient concentration analysed.

5.4 Soil carbon and nutrient stocks over the palm growth cycle

The aim of this study was to quantify stocks of C and nutrients in soil under oil palm, using a chronosequence (paired site) approach. Details are given by Goodrick et al. (2014) and Nelson et al. (in press). Grassland-to-oil palm sites were used so that the origin and fate of C could be studied, exploiting the large difference in isotopic composition ($\delta^{13}C$) of the inputs from oil palm and grass. The study was carried out at 18 paired sites, of which 16 were grassland-to-oil palm sites in Oro Province, and two were forest-to-oil palm sites in West New Britain Province. The grassland and forest sites (representing pre-oil palm conditions) were as close as possible to their paired oil palm block. The oil palm blocks had been planted 1-25 years before sampling. All study sites have humid tropical climate, recent volcanic ash soils and a history of shifting agriculture. Both regions would most likely have forest vegetation if not for human interventions. The forest sites had large trees at the time of sampling, but they had most likely been logged or cleared for food gardens in the past. The grassland in Oro is dominated by *Imperata cylindrica* and *Saccharum edule* and is maintained as grassland by regular burning. The sites had been grassland for at least 58 years prior to sampling (according to aerial photos taken in 1953) and probably much longer than that, according to oral history.

Soil samples were collected in 2010, from 4 different locations under each vegetation type. In the oil palm blocks, at each of the 4 locations, samples were taken separately from the weeded circle, frond pile and 'between zones' areas. Sampling depth increments were 0.05-0.1, 0.15-0.2, 0.2-0.5, 0.5-1.0 and 1.0-1.5 m. Samples from all depths were analysed for bulk density, total C and N content and $\delta^{13}C$. Carbon balance was determined using 9 of the 16 sites in Oro, as isotopic analysis indicated that the other 7 sites had not been grassland for very long prior to conversion to oil palm. Samples from 0-0.05 and 0.10-0.15 m were analysed for chemical properties (pH, electrical conductivity, exchangeable cations and Colwell P) and samples from 0-0.05 m were analysed for microbiological properties (bacterial and fungal community structure by DNA analysis, and presence of N cycling genes). Soil respiration was measured on two occasions, using the triangular grid approach developed in the project (Nelson et al. 2014).

5.5 Palm and soil carbon and nutrient contents over the replant phase

The aim of this study was to determine the fluxes of C and nutrients that occur during the poisoning/replanting phase. This phase was identified as a critical phase for sustainability but very little data exists on the processes that occur. A trial was established in Milne Bay (Block AL280), in which stocks of C and nutrients are being monitored over the poisoning/replant phase. Prior to poisoning, 20 palm units were selected, with 4 units selected for each of the 5 most common possibilities in an old oil palm stand: a missing palm surrounded by 5 or 6 living palms, or a living palm surrounded by 4, 5 or 6 living palms. In each of these units the soil, ground cover and palm were comprehensively and representatively sampled. Following poisoning and felling, the palms were windrowed in a manner that would facilitate subsequent sampling of the decomposing palms. Soil, groundcover, decomposing palms and the newly planted palms were then sampled at regular intervals, and inputs to the field were monitored. This trial will need to continue beyond the life of the project, and PNGOPRA has agreed to do that.

5.6 Soil acidification- effects of N fertiliser

The aim of this study was to measure the acidification rate under different N fertiliser regimes. Application of ammonium-based fertilisers is known to be one of the main management practices accelerating acidification in oil palm plantations (Nelson et al. 2010). Although the effects of fertiliser management had been examined (Nelson et al. 2011), those studies had not fully accounted for the spatial variability involved. Therefore, soil from a long-term N fertiliser source/rate trial (Trial 324 in Oro Province) was sampled intensively and soil pH was measured. At the time of sampling the palms were 15 years old and the fertiliser treatments had been in pace for 10 years. FFB was also analysed in order to calculate nutrient export. Soil was sampled on a 35-point grid in all plots, to 0.9 m depth. For most plots the samples were combined for each depth layer, but in two plots the samples were kept separate in order to measure spatial variability.

5.7 Biological nitrogen fixation

Nitrogen cycling is important for soil health and water quality considerations. While some components, such as fertiliser inputs and crop outputs are fairly readily estimated from existing data recording activities, some fluxes, including biological N fixation, are not as easy to estimate and have not been quantified as accurately. The aim of this study, carried out by Rachel Pipai in her MSc, was to determine the inputs of N from biological fixation in oil palm plantations as a function of cover crop species composition and oil palm age (shading increases with oil palm age). The xylem ureide technique was calibrated in a glasshouse experiment using ^{15}N isotope dilution for the legume cover species *Calopogonium mucunoides*, *Pueraria phaseoloides* and *Mucuna pruriens*, before being applied in 16 oil palm plantations in West New Britain to assess N_2 fixation by these cover legume species and *Calopogonium caeruleum*. Details are given by Pipai (2013).

5.8 Crop system modelling

The purpose of the modelling was a) to inform development of the indicators and b) to develop a tool that can estimate fluxes of water, C and N that are required for indicators of sustainability, and also yield. The modelling was carried out within the APSIM Community Source Framework (www.apsim.info) and tested using crop data from three sites (Figure 1). The model development is described in detail by Huth et al. (2014). Data required to build and test the model were sourced from long-term field trials carried out by PNGOPRA and long-term weather records collected and maintained by PNGOPRA and the plantation companies.

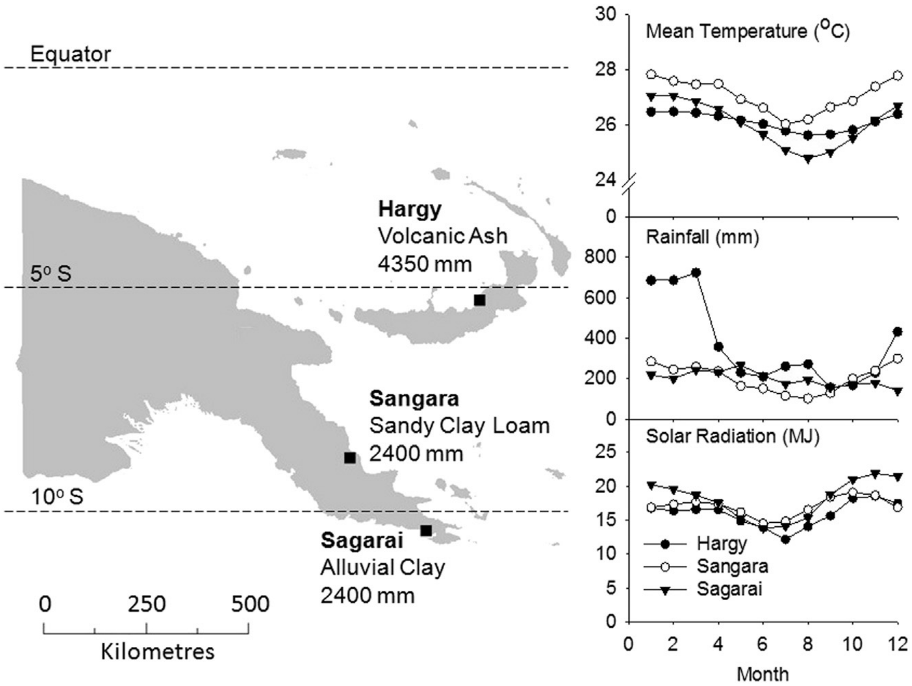


Figure 1. Location and characteristics of sites where APSIM Oil Palm was tested.

5.9 Water quality assessment

The aim of this study was to provide a comprehensive assessment of water quality across a broad range of stream conditions and levels of impact. A suite of water quality parameters was collected from 63 sites across 23 stream systems in WNB. Sites extended from Waharo Creek in the west, to the Kapiura drainage systems in the east. Greatest effort was focussed on the Dagi River catchment comprising the Dagi River and its tributaries. The Dagi River catchment provided a broad range of stream conditions from upland to lowland reaches and from small plantation drains to the relatively large Dagi River itself. As a focal system the Dagi River and tributaries were ideal because there is easy access to most of the catchment making extensive repeat data collections logistically efficient.

Replicate water quality measurements were collected along three cross-channel transects, at the upstream extent, at the middle and at the downstream extent of sampling sites including those where faunal samples were collected. Three measurements were collected from each transect, one adjacent to each bank and one mid-stream.

Seven basic water quality measures that provide biologically relevant information were examined; water temperature, salinity, total dissolved solids, conductivity, dissolved oxygen (DO) and turbidity. The relationship between oxygen reducing potential (ORP) and pH was investigated to allow further assessment of water quality, particularly with respect to human health.

To assist with characterisation of sites and interpretation of stream condition, we recorded water flow regimes, ambient light transects across study sites, and site level details of riparian condition. We also collected photographs and extensive observational notes about each site. Observational notes described and classified riparian conditions and habitats and potential for impacts at the site as well as information about adjacent areas and documented human activities associated with each site.

Potential anthropogenic chemical inputs were assessed by measuring levels of nitrate (N) and phosphate (P) and biochemical oxygen demand (BOD) in water samples collected from key locations likely to receive chemical inputs from domestic activities (road crossings, washing points etc.) or mill tailings water.

5.10 Riparian condition assessment

We categorised riparian condition across all water quality and faunal collection sites to produce an overall estimate of riparian conditions in the sampling region of WNB. Study sites included rainforest streams upstream from oil palm plantations, streams and drains within plantations (smallholder and company), streams with and without natural riparian vegetation, streams receiving mill effluent, and streams with and without extensive estuaries.

Site level assessments

Site-level riparian assessments considered a zone that extended for 100 m upstream and 100 m downstream from each site and included riparian vegetation to a depth of 50 m back from stream edges. Separate assessments were undertaken for each bank to allow finer scale interpretations of potential effects on water quality and aquatic faunas if site-scale impacts were detected.

Temporal change assessments

Comparisons of current riparian condition to historic condition were not possible at a site by site level because no baseline data exists. Evidence of continuing degradation of riparian condition prompted initiation of a detailed assessment of riparian condition for the Dagi River (the key focus stream for the study) from GoogleEarth imagery. That assessment was based on 2008 imagery so provided a proxy for baseline riparian information against which present condition could be assessed. Estimates of prior condition (2008) were validated using known riparian states from current sampling sites as well as from sites documented during initial reconnaissance trips.

Detailed video transect assessments

In response to discrepancies between the 2008 GoogleEarth imagery and known present day conditions of some sites we initiated a complete inventory of riparian condition along the length of the Dagi River from upstream of oil palm plantings to the estuary mouth during July 2013. We mounted video cameras on a canoe and launched from the most upstream site that we could deploy the canoe. Video cameras were orientated to collect imagery from both banks, one directed towards each bank, and the banks filmed as the canoe was manoeuvred along the river. This transect enabled an accurate present day assessment of riparian condition thus will provide a baseline for assessing future changes in riparian condition.

5.11 Aquatic fauna

The presence of aquatic fauna was investigated across a broad range of stream conditions and levels of impact apparent in West New Britain for three taxonomic groups; Nekton (fish and mobile crustaceans); Benthic invertebrates; and Insects. In all 43 sites were sampled across 23 stream systems.

Nekton (fish and mobile crustaceans) sampling - netting

Cast nets were initially chosen as the primary gear to collect fish data because they provided a single gear that could be used effectively and (approximately) equivalently across a broad range of habitat types and are an effective method of sampling shallow water fish faunas. Use of a single gear across multiple sites and habitat types allows for valid comparisons among sites and habitat types. Ten replicate cast net samples were collected from each habitat type in each site.

Scoop nets with a 3 mm mesh and head opening of 45 x 28 cms were used to sample flooded vegetation along stream margins. This was primarily to collect information on crustacean distribution and abundance and include fish species that may use those habitats exclusively.

Fyke nets with 5 m wings, 60 cm drop and 19 mm multifilament mesh were also used for collection of nekton. Fyke nets were positioned at the downstream extent of sampling sites. Fykes were set across the current with the lead line buried among rocks and cobble as completely as possible. Fykes were set prior to commencement of other netting activities and left in place until cast and scoop netting had ceased.

Nekton sampling - Underwater video cameras

Freshwater streams generally had clear water and were often fast flowing with uneven substrates (cobble on rock), three factors that may adversely affect the performance of cast nets. Clear water meant that video cameras had a potential to overcome these problems but the viability of video sampling was unknown and was untested under types of conditions expected in WNB streams. However video techniques had an obvious potential as a non-destructive approach for validation of the effectiveness of cast net sampling.

Oregon Scientific ATC9K high definition underwater video cameras were used to collect video data with the camera set to record at 30 frames per second with a 105° field of view. The camera housing was mounted on an aluminium base so that it would not be moved about by current flow once positioned in the water. At each sampling site cameras were deployed in different habitat types within a site and left to run for 15 minutes then retrieved and moved to a new position. Data collected from video was the presence of species and counts from the video frame that had the maximum number of individuals (nMax) for each species.

Benthic invertebrates

Benthic invertebrate distribution and abundance was examined using a small Van Veen grab where possible (soft sediments) and manual collection of soft sediments from among rocky/cobble areas in each site. Three replicate samples were collected from each site, and sieved through a 2 mm sieve. The retained material was placed in a plastic bag, labelled and placed in a cooler for transport to the laboratory where samples were frozen until required.

Aquatic insects

Insect drift traps were deployed at the downstream extent of study sites at the commencement of faunal sampling. Two traps with 120 micron mesh were deployed in each site and left in place until the completion of faunal sampling or for a minimum of one hour if sampling was completed sooner. Traps were set at the downstream extent of sites under the assumption that activities in the site may dislodge insects and facilitate collection of a more complete species list than simply relying on natural drift behaviours.

5.12 Stream condition assessment

Every stream system we visited was impacted to some degree but in the absence of baseline data it is not possible to compare streams with their historic conditions. Consequently stream and site assessments are subjective estimates formed through among-stream comparisons of water quality, suitability of water for cooking and drinking, riparian condition, the structure of fish assemblages, field observations and anecdotal information. These qualitative assessments, along with the more detailed quantitative data above, should provide a sound baseline for future assessments.

6 Achievements against activities and outputs/milestones

Objective 1: To develop indicators of soil health

No.	Activity	Outputs/ milestones	Completion date	Comments
1.1	Modelling soil health (A & PC)	Conceptual model established	Yr1 m6 2010 Jun	Completed
		Links with Obj 5 established	Yr1 m6 2010 Jun	Completed
		Process model built	Yr2 m6 2011 Jun	Completed
		Model validated and complete	Yr3 m12 2012 Dec	Completed
1.2	Process measurements (PC)	Field sites identified	Yr1 m6 2010 Jun	Completed
		Field trials established	Yr1 m12 2010 Dec	Completed
		Experimental work complete	Yr3 m12 2012 Dec	Completed
1.3	Indicator production (A & PC)	Potential indicators identified	Yr1 m6 2010 Jun	Completed
		Initial indicator assessment complete	Yr3 m6 2012 Jun	Completed
		Final indicators complete	Yr4 m6 2013 Jun	Completed
		Final package complete and operating	Yr4 m12 2013 Dec	Available for use

PC = partner country, A = Australia

Objective 2: To develop indicators of nutrient balances

No.	Activity	Outputs/ milestones	Completion date	Comments
2.1	Modelling nutrient balances (A & PC)	Conceptual model estab.	Yr1 m6 2010 Jun	Completed
		Links with Obj 5 established	Yr1 m6 2010 Jun	Completed
		Process model built	Yr2 m6 2011 Jun	Completed
		Model validated and complete	Yr3 m12 2012 Dec	Completed
2.2	Process measurements (PC)	Field sites identified	Yr1 m6 2010 Jun	Completed
		Field trials established	Yr1 m12 2010 Dec	Completed
		Experimental work complete	Yr3 m12 2012 Dec	Completed

2.3	Indicator production (A & PC)	Potential indicators identified	Yr1 m6 2010 Jun	Completed
		Initial indicator assessment complete	Yr2 m12 2011 Dec	Completed
		Final indicators complete	Yr3 m12 2012 Dec	Completed
		Final package complete and operating	Yr4 m6 2013 Jun	Available for use

PC = partner country, A = Australia

Objective 3: To develop indicators of carbon sequestration

No.	Activity	Outputs/ milestones	Completion date	Comments
3.1	Modelling carbon balance (A & PC)	Conceptual model estab.	Yr1 m6 2010 Jun	Completed
		Links with Obj 5 established	Yr1 m6 2010 Jun	Completed
		Process model built	Yr2 m6 2011 Jun	Completed
		Model validated and complete	Yr3 m12 2012 Dec	Completed
3.2	Process measurements (PC)	Field sites identified	Yr1 m6 2010 Jun	Completed
		Field trials established	Yr1 m12 2010 Dec	Completed
		Experimental work complete	Yr3 m12 2012 Dec	Completed (apart from Replant trial, which will continue)
3.3	Indicator production (A & PC)	Potential indicators identified	Yr1 m6 2010 Jun	Completed
		Initial indicator assessment complete	Yr3 m6 2012 Jun	Completed
		Final indicators complete	Yr4 m6 2013 Jun	Completed
		Final package complete and operating	Yr4 m12 2013 Dec	Completed

PC = partner country, A = Australia

Objective 4: To develop indicators of aquatic ecosystem health

No.	Activity	Outputs/ milestones	Completion date	Comments
4.1	Modelling functional ecology (A & PC)	Conceptual model established	Yr1 m6 2010 Jun	Completed
		Links with Obj 5 established	Yr1 m6 2010 Jun	Completed
		Preliminary ecosystem model for 'core' areas	Yr2 m6 2011 Jun	Completed

		Final detailed ecosystem models for 'core' areas	Yr2 m12 2011 Dec	Completed
		Final location-specific models	Yr3 m6 2012 Jun	Completed
		Ecosystem categorisations	Yr3 m12 2012 Dec	Completed
4.2	Process measurements (PC)	Study locations identified	Yr1 m6 2010 Jun	Completed
		Initial assessment of potential impacts	Yr1 m6 2010 Jun	Completed
		Report on location-specific vulnerabilities	Yr3 m12 2012 Dec	Draft completed
4.3	Indicator production (A & PC)	Potential indicators identified	Yr1 m6 2010 Jun	Completed
		Initial indicator assessment complete	Yr2 m12 2011 Dec	Completed
		Formal monitoring framework and instruction manual	Yr3 m12 2012 Dec	Completed
		Initial report card template	Yr3 m12 2012 Dec	Completed
		Final indicator package complete and operating	Yr3 m12 2012 Dec	Available for use
4.4	Postgrad (A & PC)	Postgrad identified	Yr1 m6 2010 Jun	Completed
		Postgrad enrolled	Yr1 m12 2010 Dec	Completed
		Experimental work complete	Yr3 m12 2012 Dec	Student withdrawn but project objectives achieved
		Draft thesis complete	Yr4 m6 2102 Jun	See above

PC = partner country, A = Australia

Objective 5: To develop a crop system model

No.	Activity	Outputs/ milestones	Completion date	Comments
5.1	Crop system modelling (APSIM oil palm) (A & PC)	Framework established	Yr1 m6 2010 Jun	Completed
		Existing data sources collated	Yr1 m6 2010 Jun	Completed
		Field measurement requirements established	Yr1 m6 2010 Jun	Completed
		Model complete	Yr3 m12 2012 Dec	Completed

PC = partner country, A = Australia

Objective 6: To test and implement an integrated monitoring and recommendation package

No.	Activity	Outputs/ milestones	Completion date	Comments
6.1		Potential indicators identified (see Obj. 1-4)	Yr1 m6 2010 Jun	Completed

	Implementation of indicators package (PC)	Pilot testers identified and briefed	Yr2 m6 2011 Jun	Completed
		Pilot package assembled and implemented	Yr2 m12 2011 Dec	Available for use
		Workshop held with main scientists and pilot testers	Yr2 m12 2011 Dec	Pilot testing was carried out on an ad hoc basis
		Review of pilot package and recommendations for final version	Yr3 m12 2012 Dec	Pilot testing was reviewed on an ad hoc basis
		Package implemented. Ground staff trained in collecting indicators, operating monitoring plans and interpreting outputs	Yr4 m6 2013 Jun	PNGOPRA staff have been trained in the techniques
		Package complete, with final adjustments made	Yr4 m12 2013 Dec	A manual has been drafted

PC = partner country, A = Australia

7 Key results and discussion

7.1 Production of indicators

7.1.1 Indicator characteristics and requirements

Soil health and nutrient balance indicators developed operate at the scale of individual blocks or management units (corporate plantations) or divisions (smallholder blocks). It is possible to aggregate the values up to larger scales, for example as averages weighted for the areas involved. The temporal scale is annual, with detailed sampling and analysis being proposed less frequently as a check. Soil and nutrient balance indicators are based on recording of inputs and outputs rather than point-scale soil measurements, which are resource intensive and highly variable. Aquatic health indicators operate at the scale of stream reaches.

A reporting format has been developed, in which indicators are presented visually, with input data and calculations included in the background, in Excel format. Requirements for producing the indicators are listed in Tables 1 and 2.

The indicators give actual status. They are not risk factors. Examples of risk factors relevant to the block-based indicators are: landscape position; weather; and soil type. Examples of risk factors relevant to the stream-based indicators are: proximity of roads, mill outfall, gravel extraction points and gardens; location within the stream system; and timing within the hydrograph. These risk factors must be considered when interpreting the indicators. They are critical factors to consider when determining management response within current crop and also in future plantings.

Table 1. Requirements for producing each block-based indicator: Soil acidification, soil organic matter (OM), soil erosion, plant nutrient status, change (∆) in nutrient stock, and greenhouse gas emissions (GHG).

Requirement	Soil acid.	Soil OM.	Soil erosion	Pant nut.	∆ nut. stock	GHG
Trained staff, computer, indicator spreadsheet, record-keeping system	Y	Y	Y	Y	Y	Y
APSIM software, weather and soil data	Y	Y			Y	Y
Manager records (OMP8 data base)	Y	Y		Y	Y	Y
Erosion photo score cards			Y			

Table 2. Requirements for producing each stream-based indicator

Requirement	Turbidit y	Sludge in streams	Aquatic vegetation	Riparian condition
Trained staff, computer, record-keeping system	Y	Y	Y	Y

GPS	Y	Y	Y	Y
Secchi tube & disc	Y			
Pole, tape measure		Y		
Video camera, still camera, editing software				Y

7.1.2 Indicator of soil acidification

There are a number of causes of soil acidification associated with agricultural production but the dominant ones are the use of ammonium-based fertilisers, product export, and non-use of liming materials.

As crop performance is a function of soil pH, setting a critical pH, below which it is unacceptable, would be good point of reference. An indicator of sustainability of a system might be to then determine how long it will take to reach this level. Thus "time to critical pH" may be a useful indicator of sustainability because a) it integrates current pH, acidification rate (NAAR), and vulnerability to pH change (pHBC), and b) it has meaning in relation to current and future land uses. However, the setting of a critical pH might be difficult because a) it is crop dependent and thus may not allow for future land use options, b) time to critical pH may mask inappropriate management strategies simply because of a high pH buffering capacity of the soil it is applied to, and c) to detects trends in soil acidification over time, the lateral and vertical variability of soil pH must be taken into account. Thus, the actual amount of acid introduced into the system (NAAR) is more relevant as an indicator of soil acidification as it is an absolute measure of acid production resulting from FFB production. A level of zero indicates no acidification and a negative level indicates acid soil pH remediation. NAAR can be calculated as shown in Figure 2.

Temporal scale: annual
Spatial scale: a management unit (one to several fields)

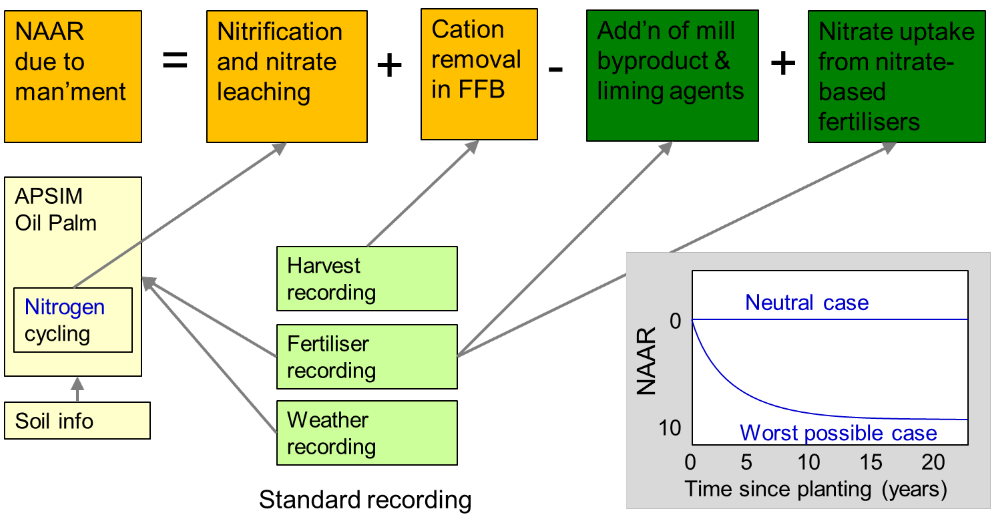


Figure 2. Soil acidification indicator (NAAR): the equation and the data inputs required to estimate the parameters, with light green indicating data collected as a matter of course by managers. The inset shows how NAAR could be plotted against palm age and compared to calculated benchmarks for the worst possible and neutral cases.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings include: yields, inputs of fertilisers and mill by-products, weather, landscape position and slope (influences leaching) and soil type (initial pH, pH buffering capacity, leaching rate).

7.1.3 Indicator of soil organic matter status

For indicators of soil organic matter we propose using a carbon balance approach rather than measuring actual soil organic matter contents. Soil organic matter content is difficult to quantify due to its extreme variability. Although occasional measurements must be made, and are useful, the main indicator is based on the concept that 'the higher the inputs the higher the soil organic matter content'. Inputs can be determined by modelling, based on site-specific inputs such as palm age and biomass (Figure 3).

Temporal scale: annual
Spatial scale: a management unit (one to several fields)

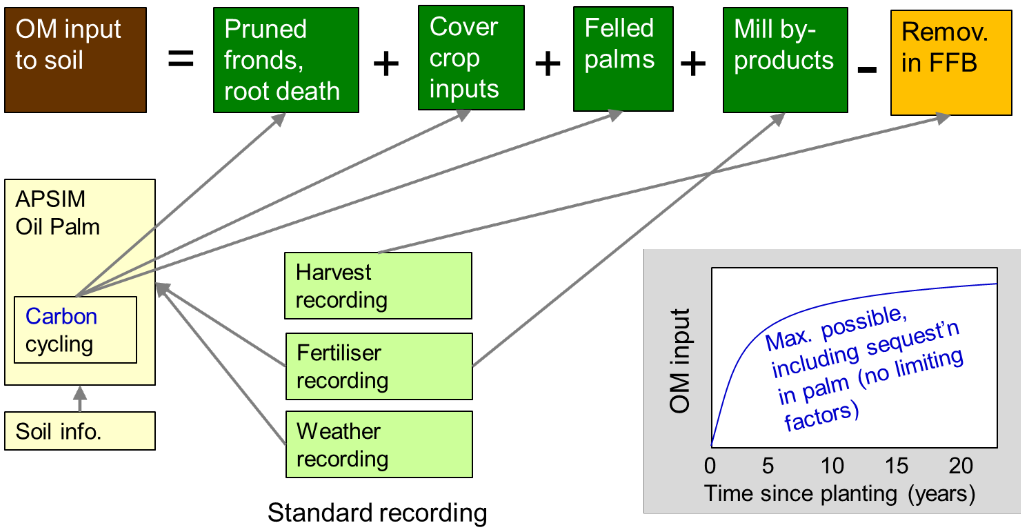


Figure 3. Soil organic matter input indicator: the equation and the data inputs required to estimate the parameters, with light green indicating data collected as a matter of course by managers. The inset shows how indicator values could be plotted against age and compared to benchmark values for the highest possible attainable in that environment.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings include: yields, inputs of fertilisers and mill by-products, weather, landscape position and slope (water balance and growth) and soil type (chemical fertility, organic matter content, physical properties).

7.1.4 Indicators of soil erosion

Soil erosion can occur in three locations: in harvest paths within the block some erosion can be expected within the weeded circle, but this is not a problem if the soil moves no further); in drains; and on roads. It can be assessed by visually scoring against photos of harvest paths, drains and roads showing a range of severity of erosion.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings include: weather; landscape position and slope; orientation of harvest paths and frond piles in relation to the slope; soil type (erodibility.); ground cover (related to palm canopy density, weeding practices, grazing by animals such as the giant African snail…); and size and catchment area of drains and roads.

7.1.5 Indicator of plant nutrient status

Plantations typically analyse the standard frond 17 leaflets and rachis for essential plant nutrients. Thus a simple indicator is the relationship between the measured nutrient in the standard sample and a deficiency/adequacy criterion. This could be a 'critical' value obtained from literature or experience or from fertiliser trials. Whatever the source of the reference value, a decision whether to increase or reduce fertiliser rates can be made.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings are: weather; landscape position and slope; soil type (nutrient holding capacity, pH); fertiliser management.

This indicator of plant nutrient status is already monitored by industry, in order to determine fertiliser recommendations. It is included here because the following indicator, change in nutrient stock, must be evaluated together with plant nutrient status. A stable nutrient stock is desirable, but only if the plant has good nutrient status.

7.1.6 Indicator of change in nutrient stock

Using a nutrient budget approach, nutrient imports to and exports from the plant-soil system can be compared to determine whether excess or inadequate amounts of nutrients are being applied. Using nitrogen as an example, a typical balance sheet is:

Nutrient balance in soil-plant system

= biological nitrogen fixation + application in fertiliser and mill wastes

–losses by erosion, leaching and conversion to gaseous forms – export in FFB.

Many of these parameters can be determined from routine measurements and records, and based on the analysis done in this project (Table 3).

Table 3. Parameters required for nutrient balance calculations and source of values.

Parameter	Measurement	Notes
Fertiliser	Company records	Fertiliser type and rate
Biological nitrogen fixation	Legume ground cover score	Pipai thesis; light penetration (palm age or leaf area index of canopy calculated from leaflet length and with and number of fronds)
Mineralisation from litter	Felling trial, ground cover score and type	Required for replant calculations, not within a plantation cycle
Returned in mill wastes	Company records (EFB etc)	nutrient analysis of EFB etc
Export of nutrients in FFB	Company records	Nutrient analysis of FFB
Losses by erosion, leaching and conversion to gaseous forms	Previous experiments	Calculate using APSIM

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings include: weather; landscape position and slope; soil type (nutrient holding capacity, pH); yield; and fertiliser/mill by-product management.

7.1.7 Indicator of greenhouse gas emissions

This indicator is designed to provide an estimate of greenhouse gas (GHG) emissions from soil in the plantation. The result can be included in a comprehensive assessment of GHG emissions, such as PalmGHG (Chase and Henson 2010; Chase et al. 2012). A full assessment of GHG emissions from field operations also includes use of machinery and the manufacture and transport of fertilisers, which are not considered here. Net emissions of GHGs from oil palm fields are small compared to those from land use conversion and mill operations and effluent (Chase and Henson 2010), but the field component is what we are interested in here.

The GHGs carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are all emitted from the soil. Their total emission is expressed in CO_2 equivalents (CO2-e). Of those gases, CH_4 emissions are only significant in anaerobic situations and can be considered insignificant in reasonably well-drained oil palm fields that are the norm in PNG. CH_4 emission is of course a significant factor in the overall GHG balance, due to its production in mill effluent ponds (Chase and Henson 2010). CO_2 is absorbed (sequestered) by the plants in photosynthesis and emitted by the plants and soil during respiration. Over the course of an oil palm crop cycle we can assume that those inputs of CO_2 are balanced and that that there is little net change in soil plus plant C over time and thus no little or no net CO_2 emission. The main component of in-field GHG emissions is thus nitrous oxide (Chase and Henson 2010).

This indicator is an estimate of N_2O emissions from the field. Emissions are 'direct', which means emitted in the field, or 'indirect', which represents emissions that occur downstream of the field, but which originate from N (mostly in the form of nitrate) that was lost from the field by leaching. It is far too complex and expensive to routinely monitor N_2O emissions, so the indicator estimates them using known relationships with determining factors and a crop system model (Huth et al. in press). N_2O emissions are sensitive to management.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings include: weather; landscape position and slope; soil type (wetness, organic matter content); and fertiliser/mill by-product management.

7.1.8 Indicator of stream turbidity

Turbidity, as measured by Secchi tube or disc, provides measures of suspended particle load, and/or discolouration of water that leads to sedimentation and/or reduced light penetration into the water column. Turbidity represents erosion and loss of soils and delivery of palm oil mill effluent (POME) to streams. Increased turbidity and delivery of POME both degrade the quality of water, particle load increases sedimentation, and reduced light penetration negatively impacts benthic productivity. These problems contribute to a reduction in the ability of streams to support historical levels of biodiversity.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings include: mill effluent treatment processes; proximity of mill outfall, roads, gravel extraction sites and gardens; discharge and time within hydrograph; and riparian condition.

7.1.9 Indicator of sludge in streams

Sludge provides an effective measure of pollutant discharge into stream systems. Fibrous sludge deposits prevent natural benthic processes from occurring in stream beds, change the nature and function of in-stream habitat and deliver organic material to streams that would normally have a low nutrient status.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings: mill effluent treatment processes; proximity of mill outfall; size and hydrology of receiving stream.

7.1.10 Indicator of aquatic vegetation

Estimates of the extent of aquatic vegetation provide a proxy measure for leakage of nutrient from plantations into low nutrient stream systems. Excessive inputs of nutrient can lead to eutrophication of streams with subsequent loss of aquatic biodiversity and degradation of water quality. In well flushed systems eutrophication may be less likely but degradation of water quality and increased plant growth are still problematic issues for freshwater streams. Ultimately excess nutrient is delivered to coastal waters where it may have detrimental effects on coastal ecosystems.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings: proximity of mill effluent outfall and sites of fertiliser application; stream reach characteristics.

7.1.11 Indicator of riparian condition

Riparian surveys provide a reliable method of assessing change in riparian condition over time, thereby documenting improvements that have a beneficial effect on health of aquatic ecosystems and identifying areas of degradation where attention is required. Healthy riparian buffers promote improved water quality through reductions in sediment and nutrient delivery to streams (4.3, 4.4), provide shade, which can help reduce growth of aquatic vegetation and moderate water temperatures (potentially critical for some aquatic fauna) and supply complex habitat for aquatic fauna through production of woody debris (5.1, 6.11, 7.3, 8.1). Together these benefits are crucial for maintenance or improvement to in-stream biodiversity. Water-based riparian surveys provide a complete inventory that is rarely possible with land-based surveys because access to the riparian along the whole length of the stream is possible. Consequently water-based surveys are both time efficient and can provide a level of completeness not possible with land-based surveys. The completeness of water-based surveys means they are ideal for identifying problem areas that can then become the focus of specific on-ground evaluation and remedial action.

Risk factors that need to be taken into account when interpreting results and deciding management responses in current crop or in future plantings: nearby population and pressure to grow cash or food crops.

7.2 Soil sampling designs

Three ways of accounting for spatial variation within the repeating tree unit (a hexagon) were deduced. For visible patch patterns, patches can be delineated and sampled separately. For radial patterns, measurements can be made in radial transects or a triangular portion of the tree unit. For any type of pattern, including unknown patterns, a 35-point triangular sampling grid covering the half-hexagon repeating unit is appropriate (Figure 4). In zones with steep gradients in parameters, sampling density has a large influence on calculated mean values. The methods defined (reported by Nelson et al. 2014) provide a basis for representative sampling and calculation procedures in studies requiring scaling up from point sampling, but more efficient methods were needed for routine sampling.

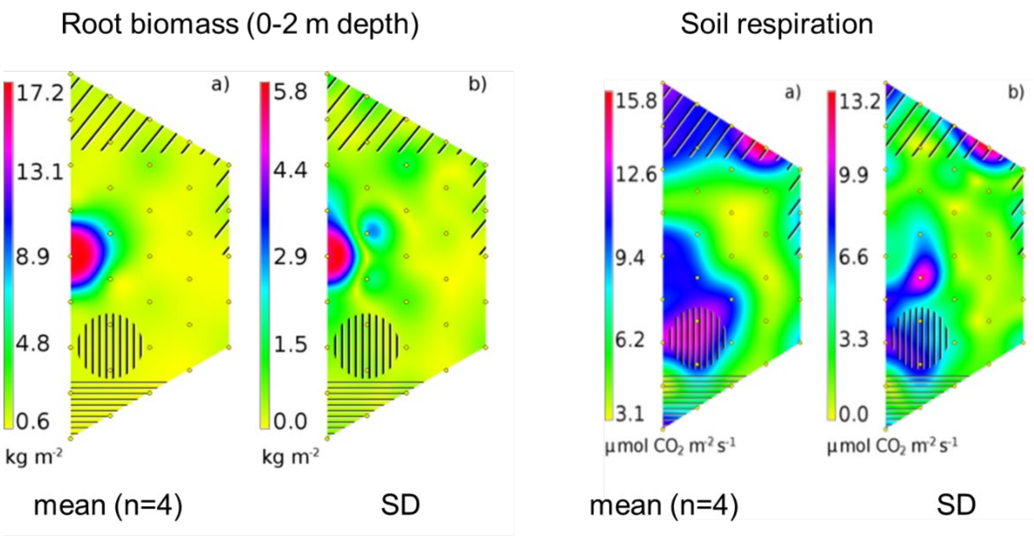


Figure 4. Interpolated surfaces of root biomass and soil respiration in the repeating unit of plantations, derived from measurements made on a 35-point grid (points shown) in Bebere plantation (20-year old palms). The hatched areas are the frond pile (top), harvest path (bottom) and zone of EFB placement (circle).

We designed a sampling approach starting with the premise that it will be most feasible and simple if sampling can be carried out by no more than two people and does not require them to make any calculations. To meet that specification we assessed linear transects that start at one palm stem and end at another palm stem, visible from the first. Six transects, traversing 2-6 rows (crossing frond piles and harvest paths in equal numbers), were feasible and gave even coverage of the tree unit. Even coverage of the tree unit is indicated by taking the location of the portion of the transect within each tree unit it traverses and redrawing those portions as lines within a single tree unit (Figure 5).

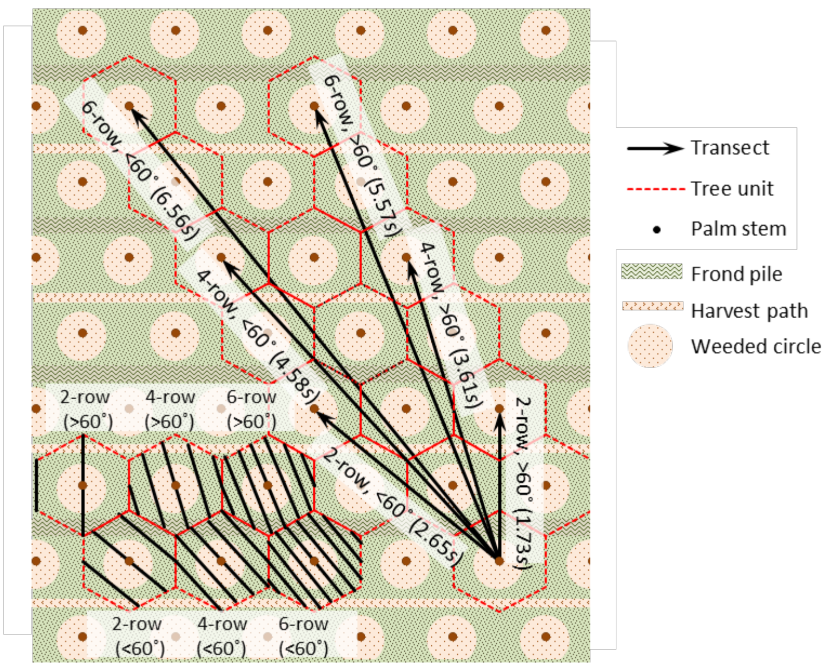


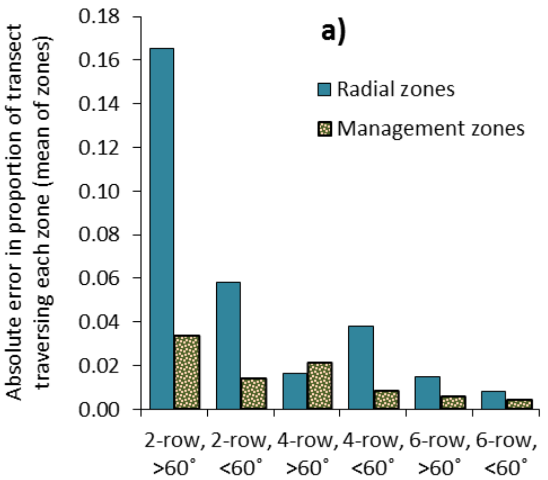
Figure 5. Section of an oil palm plantation, showing orientation of palms, management zones and the 6 sampling transects assessed, with lengths in brackets (*s* = triangular palm spacing). Also shown are 'tree units' (the repeating unit in the plantation) traversed by the transects and, in the lower left part of the figure, the equivalent coverage of one tree unit by each transect.

The longer the transect, and the higher the sampling density along the transect, the closer the coverage of each radial and management zone was to their areal proportion in the plantation. With 10-30 sampling points some of the radial zones were missed entirely. The mean errors in proportions of the radial zones and management zones estimated by the transect decreased with transect length and sampling density (Figure 6). If we take <2% as an acceptable absolute error in coverage of zones by the transects, then the 6-row >60˚ transect was the shortest acceptable transect. The length of that transect is 50.1 m for a planting density of 143 ha^{-1}. Taking that transect, absolute error in zone coverage reached <4% with 50 sampling locations (Figure 6). The spacing of those points along the transect is approximately 1.0 m for a planting density of 143 ha^{-1}.

The effect of sampling point density was further examined with measured data (Figure 7). For the 6-row >60˚ transect, deviation between transect-derived mean values of parameters and the overall mean values decreased with sampling density. Increasing the number of sampling points from 10 to 50 decreased the maximum deviation from 15.9 to 5.6% for respiration, 7.5 to 0.5% for ECEC, 6.9 to 0.6% for total C content, 4.4% to 0.2% for pH, and 3.2 to 0.2% for bulk density.

We agreed that an easily and consistently achieved way of defining zero sampling depth in the frond pile is to choose the depth at which fragments of fronds greater than 10 mm in size are no longer encountered in an area of approximately 0.4 x 0.4 m.

In conclusion, we suggest that the transect method presented here be used as a standard method for producing representative composite soil samples for monitoring commercial oil palm fields. Sampling transects can be set up by two operators, using no measurements. The 6-row >60 ˚ transect, with 40 sampling points, provides acceptable representation of tree-scale variability. For a plantation planted at 143 ha^{-1}, this means a 50.11 m transect (between palm centres), with sampling points at 1.22 m intervals (starting 1.22 m from the centre of the first palm). Several transects should be sampled within each management unit, with the number depending on the size and variability of the management unit. Zone- or distance-from-stem based approaches cannot be used to monitor changes from one cycle to the next because the position of the zones and stems changes. Thus, importantly, this approach can be used to follow temporal trends from one crop cycle to the next (and within a crop cycle). The number of samples prepared for analysis would not need to be any larger than from the current method, but the coverage is more representative.



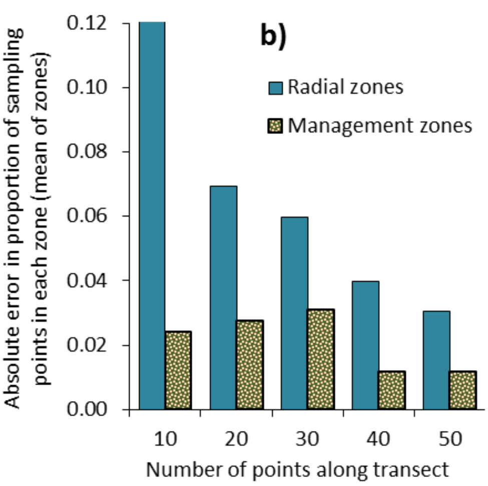


Figure 6. Mean of absolute differences between actual proportion of the plantation in each zone (see text for zone dimensions used) and a) proportion of the transect traversing that zone (6 transects shown in Figure 5), or b) the number of sampling points in each zone, for the 6-row, >60˚ transect.

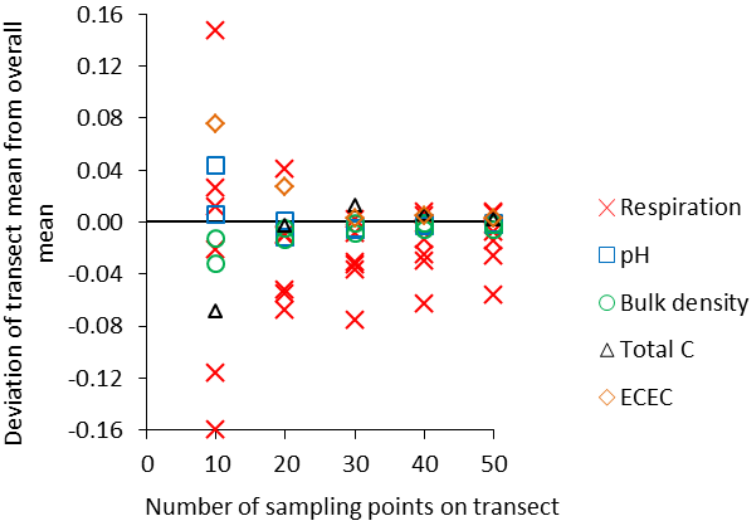


Figure 7. Difference between mean value of points along a simulated transect (6-row, >60˚, see Figure 5) and the spatially averaged mean value for the entire area, expressed as a fraction of the overall mean value, for respiration (6 plots), pH (2 plots), bulk density (2 plots), total C content (1 plot) and effective cation exchange capacity (ECEC, 1 plot). All values originate from a spline interpolation from 35 measurement points on a half-hexagon grid and assuming that the pattern is replicated across the entire area.

7.3 Palm carbon and nutrient stocks over the growth cycle

Palms of three ages (5, 10, and 20 years) were sampled and analysed for biomass, nutrient contents and other vegetative parameters.

Frond biomass

Frond 17 biomass (*F17DM*) could be estimated from petiole cross section (*PCS*) by

$F17DM = 0.077\ PCS + 1.65$, $r^2 = 0.89$ (Figure 8).

Using this relationship, along with some others detailed in (PNGOPRA 2012), it is possible to calculate the total dry matter of fronds on a palm. For example, if frond 17 has a PCS of 50 cm^2, and there are 33 fronds on the palm, our relationships would predict a total frond weight of 175 kg. Frond weights estimated using our results are similar to those made using relationships developed previously by Corley (1971) (Table 4), but the new relationship will be used as it was determined with current genetic material.

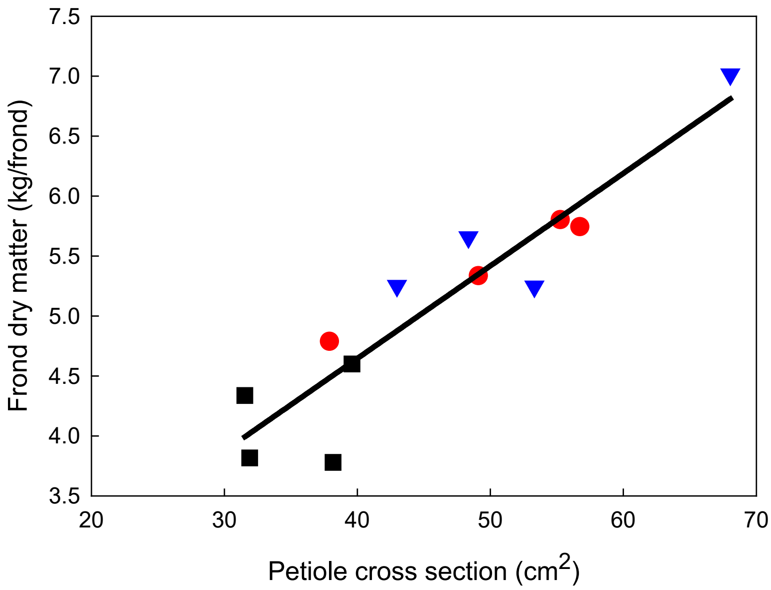


Figure 8. Relationship between frond dry matter and petiole cross section for frond 17 of palms that are 6 years old (squares), 10 years old (circles), or 20 years old (triangles).

Table 4. Comparison of predicted frond 17 dry matter and total frond dry matter by the method presented in this report and that of Corley et al. (1971) for a range of petiole cross sections (PCS). The calculations were made assuming 33 fronds on the palm.

PCS (cm^2)	Frond 17 Dry Matter (kg/frond)			Total Frond Dry Matter (kg/palm)		
	This paper	Corley	Difference	This paper	Corley	Difference
35	4.3	3.8	+0.5	139	125	+14
50	5.4	5.3	+0.1	177	175	+ 2
65	6.6	6.8	-0.2	215	226	- 11

Nutrient content of fronds

Using relationships developed for frond age and nutrient concentration, we have estimated total nutrient content of various fronds from a standard frond 17 measurement. These data can now be used to assess nutrient budgets and nutrient movement for a single palm or an area (Table 5).

The results show that large amounts of nutrients are stored and returned to the soil each year and that this varies with palm age. There is 148 kg of dry matter stored in just the fronds of a single 6-year old palm and this increases with palm age. This biomass contains several kg of N and K and 65 kg of C; all increasing with palm age.

The story on a 'per ha' basis is of course the same as the per palm basis as it is simply a multiple of the planting density. However, it is the magnitude of these values which is relevant. The amount of N and K either stored or recycled through pruning is similar to the annual rates of application of that nutrient in fertiliser. Thus the management of canopy and pruning is vital to reducing inputs. It is expected that the trunk will be a major store of nutrients and provide a major input upon replanting.

Table 5. Biomass and nutrient contents of the palm crowns and pruned fronds for different aged palms. We have assumed 33 fronds per palm, based on the measurements made, and 26 fronds pruned per year. The planting densities of the palms we measured are 126, 130, 130 palms per ha for 6-, 10-, and 20-year old palms respectively.

Stored in Fronds (per palm)					Stored in Fronds (per ha)				
Age (y)	Biomass (kg)	N (kg)	K (kg)	C (kg)	Age (y)	Biomass (kg)	N (kg)	K (kg)	C (kg)
6	148	1.3	2.0	65	6	18,605	163	253	8,186
10	174	1.5	2.4	76	10	21,879	198	307	9,627
20	188	1.6	2.6	83	20	23,714	214	333	10,434
Returned in pruned fronds (per palm)					Returned in pruned fronds (per ha)				
Age (y)	Biomass (kg)	N (kg)	K (kg)	C (kg)	Age (y)	Biomass (kg)	N (kg)	K (kg)	C (kg)
6	117	1.0	1.6	52	6	14,764	128	199	6,496
10	138	1.2	1.9	61	10	17,362	156	242	7,639
20	149	1.3	2.0	66	20	18,819	169	262	8,280

Frond area

Frond area is used in the calculation of light interception by the canopy and thus important for the model. Total area of leaflets in a palm was calculated from the area of leaflets along a frond and then aggregated up to the whole palm. The relationship derived for this estimate is given in PNGOPRA (2012) and a typical calculation is shown below.

In the example, Palm age: 12 yrs; Number fronds: 38; Petiole thickness: 4.8 cm; Petiole width: 9.1 cm; Rachis Length: 651 cm; F17 Leaflet Length (at 0.6 sampling point): 95.7 cm; F17 Leaflet Width (at 0.6 sampling point): 5.6 cm; F17 Number of leaflets (on one side): 197; and equation numbers are from PNGOPRA (2012).

Step 1: Calculate total leaflet area of F17 from Equation (10).

For example, from equation (10);

= (LL x LW x 226) + PCS x 1337) – (RL x 169) + 28112

= (95.7 x 5.6 x 226) + (4.8 x 9.1 x 1337) - (651 x 169) + 28112

= 97611 cm^2

Step 2: Calculate slope of total leaflet area vs frond number from equation ()

= -629 + 585 x (1-EXP(-0.184 x Age)

= -629 + 585 x (1-EXP(-0.184 x 12)

= -108

Step 3: Calculate y-intercept of total leaflet area vs frond number

= TLA F17 – (slope x 17)

= 97611 – (-108 x 17)

=99452

Step 4: Calculate total leaflet area for whole palm (integrate the linear equation from step 3)

= (-108 x $NumberFronds^2$) + (99452 x NumberFronds)

= (-108 x 38^2) + 99452 x 38

= 3700990 cm^2

= 370 m^2.

Mass and nutrient content of roots

Root mass increased with age, up to 18 t DM/ha at 20 years of age. Most of the root mass was close to the stem, increasingly so with age (Figure 9). Samples have been analysed for C and N content and are currently being analysed for the content of other nutrients.

Samples of the trunk and cabbage have been taken, mass determined, and nutrient content is being analysed.

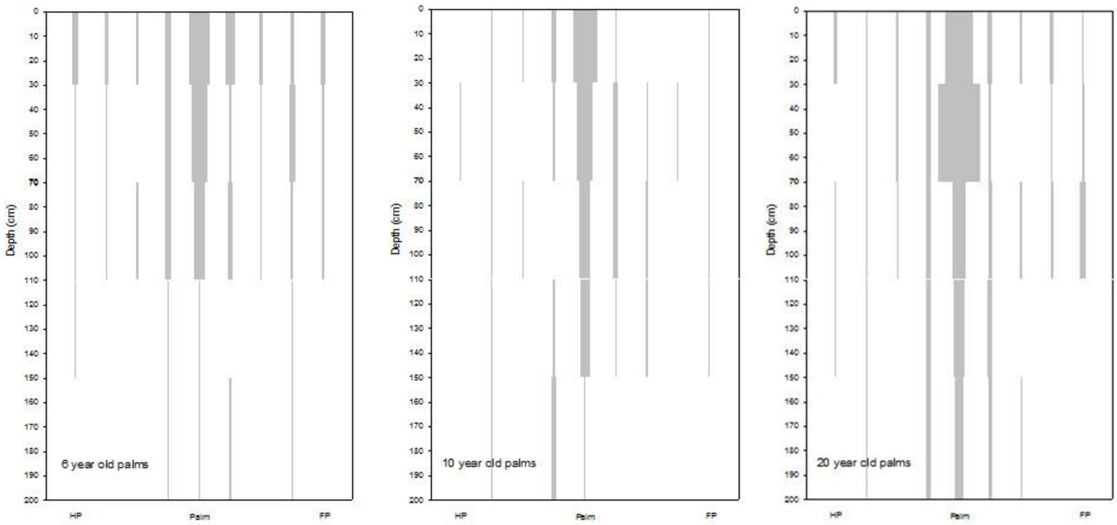


Figure 9. Distribution of roots from the harvest path to the frond pile (left to right in each profile) for 6-, 10-, and 20-year-old palms (left to right). The width of the bars shows the relative root mass density for that depth increment.

Mass and nutrient content of trunk and cabbage

Trunks of 20-year-old palms had an average volume of 1.3 m^3 (range 1.2 – 1.4) and average dry weight of 286 kg (range 234 – 373 kg). This represents an average C content of 126 kg and K content of 5.0 kg. The average dry matter is similar to Malaysian palms of the same age (Corley and Tinker 2003). Similarly, the nutrient concentrations of different palm tissues are similar to those in Malaysian palms (Ng et al. 1968, cited by Corley and Tinker 2003). However, the K content five-fold higher than that of Nigerian palms (Tinker and Smilde 1963, cited by Corley and Tinker 2003), probably due to the higher K concentration in the trunk tissues (1.7% in this study vs 0.19% in theirs).

Cabbage contributes only a small amount of dry matter to the whole palm (6.6 kg) with the majority coming from the spear leaves. Nutrient contents have not yet been analysed but presumably will not contribute much to the overall palm nutrient content compared with trunk and leaves.

7.4 Soil carbon and nutrient content over the palm growth cycle

Following conversion of grassland to oil palm, there was no overall significant change in soil organic C (SOC) stocks (to 1.5 m depth) over 25 years, but stocks increased in 7 of the 9 sites (Figure 10). On average, in the 0-0.05 m depth interval, 0.79 kg m^{-2} of SOC was cycled, meaning that this amount of the original grassland-derived SOC stock was replaced by inputs from oil palm. Over the whole soil profile (0-1.5m), 3.4 kg m^{-2} of SOC was gained from new oil palm inputs with no significant losses. Compared to other studies of SOC stocks in soils that are converted to agricultural land uses, SOC in these soils was more resistant to change. Black carbon produced in grassfires could partially but not fully account for the persistence of the original SOC stocks. The balance between grass- and oil palm-derived carbon also appeared to be related to soil nitrogen contents. In the majority of cases, conversion of grassland to oil palm plantations in this region resulted in net sequestration of soil organic carbon. Results are described in detail by Goodrick et al. (2014).

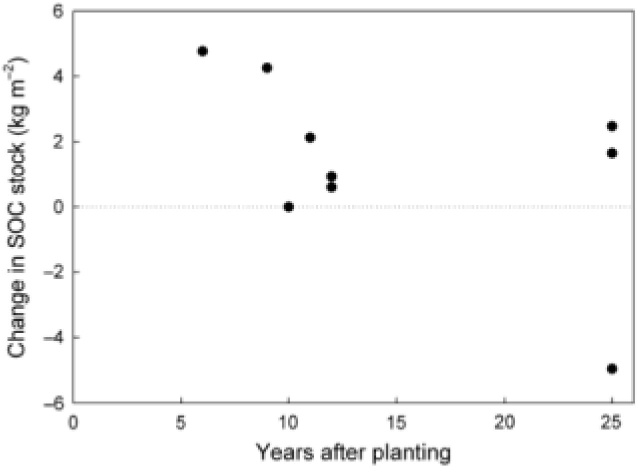


Figure 10. Difference in soil organic carbon (SOC) stock (0-1.5 m depth) in oil palm blocks planted on grassland, compared to adjacent grassland, plotted against time since the oil palm was planted.

The only consistent and significant change in soil fertility during the 25 years following conversion of grassland to oil palm in these recent volcanic ash soils was acidification and a subsequent decrease in exchangeable cation contents in surface layers (Figure 11). Soil pH and exchangeable cation contents did not reach excessively low levels under oil palm during the 25-year period studied, but they may need to be managed to prevent them becoming a problem for plant growth in the future. Results are described in detail by Nelson et al. (in press).

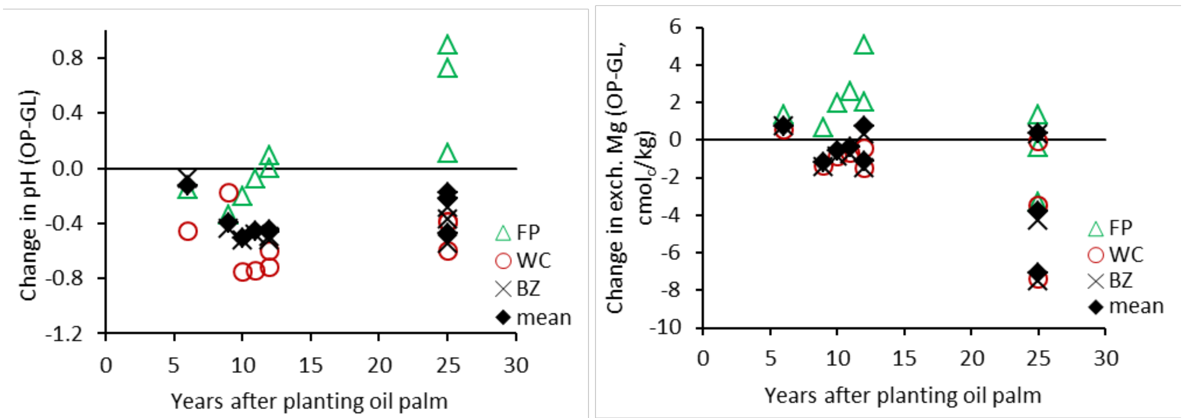


Figure 11. Difference between soil pH (left) and exchangeable Mg (right) under oil palm (OP) and adjacent grassland (GL) versus age of the oil palm, showing values for the oil palm frond pile (FP), weeded circle (WC) and between zones (BZ) areas and the area-weighted mean of those zones, at 0-5 cm depth.

7.5 Palm and soil carbon and nutrient contents over the replant phase

Soil and all biomass was comprehensively and representatively sampled and analysed in the pre-felling phase and in the replant phase, at 6 and 12 months after replanting. The data are being checked and analysed so they can be published. PNGOPRA will continue the trial, with the 24-month sampling to be carried out in Sep/Oct 2014.

7.6 Soil acidification- effects of N fertiliser

Soil pH was significantly affected by N source, N rate and depth. Ammonium chloride and sulphate of ammonia were the most acidifying fertilisers and urea was the least acidifying (Figure 12). The acidification was occurred under the zone where fertiliser was applied, to a depth of approximately 0.6 m. pH buffer capacity of the soils was not significantly affected by the fertiliser treatments.

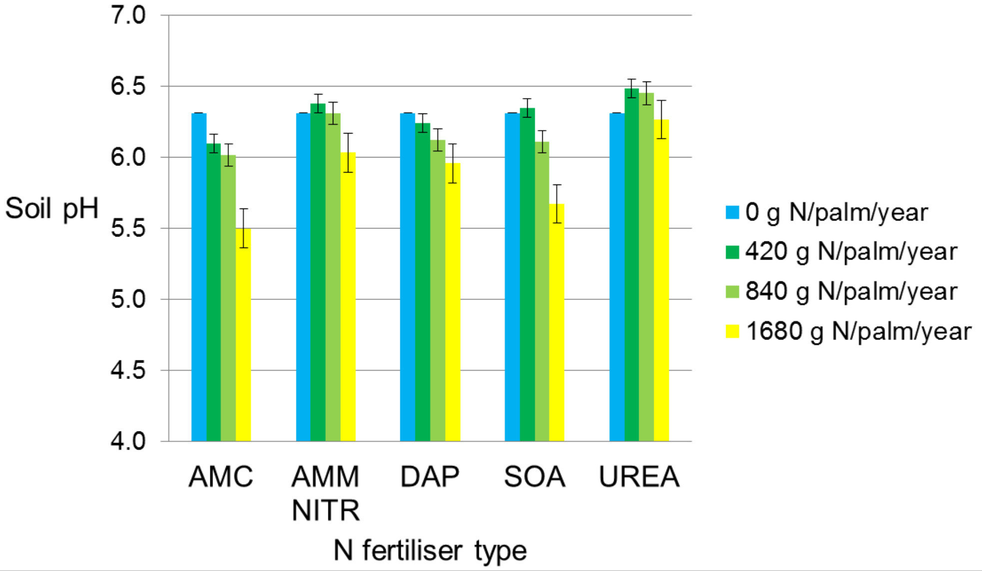


Figure 12. Soil pH (0-0.1 m depth, taken over 35-point palm-scale grids), as affected by type and rate of fertiliser applied over the previous 10 years. AMC is ammonium chloride, AMM NITR is ammonium nitrate, DAP is diammonium phosphate and SOA is sulphate of ammonia.

7.7 Biological nitrogen fixation

Legume standing shoot biomass under 2- to 25-year-old plantations was 144 to 443 g/m^2 and litter was 100 to 804 g/m^2, equating to an estimated mean 400 kg/ha shoot biomass per plantation. Legume shoot N was 3.5 to 12 g/m^2 while the litter N was 1.8 to 22 g/m^2 with a mean plantation shoot N estimate of 10 kg/ha. Dependence on N_2 fixation was highly variable, ranging from 18 (*P. phaseoloides*) to 75% (*C. mucunoides*), and did not show any relationship with age of plantation but was significantly lower where soil nitrate-N content was high.

Amounts of N fixed were 1.5 to 4.4 g/m^2 for standing shoot and 0.9 to 6.0 g/m^2 for litter equating to plantation estimates from 0.3 (*C. mucunoides*) to 34 (*P. phaseoloides)* kg N fixed/ha. These were conservative estimates since the study did not account for N in roots and furthermore only measured standing biomass rather than annual production. Estimates were based on measures of actual percent legume cover (0.6 to 44%) - hence indicated potential for increasing inputs of fixed N by managing for greater cover. Further research is recommended to quantify legume biomass production over time, including litter and root accumulation and turnover.

7.8 Crop system modelling

The model captures observed trends in growth, canopy development and yield components with respect to time after sowing and rates of nitrogen fertiliser (Figures 13 and 14). Simulated responses of the crop to climate and nitrogen supply appear to be captured by the model and results are given in detail by Huth et al. (2014). The model can be used to simulate stocks and fluxes of C and N (Figures 15 and 16). Simulated N_2O

emissions and nitrate leaching losses during the mature phase at Sangara were similar to those measured by Banabas (2007) and Banabas et al. (2008a,b) in the same plantation.

The use of an existing crop system modelling framework greatly increased the efficiency in developing a model for a new crop system. The use of existing soil water, carbon and nitrogen models, and an existing framework for developing detailed crop models allowed a relatively straightforward construction of model for a somewhat complex cropping system. However, whilst application of the model is promising, availability of key data is likely to restrict use of the model. Long term weather data and local soil hydraulic and chemical properties are not available in adequate detail for many of the major oil palm production areas in PNG. Furthermore, system complexity such as small-scale heterogeneity within the oil palm ecosystem is important but is both difficult to measure and model. Whilst modern modelling frameworks have addressed many of the constraints on complex model development, the use of dynamic models for agroforestry systems in developing countries is likely to become limited by data availability.

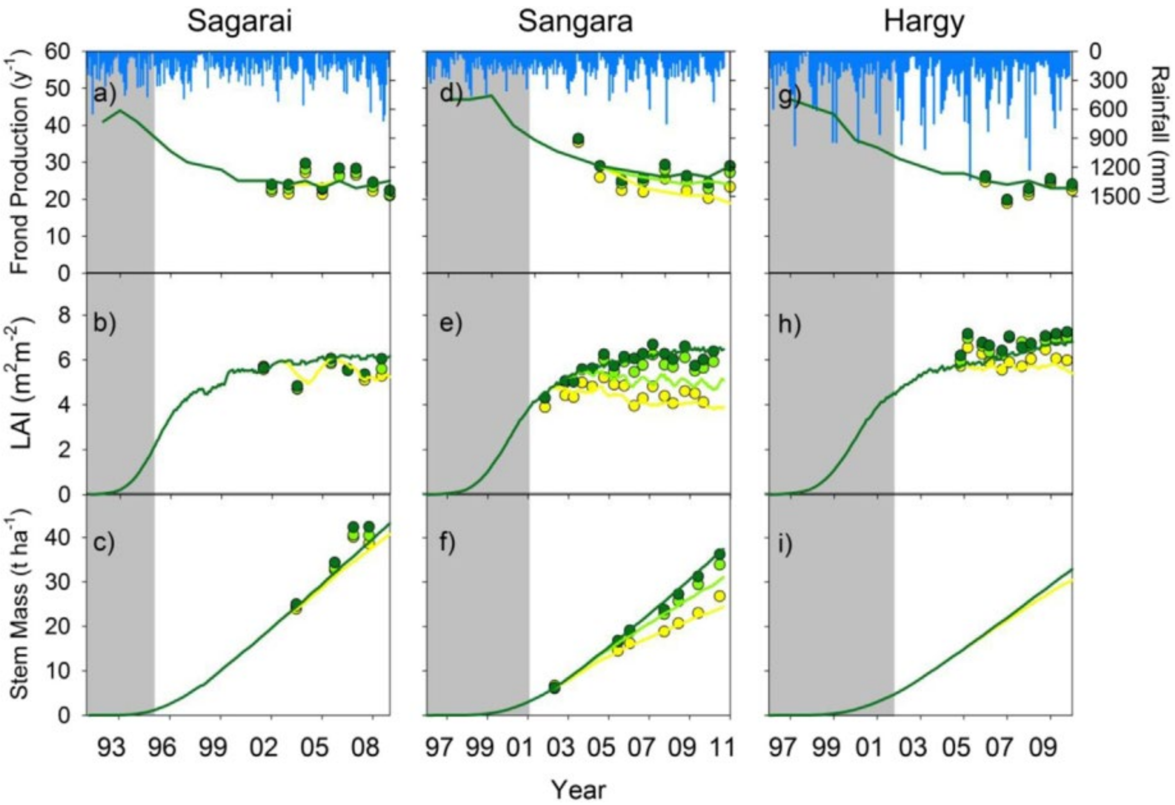


Figure 13. Observed and predicted growth parameters at the three model testing sites. Points are measured data and lines are model outputs. Colours refer to annual N application rates per palm, being 0, 0.42 and 1.68 kg for yellow, light green and dark green, respectively.

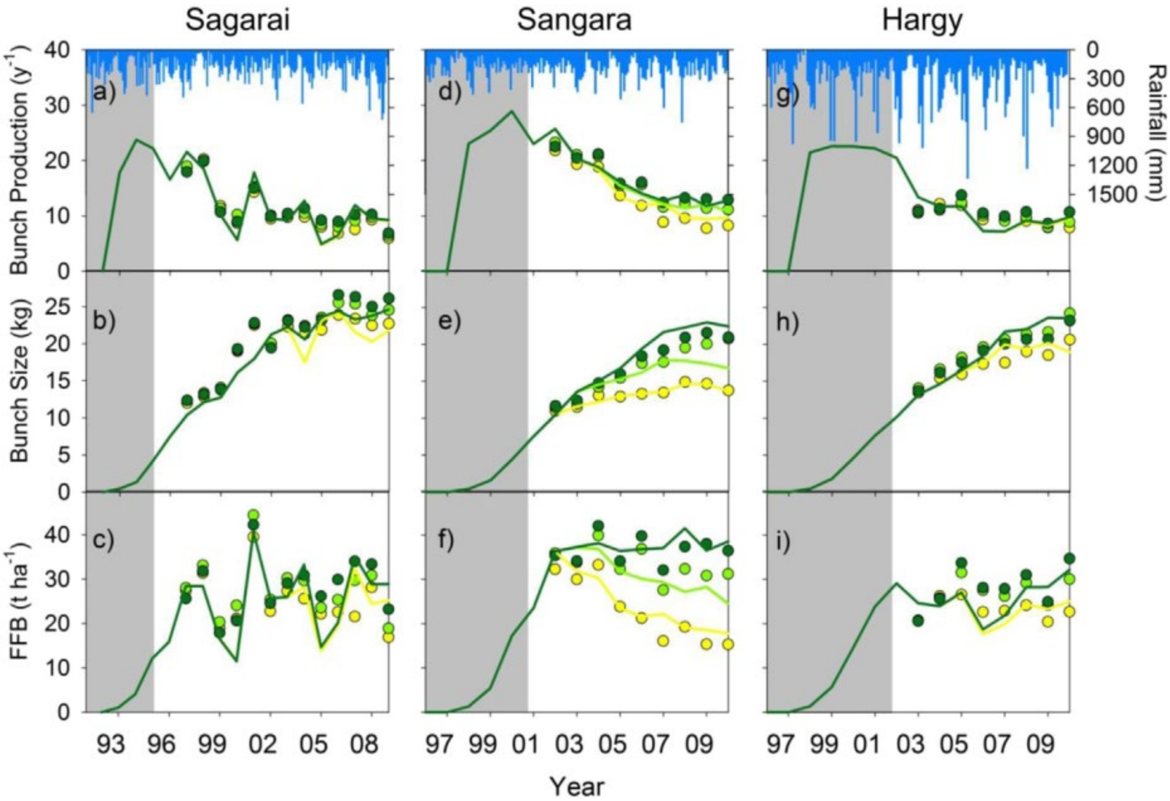


Figure 14. Observed and predicted yield and yield components at the three model testing sites. Points are measured data and lines are model outputs. Colours refer to annual N application rates per palm, being 0, 0.42 and 1.68 kg for yellow, light green and dark green, respectively.

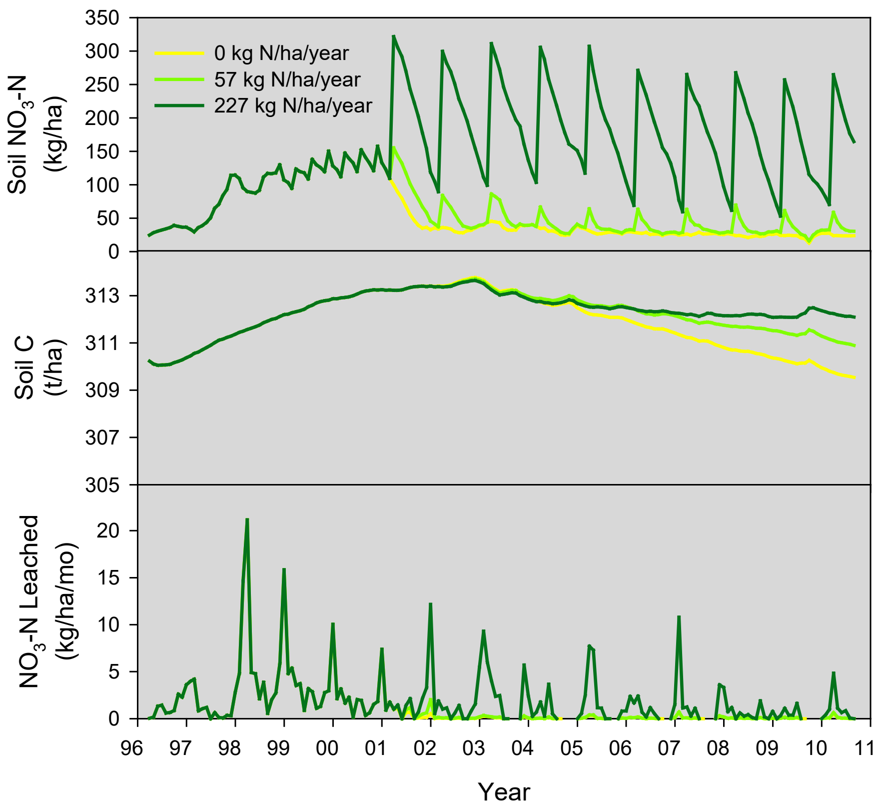


Figure 15. Simulated stocks and flows of C and N in soil at the Sangara site.

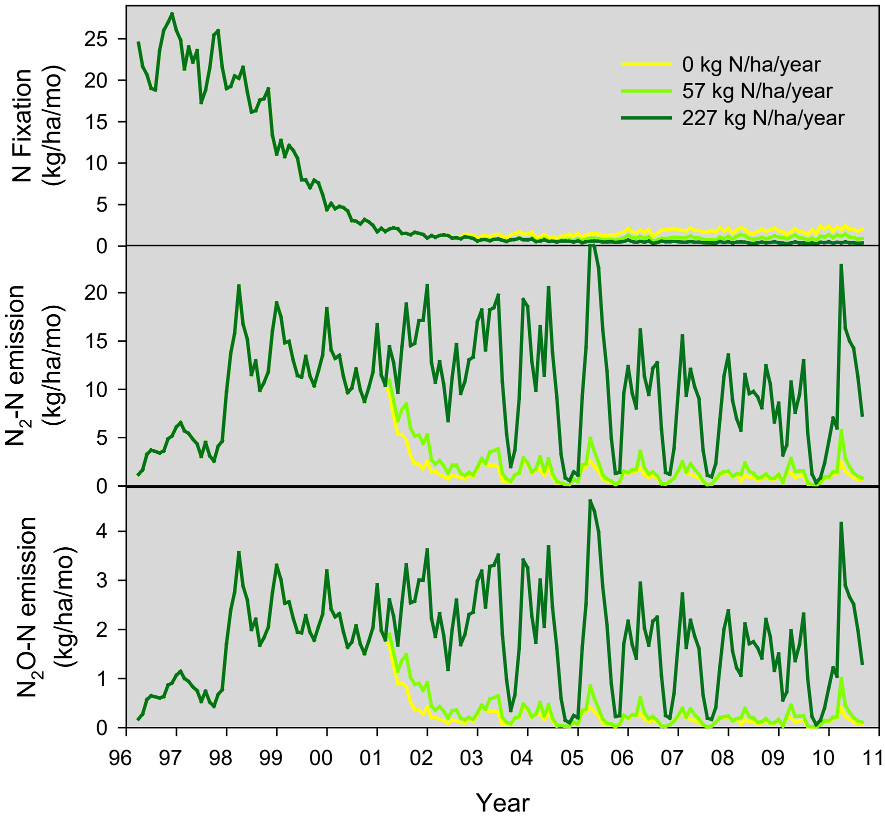


Figure 16. Simulated fluxes of N between soil and the atmosphere at the Sangara site.

7.9 Water quality assessment

Detailed water quality assessments were completed for 67 sites in 23 stream systems in WNB. Water quality assessments highlighted problem areas, the main ones being release of palm oil mill effluent into streams and elevated levels of turbidity from a number of sources. Elevated turbidity and low dissolved oxygen (DO) levels were associated with streams receiving mill effluent. Gardens, fords and roadside drains, gravel extraction operations and new palm oil plantings appeared to be the main sources of turbidity in oil palm areas. There was also evidence of turbid water entering the upstream boundaries of plantations but the specific sources for this could not be unequivocally identified.

Water temperature, pH, TDS and salinity were generally consistent with patterns expected along an upstream-downstream gradient and among streams with potentially different geomorphology. Previous WNB studies have suggested that conversion of natural riparian vegetation to oil palm resulted in increased water temperatures however we found no such relationship between water temperature and type of riparian vegetation.

Turbidity varied among our sampling sites for a number of reasons including rainfall events, gravel extraction operations un-bridged road crossings and bankside gardens. In a few instances water entering upstream boundaries of palm plantations had elevated turbidity readings but the ultimate source of that turbidity could not be reliably determined. Generally turbidity levels were low (< 10 NTU) among similar stream types. Most elevated readings were directly related to local events such as traffic on road crossings or run-off from roadside drains during rainfall events. There was no evidence to suggest that these individual events had more than a short-term, localised impacts. However it is likely that in combination they do contribute appreciably to background turbidity levels over a much larger spatial scale.

Effluent from palm oil mills substantially increased turbidity levels in receiving streams and carried high loads of fibre and dissolved material that produced a tannin-like colouration in the water. Effects of outfalls were detectable up to two kilometres downstream from sources. The distance over which outfall effects could be detected depended on a number of factors; volume of effluent discharge, volume of clean-water flow through the stream itself and the number of clear tributary streams entering between outfall and recording site.

Streams receiving effluent had low DO saturations compared to adjacent natural systems and adjacent plantation drains, however this problem was quite localised (Figure 17). If low DO water is a direct result of pond effluent entering streams then there is an imperative to improve pond management and move towards alleviating the problem.

Phosphate levels tended to be elevated in smaller, slow flowing streams and at this point in time it is unclear why. Possible sources of phosphate in those streams include fertilisers, soaps and detergents or possibly different geomorphology and/or water sources.

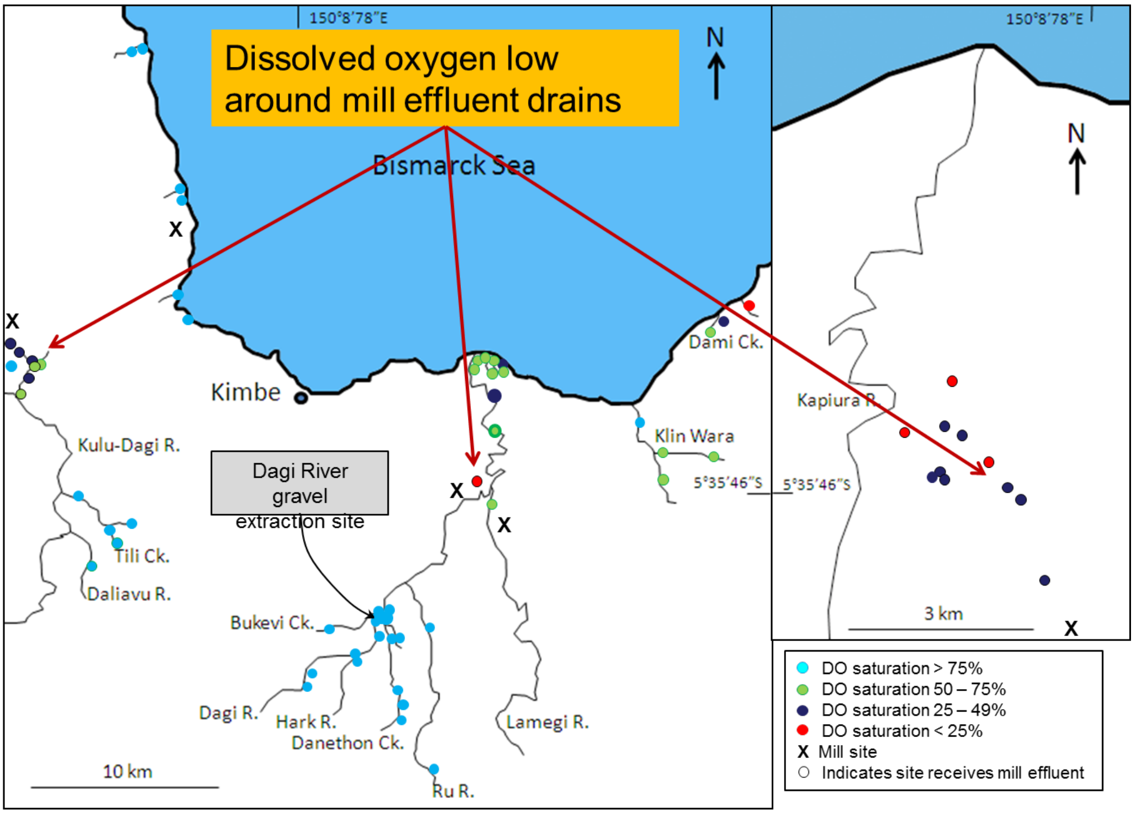


Figure 17. Dissolved oxygen content in the Dagi and Kapiura systems.

7.10 Riparian condition assessment

Riparian condition assessment indicated a high level of degradation, just 33.3% of upland and 2.5% of lowland sites retained natural riparian buffers along streams (Figure 18). In freshwater reaches of the Dagi River, the largest river investigated, 80% of the riparian was classified as degraded or very degraded and just 11% retained intact natural vegetation (all in upstream reaches) based on Google Earth images from 2008. In 2013 the amount of intact natural riparian had reduced to 4%, largely as a result of conversion of riparian zones to gardens.

At both the regional scale (site-level assessment) and for the Dagi River (Google Earth & Video transect) riparian buffer zones were in very poor condition. In 2013 just 4% of the natural riparian remained along the Dagi River. Healthy riparian vegetation provides shade, refuges and food for aquatic communities. The shading effect is particularly important in the tropics where it is a major moderator of stream temperatures. The riparian zone is also a critical contributor to in-stream structure that increases habitat diversity, and in turn species diversity. Consequently loss of riparian buffers changes the way in-stream processes function and degrades habitat quantity and quality and modifies food resource availability.

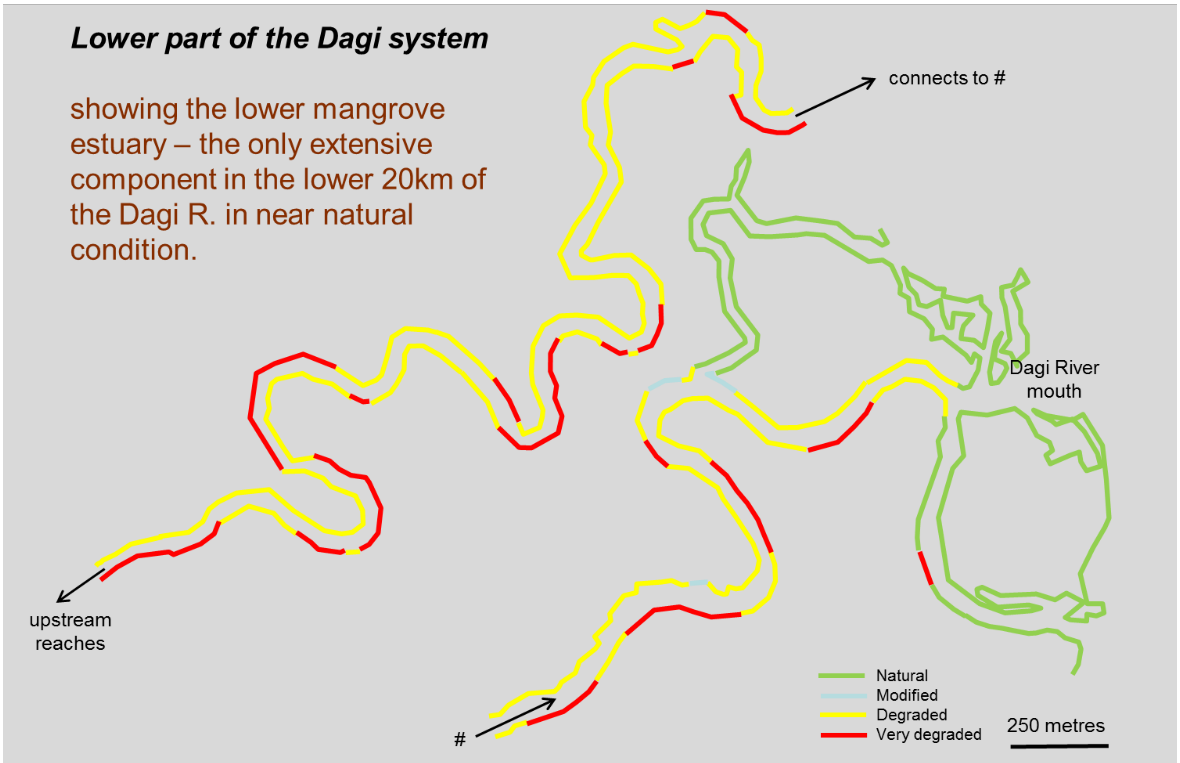


Figure 18. Riparian condition in the lower 12 km of the Dagi River in 2013.

7.11 Aquatic fauna

Faunal abundances were very low across the spectrum of sites assessed (44 sites in 22 streams). In particular, the structures of fish assemblages were indicative of highly overfished systems. Species richness was positively correlated with increases in fishing pressure, a pattern that suggest overharvesting of the resource. Assemblages were dominated by small juveniles and adult individuals were rare (Figure 19). Key species had specific habitat requirements (fallen timber) but potential to supply suitable habitat is greatly reduced in the absence of natural riparian vegetation.

Fish and crustacean abundances in freshwater streams were very low (no prior study with comparative data as a reference point) and were dominated by small-sized individuals. Most species, and in particular species in which adults are large fish, were almost exclusively represented by juvenile individuals. The relationship between species richness and fishing pressure provided clear indications of overfishing of the resource. The high proportion of juveniles in our catch, 88% of individuals overall and 100% for many of the larger species, suggests there is little likelihood that fish stocks will increase in the short-term without a massive reduction in fishing pressure.

Many species demonstrated clear associations with particular habitat types. Most notably there was a clear distinction in assemblage compositions between upland freshwater, lowland freshwater and estuary reaches of streams..

The present status of WNB fish and crustacean faunas in estuaries and freshwater streams is poor, displaying classic signs of overfishing. Fish assemblages are likely in decline and the prospect of improvement in the immediate future is bleak because of the high level of fishing pressure on juveniles. On a positive note we captured a few large individuals of the black bass, *L. goldiei*, in video footage and juvenile *L. goldiei* were one of the more frequently occurring taxa in estuary sites. In addition, at least six additional lutjanid species, several of which grow to become large and much sought after taxa, were recorded from WNB streams and estuaries. Iconic species such as the large Lutjanids have a potential to provide a valuable alternative source of income through development of guided catch and release fisheries for overseas sport fishermen.

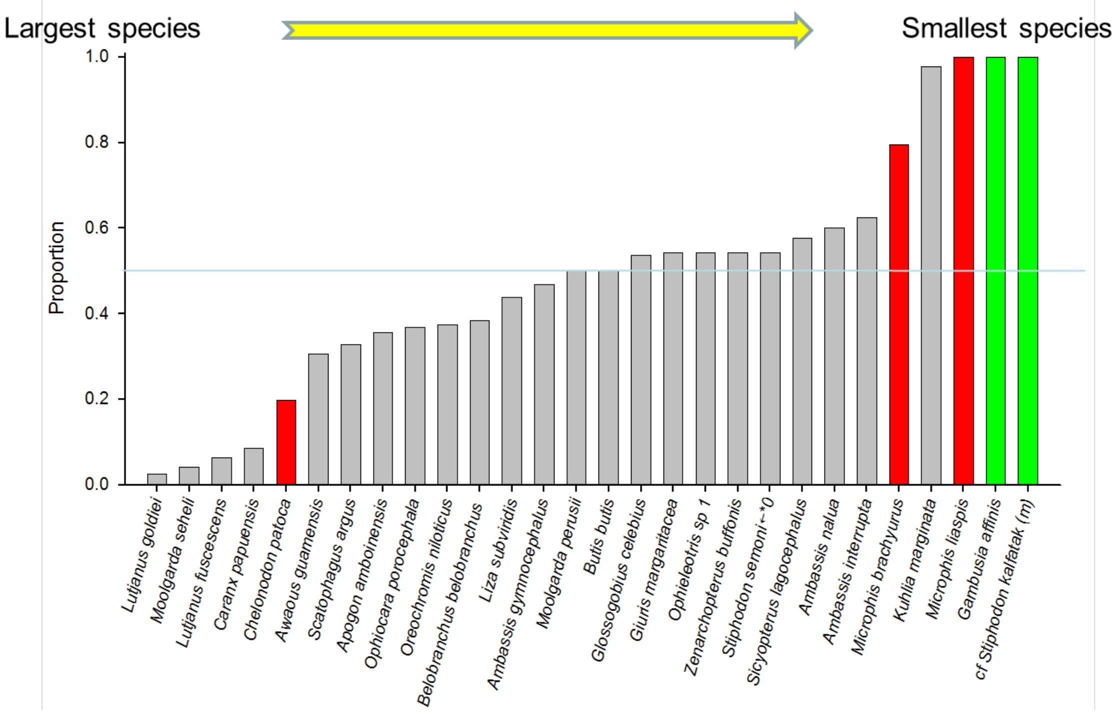


Figure 19. Size structure (proportion of maximum size) of fish in June 2011 sampling. Few species had individuals over 50% of maximum size, which is taken as the default size of first reproduction for species without recorded reproductive information. Red bars are inedible species and green bars are species that would normally be considered too small for consumption and ignored if there were sufficient larger fish.

7.12 Stream condition

Every stream we accessed had noticeable evidence of human impact at some level, and severe impact in most. Few streams were in very poor condition overall, but similarly there were few in near pristine condition. Most streams had moderate levels of impact suggesting there is a need for further research to pinpoint specific stressors and remediation approaches to improve aquatic ecosystem health and productivity.

This study provides the most extensive examination of WNB waterways to date and thus provides the *first*, substantive baseline for future monitoring of physical parameters of water quality and nekton assemblages. Continuation of monitoring will lead to better understanding of the extent of natural variability in these systems which in turn will provide improved reference points against which suspected change can be measured.

Many potential impacts were identified including direct oil palm issues such as release of mill effluent, delivery of nutrient to streams and fords. There were also many indirect issues, primarily related to high population densities. Indirect issues included use of streams for bathing and household domestic tasks (eg. laundry and cleaning cooking utensils) and excessive fishing pressure on limited stream resources. A majority of streams are small so even small local impacts can have a large effect however because

WNB receives high rainfall most streams are well flushed making detection of impacts more difficult.

7.13 Related additional work

During the life of this project the oil palm industry became controversial in PNG due to the recent (2003-2011) exponential expansion in the area of land held under Special Agricultural and Business Leases (Winn 2012). A team including Nelson, Banabas and Koczberski investigated the oil palm developments proposed under these leases and found approximately 980,000 ha of new oil palm plantations is being proposed, virtually all of which is by companies not currently producing palm oil in PNG (Nelson et al. 2014). This represents a possible seven-fold expansion of the industry. However, the authors concluded that most of these proposed developments are unlikely to eventuate in the foreseeable future. Rather, most appear to be logging exercises using oil palm proposals as a means of obtain clearing permits that allow them to export logs. However, it is possible that some of the larger developers will successfully establish plantations in the near future, which will substantially change the composition of the industry.

Nelson, Nake, Koczberski and Banabas instigated a small project to determine perceptions of soil fertility and sustainable soil management among VOP smallholders in WNB. The main aim is to determine a) how soil management practices compare between food gardens and oil palm blocks, and b) how grower perceptions of soil fertility compare to those of the RSPO Principles and Criteria. The work was carried out and published as a thesis by Honours student Claire Docherty (Docherty 2013).

8 Impacts

8.1 Scientific impacts – now and in 5 years

Now

Research related to the project was published in several peer-reviewed journal articles (see Section 8.4), with a total of 6 citations to date. Three papers reporting project work are currently in press. A further 12 scientific papers arising from project work are planned or in preparation (see Section 8.4).

Scientific interest has been generated by presentations given by project staff to several audiences (Section 8.4). The project has generated considerable interest among the international environmental indicators community and project staff have been invited to speak at several for a, particularly the 'PalmInet' meetings (PalmInet is a network of scientists working on environmental sustainability indicators for oil palm, coordinated by CIRAD), the International Conference on Oil Palm and the Environment (ICOPE), held in Bali each year, and trhe 6th Oil Palm Summit, held in Jakarta in August 2014. Scientists who have contacted us for discussions about implications of our work include ecologists Dr Claude Garcia (Tropical Forest Goods and Ecosystem Services Unit, CIRAD), Ed Turner (Cambridge Uni), Jake Snaddon (Oxford Uni); life cycle analysis scientist Dr Cecile Bessou and several other scientists from CIRAD; carbon cycling scientists Dr Samuel Abiven (UZ) and Dr Emmanuelle Lamade (CIRAD).

An international workshop on sustainability of soil management under oil palm was organised by project staff, in collaboration with CIRAD and PalmInet, and held in Medan, Indonesia in November 2013.

Project activities are already informing NBPOL's activities regarding carbon cycling in oil palm systems. Since their purchase of CTP Holdings in April 2010, NBPOL now produce over 80% of Papua New Guinea's palm oil. Dr Simon Lord, NBPOL Director of Sustainability, who is developing a framework for carbon accountability, requested relevant information from the project activities.

A definition of fragile and marginal soils was produced for the PNG National Interpretation Working group of the RSPO.

In 5 years

The approaches developed in this project have considerable promise for helping managers monitor and improve condition of soil and aquatic ecosystems in oil palm agro-ecosystems throughout the world.

8.2 Capacity impacts – now and in 5 years

Now

PNGOPRA staff

Skills in monitoring soils and plants: Throughout the project, Susan Tomda, Merolyn Koia, Steven Nake and field staff learned new methods of sampling plants and soil for carbon balance, erosion, nutrient cycling and N fixation research. New techniques in intense sampling of oil palms and soil included detailed measurement of frond dimensions (petiole, rachis and leaflets), trunk parameters (length, diameter, density), and root biomass. The latter involved learning new techniques of establishing an intense sampling grid which provides a representation of the heterogeneity around a single oil palm. In May 2011, senior recording staff in Milne Bay were involved in the design of a sampling strategy to 'capture' nutrient and carbon changes during the plantation replanting phase.

Skills in monitoring stream health: Throughout the project, OPRA staff have been included in data collection trips to familiarise them with equipment and protocols for monitoring stream health. Some staff members are now proficient enough to undertake reliable monitoring and train others in use of equipment and protocols. Information from the project has been disseminated via meetings with industry representatives, smallholder groups and in discussions with local landholders..

Dr Murom Banabas was successful in obtaining a John Dillon Fellowship for the period 15 February to 25 March 2011. The fellowship was aimed to improve his leadership skills in leading and managing agriculture research and development projects within PNGOPRA and contribute to his personal development. The skills obtained are not only applicable to the current working environment but also in his personal life and for those around him and the community activities he is involved in.

The John Dillon Fellowship provided the opportunity to achieve the aims through;

- Learn scientific communication skills,
- Learning leadership skills,
- Learning to plan, manage and evaluate agriculture research projects,
- Visiting certain agricultural research institutes, universities, government institutions and commercial farming enterprises (and markets) in Australia and
- Learning the experience from other fellowship awardees from the other countries.

Dr Banabas also succeeded in obtaining a Crawford Training Award. The training, carried out by Dr Andrea Bassi (Millenium Institute) and Prof Jeff Sayer (JCU) on 19-21 April 2011 in Cairns, involved participatory modeling for exploring scenarios of livelihoods and environment. Murom applied the concepts to the problem of poor oil palm smallholder productivity in PNG.

Rachel Pipai successfully applied for a John Allwright Fellowship and enrolled in an MSc in the University of Adelaide in June 2010. The project involved glasshouse and laboratory work in Adelaide and field sampling in PNG. Rachel submitted her thesis for examination in 2013. The thesis is entitled ‘Biological nitrogen fixation by cover legumes under oil palm plantations in Papua New Guinea’.

NARI staff

During the project staff meetings in WNB in May 2010, Debbie Kapal learned how to design experiments and has participated in river sampling.

OPIC staff

Through their participation in smallholder block sampling in May 2010 and other sampling activities, several OPIC officers have learned or improved skills in environmental assessment. In particular, Barak Hegufec (WNB) and Francis Kimeta (Oro) learned new methods of sampling for carbon balance and nutrient cycling.

Other people

Students from the PNG University of Natural Resources (formerly ‘Vudal University’, Rabaul and Popondetta Campuses) on industrial training were involved in soil and plant sampling and measurements as part of their training.

Pierre Couvreur of Hargy Oil Palms Sustainability Department and his staff learned how to evaluate current impact status and develop best practice environmental monitoring for the Hargy Mill effluent water outfall. This work was undertaken cooperatively with Gomu and Ewasse villagers, particularly Helen Toirima.

Equipment and facilities

OPRA received a Toyota Landcruiser utility, which is being used for field work in West New Britain, several GPS units and plant grinder (for coarse grinding).

Training courses

A Scientific Paper Writing Workshop was organised by project staff and run in Townsville on 9-12 April 2013. Dr Chris Beadle, CSIRO, ran the workshop, which was sponsored by the Crawford Fund, CSIRO and JCU. Participants included project staff (Murom Banabas and Rachel Pipai from PNGOPRA) plus Terence Simbiwen, a PNG PhD candidate associated with the project, Noto Prabowo, a JCU PhD candidate working on sustainability aspects of oil palm cultivation in Indonesia, and 5 Pacific Island scientists from the ‘Mangrove Ecosystems for Climate Change Adaptation & Livelihoods’ (MESCAL) project.

A training course on APSIM Oil Palm, the crop system model developed in the project, was held in West New Britain in September 2013. There were 13 participants, including 4 Australian project team members, 4 from PNGOPRA, 3 from NBPOL, 1 from HOPL and 2 from OPIC.

In 5 years

The expertise and resources developed in this project will continue to inform and equip technical staff and growers in the oil palm industry.

8.3 Community impacts – now and in 5 years

Through involvement in the meetings at Nahavio and Bialla in WNB and Higaturu in Oro, approximately 35 OPIC staff, 20 company staff and 10 smallholder oil palm growers have become more aware of environmental issues and their relationship to market access for their produce.

Live and Learn coordinator for WNB, Paul Lewthwaite, learned about the environmental aspects of oil palm production at the project inception meeting. The WNB Director of The Nature Conservancy (Barbara Masike) and Program Director of Mahonia na Dari (Monica Muye) were also invited.

8.3.1 Economic impacts

Although we have not been able to quantify the economic impact, the existence and activities of this project are being used by PNG palm oil producers as evidence that they are adhering to Roundtable on Sustainable Palm Oil (RSPO) Principle 8: ‘Commitment to continuous improvement in key areas of activity’. RSPO certification is vital for continued market access for palm oil produced in PNG.

8.3.2 Social impacts

For each smallholder reached during field days and other activities, many other people are learning about sustainability issues related to oil palm cultivation.

8.3.3 Environmental impacts

Apart from awareness, we are not yet able to estimate environmental impacts. However, the seriousness with which the General Managers of both NBPOL and HOPL are embracing our research gives us confidence that this project will have substantial positive environmental outcomes.

8.4 Communication and dissemination activities

PNGOPRA/OPIC Field days etc for oil palm smallholders (in which sustainability issues were covered)

Concerns about the environment and pollution are frequently brought up by smallholders during field days, so although field days may not be specifically on the project or environmental effects of oil palm cultivation, these topics are always covered. Talks given about production always also mention sustainability issues, pointing out that long-term productivity of oil palm and other components of the landscape are linked with the environmental effects of agricultural management.

In April-May 2010, 5 field days were held in Popondetta (at Igora, Sangara and Trial 324), with a total of 40 growers in attendance, and 5 field days were held in West New Britain (Buvussi, Kavui), with a total of 605 growers in attendance.

In the June 2010-May 2011 period, a number of field days were carried out in Oro and West New Britain Provinces. In Oro Province, 22 two “ute” field days (10-15 attendees at each) were conducted in Trial 324 at Popondetta and 1 large field day (100-150 attendees) at Hanau during 2010. Issues discussed during these field days included best management practices, HIV-AIDS, gender, food security and sustainability issues. There were also 20 other OPIC-organised field days which PNGOPRA was involved carried out in the other oil palm growing areas in the country.

In the June 2011-May 2012 period, instead of field days, Steven Nake presented an overview of the Sustainability Project activities to the OPIC officers meeting at Popondetta.

In the June 2012-May 2013 period, several field days, radio broadcasts and training activities were carried out. Three radio broadcasts were done in New Ireland and two in West New Britain Provinces. Their primary purpose was to discuss fertilizer issues but they also included discussion of activities undertaken in the sustainability project with relevance to health of soil and aquatic ecosystems. Steven Nake trained OPIC staff in WNB and Oro Provinces on fertilizer issues including sustainability activities. The number of organized field days were reduced and put on hold during the mid-2012 period because of the national elections. However, two were held in Popondetta, seven in Bialla and two in Hoskins.

An important part of Objective 6 that needs to be in place for testing and implementing the indicators, is for the industry to develop a a reliable data capturing process and data base recording system. At Popondetta, Murom Banabas has been facilitating officers from NBPOL Smallholder and Technical Services Departments and OPIC IT section to come together and share smallholder data. OPIC has purchased a license for the oil palm data management program OMP for smallholders, and it was agreed that collected data will be used by both organisations. Data compiling has commenced and reports are being produced. This will pave the way for trialing the models and indicators. The other issue was that certain measurements had to be done by the industry for the models developed to be used. Work has commenced and extra measurements are now done in the field, in addition to what was being measured in the past. These measurements have started in PNGOPRA. Smallholder leaf sampling and NBPOL TSD sampling in Kavieng will be rolling out to other sites in the near future.

Other communication activities with PNG oil palm industry

PNGOPRA Annual reports (2010, 2011, 2012) These publically available reports each include a section on the project.

PNGOPRA Scientific Advisory Committee meetings in 2009, 2010, 2011, 2012. The complete project proposal was presented at this meeting in Nov 2009, and annual proposals were presented each year thereafter. The meetings were open to the public and included representatives of the PNG oil palm community as well staff from Conservation International, AusAID and other organisations.

PNGOPRA board meetings: Proposal drafts were tabled at PNGOPRA board meetings on 2/4/2009, 18/6/2009, 21/10/2009, 26/11/2009.

Integration of the project activities with developments in the RSPO national interpretation are a critical aspect of the project. To this end, Bill Page forwarded relevant documents from the Sustainability Project and RSPO to stakeholders during the project and was involved in finalising the draft criteria and indicators for smallholders.

Other specific communication activities included:

- Feb 2010: Popondetta, PNG. Merolyn Koia did a radio talk on the project.
- 16-17/03/2010, Milne Bay, PNG. Briefing on project by Murom Banabas for plantation and OPIC staff.
- 23/03/2010 Higaturu, PNG. Murom Banabas and Gina Koczberski ran an awareness meeting with OPIC officers and plantation staff. 21 participants including OPIC Project Manager Leo Ruki.
- 10/5/2010. Mosa, PNG. NBPOL briefing meeting. Project staff met with NBPOL senior management staff to brief them on the project. NBPOL produces most of the palm oil in PNG. 4 NBPOL, 3 OPRA and 1 JCU staff participated.
- 11/05/2010, Nahavio, PNG. First meeting of project pilot team. 5 smallholder growers, 6 OPIC officers, 4 OPRA staff, 1 NARI staff and 2 Aust project staff participated.
- 12/5/2010. Walindi, PNG. Inception meeting. Project staff introduced the project to industry and interested stakeholders. 26 participants.
- 17/5/2010. Bialla, PNG. Inception meeting. Project staff introduced the project to industry and interested stakeholders. 14 participants.
- 20/5/2010. Higaturu, PNG. Inception meeting. Project staff introduced the project to industry and interested stakeholders. 24 people from HOP, OPIC and smallholders participated.
- May 2011. Paul Nelson and Mike Webb met with Mike Hoare (General Manager, NBPOL) and Simon Lord (NBPOL Director of Sustainability) to brief them on current and future goals and activities of the project.
- 27 February 2012, Walindi. The project team met with Dr Gamini Keerthesinghe (ACIAR SMCN Program Manager) and Emily Flowers (ACIAR PNG Country Manager) for the ACIAR mid-term review of the project.
- 28 February 2012, Walindi. In a public meeting, the project team gave presentations on progress in the project, and sustainability officers from New Britain Palm Oil (Ian Rove Sahota, NBPOL) and Oil Palm Industry Corporation (John Hulo, OPIC) gave an update on their activities.
- 1 March 2012, Walindi. A consultative meeting was held between project leaders and senior managers from NBPOL and OPIC in order to obtain feedback on the project.
- March 2013. Nelson P, Banabas M. Sustainability of soil and water management news. NBPOL Group Bulletin 30, 14-15.
- July 2013. Meeting with Sander van den Ende (NBPOL Environmental Manager) - progress and objective 4 outcomes.
- 17-18 September 2013. APSIM Oil Palm Model Training Workshop, Walindi, PNG. 9 industry technical and scientific staff undertook the training.

Communication activities with the broader public (chronological order)

17/03/2010 General project flyer produced and distributed

16/04/2010, Australia. ABC Radio National, 'PM' program. Paul Nelson was interviewed about sustainability of oil palm cultivation.

17/04/2010 PNGOPRA project flyer produced and distributed

26/05/2010, Cairns, Australia. Paul Nelson gave seminar at JCU on the project.

18/8/2010. *Cairns Post*. 'Good palm oil for rainforests'

18/8/2010. *James Cook University Public Lecture.* 'Oil palm – scourge on the environment?' (Paul Nelson, Cairns, Australia).

20/9/2010. *Radio Australia, Connect Asia* 'Palm oil disputes overshadowing real issues' (Interview with Alan Oxley, World Growth; Belinda Fletcher, Greenpeace; Paul Nelson, James Cook University)
http://www.radioaustralia.net.au/connectasia/stories/201009/s3016309.htm

15/2/2011. *Radio Australia, In the loop* 'Tropical soils' (Interview with Paul Nelson)

15/4/2011*. Papua New Guinea and Pacific Nius,* April 2011, p 6-9, 'Sustainable management of oil palm production systems'

2/2/2012. *Improving productivity and sustainability of tree crops in PNG.* Presentation to incoming Deputy High Commissioner to PNG, Ms Margaret Adamson, Cairns

28/2/2012, Walindi. *Public presentation at mid-term review (see above)*

20/5/2013. *ABC TV* 'The Business' 'The high price of palm oil..'
http://www.abc.net.au/news/2013-05-20/the-high-price-of-palm-oil-the-campaign-to-get/4701798

Crawford Fund website April 2013 'Training to spread word on palm oil sustainability'
http://www.crawfordfund.org/states/qld/news/palm-oil.html

23/4/2013. *Radio Australia* 'PNG palm oil farming' Interview with Murom Banabas
http://www.radioaustralia.net.au/tokpisin/radio/onairhighlights/png-palm-oil-farming/1120502

17/4/2013. *Radio Australia* 'PNG oil palm indastri helpim pipal'.
http://www.radioaustralia.net.au/tokpisin/2013-04-17/png-oil-palm-indastri-helpim-pipal/1117620

15/4/2013. *Radio Australia* 'Australia backs research into sustainable palm oil' Interview with Murom Banabas. http://www.radioaustralia.net.au/pacific/radio/program/pacific-beat/australia-backs-research-into-sustainable-palm-oil/1116044

10/4/2013. *Townsville Sun* 'Workshop aids research paper writing'

9/4/2013. *Win News* (*Townsville, Toowoomba)* 'Pacific and Australian academics have united..'

27/8/2013 *The National* (PNG) 'Long wait for full SABL report'
http://www.thenational.com.pg/?q=node/55075

21/8/2013 *Radio Australia*. Claims of a major fraud that's exploiting PNG's jungles
http://www.radioaustralia.net.au/international/radio/program/pacific-beat/claims-of-a-major-fraud-thats-exploiting-pngs-jungles/1179356

21/8/2013 *Radio Australia*. Companies exploit loophole in PNG logging ban
http://www.radioaustralia.net.au/international/2013-08-21/companies-exploit-loophole-in-png-logging-ban/1179438

21/8/2013 *The National* (PNG). 'NGO: Speed up report' http://www.thenational.com.pg/?q=node/54851

19/8/2013 *Post-Courier* (PNG) 'Oil palm just a coverup' (front page) http://www.postcourier.com.pg/20130819/news.htm

15/8/2013 *Mongabay.com News* 'Palm oil licenses provide cover for logging in New Guinea' http://news.mongabay.com/2013/0814-palm-oil-png-sabls.html

14/1/2014 Rainforest news review for 2013 *Before it's News* http://beforeitsnews.com/environment/2014/01/rainforest-news-review-for-2013-2489166.html

31/05/2014 The effects of palm oil populations on surrounding water resources http://betterpalmoildebate.org/features/post.php?s=2014-05-22-the-effects-of-palm-oil-populations-on-surrounding-water-resources

Conference papers and seminars (chronological order)

Nelson PN, Banabas M, Webb MJ, Sheaves M, Huth N, McNeill A, Koczberski G, Berthelsen S, Orrell I. 2010. Environmental sustainability indicators for oil palm in Papua New Guinea – conceptual framework for a research and development project *'Agri-environmental Indicators Workshop', 26-27 February 2010, associated with the 2nd International Conference on Oil Palm and the Environment (ICOPE) 23-25 February, Bali, Indonesia* (unrefereed, unpublished)

Berthelsen S, Webb MJ and Nelson PN. 2010. Limited movement of fertiliser-derived Mg and K through volcanic ash and alluvial clay soils of Papua New Guinea. In: Gilkes RJ, Prakongkep N, editors. *Proceedings of the 19th World Congress of Soil Science; Soil Solutions for a Changing World; ISBN 978-0-646-53783-2; Published on DVD; http://www.iuss.org; Division Symposium 3.2; Nutrient best management practices; 1-6 August 2010.* Brisbane, Australia: International Union of Soil Science. p 140-143.

Nelson PN, Berthelsen S, Webb MJ and Banabas M. 2010. Acidification of volcanic ash soils under oil palm in Papua New Guinea: effects of fertiliser type and placement. In: Gilkes RJ, Prakongkep N, editors. *Proceedings of the 19th World Congress of Soil Science; Soil Solutions for a Changing World; ISBN 978-0-646-53783-2; Published on DVD; http://www.iuss.org; Division Symposium 3.2; Nutrient best management practices; 1-6 August 2010.* Brisbane, Australia: International Union of Soil Science. p 8-11.

Webb MJ 2010. Development of a fertiliser optimisation technique using multi-nutrient factorial trials and leaf tissue nutrient analysis in commercial oil palm plantations. . In: Gilkes RJ, Prakongkep N, editors. *Proceedings of the 19th World Congress of Soil Science; Soil Solutions for a Changing World; ISBN 978-0-646-53783-2; Published on DVD; http://www.iuss.org; Division Symposium 3.2; Nutrient best management practices; 1-6 August 2010.* Brisbane, Australia: International Union of Soil Science. P 40-43.

Pipai R, Unkovich M, McNeill A, Banabas M, Webb M, Herridge D, Nelson P. 2011. Nitrogen fixation by legumes under oil palm plantations in Papua New Guinea. 17th International Congress on Nitrogen Fixation, 27 Nov. -1 Dec. 2011, Perth (oral, unpublished).

Nelson P, Banabas M, Page B, Nake S, Webb M, Huth N, Sheaves M, Johnston R, Bower M, Goodrick I, McNeill A, Koczberski G, Wakelin S. 2012. Indicators of sustainable soil and water management for the Papua New Guinean oil palm industry. *International Conference on Oil Palm and the Environment (ICOPE)*, 24 February 2012, Nusa Dua, Bali (oral, distributed on memory stick).

Nelson P, Banabas M, Webb M, Sheaves M, Johnston R, Bower M, Huth N, McNeill A, Nake S, Goodrick I, Koczberski G, Page B. 2012. Producing indicators of sustainable soil and water management for the Papua New Guinean oil palm industry. *PalmiNet workshop*, 20 February 2012, Nusa Dua, Bali (oral, unpublished).

Nelson PN, Orrell I, Filer C, Banabas M, Curry G, Koczberski G. 2012. Oil palm in Papua New Guinea: the current, emerging and virtual industries. *Papua New Guinea: Securing a prosperous future.* 12-13 April 2012. Geelong, Australia. (oral. Abstract published at: http://www.deakin.edu.au/alfred-deakin-research-institute/events/png-conf-2012/png-2012-program.php)

Nelson PN. 2012. Palm oil and the environment. Seminar for JCU 'Master of Development Practice' forum. 14 April 2012 Cairns.

Webb MJ, Nelson PN, Banabas M. 2012. Sampling strategies for understanding variability under oil palm. *Presentation at ACIAR*, Canberra, 29 May 2012. (oral, unpublished)

Nelson PN. 2012. Oil palm in Papua New Guinea: 'actual', 'possible' and 'virtual' expansion of the industry. *Presentation at Centre for Tropical Environmental and Sustainability Science, James Cook University*, 29 August 2012. (oral, unpublished)

Nelson PN, Banabas M, Goodrick I, Gabriel E. 2012. Soil fertility changes following conversion of grassland to oil palm. *Joint ASSSI and NZSSS Soil Science Conference 2012. Soil solutions for diverse landscapes*. 2-7 December 2012. Hobart, Australia. (poster)

Goodrick I, Nelson PN, Banabas M, Wurster C, Bird MI. 2012. Soil carbon balance following conversion of grassland to oil palm. *Joint ASSSI and NZSSS Soil Science Conference 2012. Soil solutions for diverse landscapes*. 2-7 December 2012. Hobart, Australia. (poster)

Nelson PN. 2013. Soil carbon change over 25 years in a C4-to-C3 sequence in the humid tropics. *Presentation at Soil Science and Biogeography Unit, University of Zurich*, 10 January 2013. Zurich, Switzerland. (oral, unpublished)

Nelson PN. 2013. Oil palm developments in Papua New Guinea: drivers, actors and possible trajectories. *Presentation at Institute for Terrestrial Ecosystems, ETH*, 11 January 2013. Zurich, Switzerland. (oral, unpublished)

Webb MJ, Nelson PN, Curry GN, Reddell PW. 2013. A length of rope, a $17 kitchen scale, and some hot rocks; em tasol. *Presentation to CSIRO Land and Water Science Executive*, Townsville, 23 July 2013 (oral, unpublished)

Webb MJ, Nelson PN, Curry GN, Reddell PW. A length of rope, a $17 kitchen scale, and some hot rocks; em tasol. *Presentation at ACIAR*, Canberra, 13 May 2014 (oral, unpublished)

Webb MJ, Nelson PN, Berthelsen S, Banabas M, Curry GN. 2013. Improving fertilizer recommendations for oil palm growers in Papua New Guinea. XVII. International Plant Nutrition Colloquium. 19-22 August 2013. *In*: XVII. International Plant Nutrition Colloquium and Boron satellite Meeting Proceedings Book, pp 695-696, Sabanci University, Istanbul, Turkey. ISBN 978-605-4348-62-6. Retrieved from http://www.plantnutrition.org/en/2013ipnc-b-proceedings.html. (poster, distributed on memory stick)

Banabas M, Nelson PN, Webb MJ. 2013 Influence of soil nitrogen fertilisers on soil acidification in Papua New Guinea. *Sustainable management of soil in oil palm plantings.* 7-8 Nov. 2013. Medan, Indonesia. (Oral, abstract to be published)

Goodrick I. 2013. Soil carbon cycling following conversion of grassland to oil palm. *Sustainable management of soil in oil palm plantings.* 7-8 Nov. 2013. Medan, Indonesia. (Oral, abstract to be published)

Huth NI, Nelson PN, Banabas M, Webb MJ. 2013. Understanding soil processes in oil palm plantations using an agricultural system *Sustainable management of soil in oil palm plantings.* 7-8 Nov. 2013. Medan, Indonesia. (Oral, abstract to be published)

Nake S, Nelson PN, Banabas M. 2013. Potassium fixation and release: effects of management under oil palm in alluvial clay soils, Milne Bay Province, Papua New Guinea. *Sustainable management of soil in oil palm plantings.* 7-8 Nov. 2013. Medan, Indonesia. (Oral, abstract to be published)

Nelson PN, Banabas M, Huth NI, Webb MJ. 2013. Quantifying trends in soil fertility under oil palm: practical challenges and approaches. *Sustainable management of soil in oil palm plantings.* 7-8 Nov. 2013. Medan, Indonesia. (Oral, abstract to be published)

Webb MJ, Nelson PN, Banabas M, Nake S. 2013. Soil acidification processes and indicators. *Sustainable management of soil in oil palm plantings.* 7-8 Nov. 2013. Medan, Indonesia. (Oral, abstract to be published)

Nelson PN et al. 2014. Sustainable management of soil and water resources for oil palm production systems in PNG. *ACIAR SMCN Program Meeting.* 24-25 June 2014. Canberra, Australia. (Oral, unpublished)

Nelson PN et al. 2014. Sustaining soil and water resources in oil palm agro-ecosystems of Papua New Guinea. *TESS Seminar.* 30 July 2014. Cairns, Australia. (Oral, unpublished)

Webb MJ, Nelson PN, Banabas M, Huth N. 2014. Quantifying trends in soil fertility under oil palm: practical challenges and approaches. *6th Oil Palm Summit*, 13 August 2014. Jakarta, Indonesia. (Oral, unpublished)

Other

Nelson PN, Webb MJ, Orrell I, van Rees H, Banabas M, Berthelsen S, Sheaves M, Bakani F, Pukam O, Hoare M, Griffiths W, King G, Carberry P, Pipai R, McNeill A, Meekers P, Lord S, Butler J, Pattison T, Armour J and Dewhurst C. 2010. *Environmental sustainability of oil palm cultivation in Papua New Guinea*. ACIAR Technical Report No. 75. The Australian Centre for International Agricultural Research, Canberra. 66 pp.

Submission to the World Bank Palm Oil Strategy 2010 (submitted online, 25/6/2010)

Project staff communicated about the project with various people from the research, government, NGO and business sectors, including: Jan Maarten Dros, Coordinator Sustainable Agri-commodities Programme, Solidaridad (‘Palm Oil Producer Support Initiative’ programme); Prof Gilles Pinay, Uni de Reims (research project on effects of riparian forest buffer strips on nutrients in runoff from oil palm plantations in Sabah); Paul Voutier, Business for Millenium Development, Australia.

Scientific journal articles published or accepted for publication

See Section 10.2

Scientific journal articles in preparation

Banabas et al. Soil acidification rates as affected by nitrogen fertiliser types and rates under oil palm systems

Banabas et al. Carbon and nutrient stocks in an oil palm plantation just prior to replanting.

Nelson et al. Development of indicators for sustainability of soil and water resource management under oil palm.

Nelson et al. Soil sampling in oil palm plantations: a practical design that accounts for systematic lateral variability at the tree scale

Pipai et al. Biological nitrogen fixation by cover legumes under oil palm plantations in Papua New Guinea

Sheaves et al. Interaction of habitat and connectivity shapes tropical stream fish assemblages

Sheaves et al. Indirect effects can be as important as direct impacts on aquatic environments in tropical plantation agricultural regimes

Sheaves et al. Stable isotopes as markers of aquatic environmental impacts in a tropical plantation agricultural system

Sheaves et al. Aquatic ecosystems in tropical plantation agricultural landscapes; food security, threats, vulnerability and change

Wakelin et al. Soil microbiological changes following conversion of grassland and forest to oil palm.

Webb et al. Distribution of carbon and nutrients between components of the oil palm. And perhaps a second one on allometrics

Technical and industry awareness publications planned

ACIAR Technical Report: “Sustainable management of soil and water resources for oil palm in Papua New Guinea: Guidelines for smallholder growers”

ACIAR Technical Report: “Sustainable management of soil and water resources in oil palm plantations of Papua New Guinea: Monitoring and indicators”

Series of management focussed papers in industry-focussed outlets eg. OPRA-tive Word, The Planter, Better Crops, ACIAR Technical report, ACIAR brochures.

9 Conclusions and recommendations

9.1 Conclusions

Production of agro-environmental sustainability indicators that are meaningful and can be maintained by industry is a challenging task. Many indicators exist in the literature but few if any are used and none are applicable to the PNG oil palm industry. Devising sustainability indicators for the PNG oil palm industry proved difficult and complex. However, the structure of the industry also provides unique opportunities for successful development and implementation of such indicators. The indicators we have designed appear to represent the oil palm growing conditions of PNG in a meaningful way and should be reasonably straightforward for the industry to maintain.

Several research activities were necessary to obtain information required to develop the indicators and to ensure that future monitoring can be carried out simply and meaningfully. Field trials were instigated to measure fluxes of carbon, nutrients and soil in key locations and crop management phases. Stream and riparian condition was measured throughout the Dagi catchment, one of the most heavily impacted parts of the industry. Soil fertility and stream physical health are generally good in the oil palm growing areas of PNG, with few physical, chemical or biological constraints. However, the streams are heavily impacted by over-fishing and degradation of riparian vegetation, water quality is impacted at mill outfalls, and the soils face potential threats, such as acidification.

The PNG oil palm industry can continue to sustainably manage soil and water resources and improve its practices given attention to the issues identified. Use of the techniques developed in this project to monitor its performance will help ensure the soil and water bodies of oil palm-growing regions will be maintained in a healthy and productive state for future generations.

9.2 Recommendations

We recommend that:

1. The indicators developed be implemented throughout the industry and be incorporated into sustainability reports.
2. The replant trial be continued by PNGOPRA until the palms are 5 years old. That will result in a continuous record of stocks and fluxes of carbon and nutrients throughout the oil palm cycle.
3. Project scientists continue their engagement with the PalmInet network.
4. Knowledge gaps identified during the course of this project are prioritised and investigated. Particular questions include:
    - Do significant gaseous losses of nitrogen, particularly the greenhouse gas nitrous oxide, occur in any oil palm growing situations in PNG? If so, when and where?.
    - In what ways does riparian zone management in oil palm-dominated landscapes regulate aquatic ecosystem functioning and downstream resources?
    - Large stocks of carbon and nutrients are present in oil palms at the time of felling, and these stocks are susceptible to loss. Initial comparisons of our data with similar studies in other countries suggests the stocks are highly dependent on environment and management (and method of assessment).

It would be useful to assess these stocks in well-defined existing fertiliser trials across a range of environments, using uniform sampling protocols

- The APSIM Oil Palm model might be extended to a wider range of environments. Testing to date has covered a limited range of environments. For example, the inclusion of a water table within the root zone would make the model more widely applicable. Another useful possibility would be to develop a K cycling module. Potassium is interesting because a K module has recently been developed for cereals, and K is a nutrient of major importance for oil palm.
- What are the factors limiting incorporation of organic matter from pruned fronds and mill by-products into the soil in oil palm plantations? These applications of organic matter have large potential benefits for the soil and for sustainability but much of the organic matter is decomposed before being incorporated into the soil. Soil fauna are the main agents of incorporation but nothing is known about their ecology, effectiveness or response to environmental factors and management practices.
- How does nutrient use efficiency differ between different planting materials and environments? What are the inputs of nitrogen in different environments? Inputs in precipitation and from mineral weathering may be significant in active volcanic areas. How much nitrogen is fixed by free-living nitrogen fixers in oil palm plantations? Considerable nitrogen fixation is carried out by endophytic and epiphytic organisms in forests and this may also be occurring in some oil palm plantations. There has been no little or no response to applied nitrogen in fertiliser trials in the Hoskins region of WNB for several decades and non-fertiliser non-legume inputs may be a possible explanation.
- Is soil acidification occurring in acidic soils without pH change? While not a concern in PNG, our work suggests that accelerated soil acidification and irreversible loss of nutrient retention capacity is widespread in the humid tropics in soils with pH around 3.5-4.0. Soil pH does not drop any further in these soils due to virtually infinite pH buffering capacity at this pH due to the dissolution of clay minerals. The degradation problem may be further masked by the cultivation of acid-tolerant crops such as oil palm and cassava.
- What opportunities are there for more efficient assessment of soil properties in the highly variable oil palm system? Promising examples included visual to mid infrared spectroscopy for properties related to organic matter, gamma ray spectrometry for properties related to mineralogy and fertiliser history and electromagnetic induction for properties related to electrical conductivity.
- Is the increase in incidence of Ganoderma over time related to soil properties and management?
- How can climate data for agricultural regions of PNG be improved?

10 References

10.1 References cited in report

Banabas M. 2007. Nitrogen loss pathways in oil palm on volcanic ash-derived soils. PhD thesis, Massey University, New Zealand.

Banabas M, Turner M, Scotter DR, Nelson PN. 2008a. Losses of nitrogen fertiliser under oil palm in Papua New Guinea: 1. Water balance, and nitrogen in soil solution and runoff. Australian Journal of Soil Research 46(4), 332–339.

Banabas M, Scotter DR, Turner M. 2008b. Losses of nitrogen fertiliser under oil palm in Papua New Guinea: 2. Nitrogen transformations and leaching, and a residence time model. Australian Journal of Soil Research 46(4), 340–347.

Chase L, Henson I. 2010. A detailed greenhouse gas budget for palm oil production. International Journal of Agricultural Sustainability 8:199-214.

Chase LDC, Henson IE, Abdul-Manan AFN, Agus F, Bessou C., Milà i Canals L, Sharma M. 2012. *The PalmGHG Calculator: The RSPO greenhouse gas calculator for oil palm products, Beta-version.* The Roundtable for Sustainable Palm Oil – RSPO. Kuala Lumpur, Malaysia

Corley, R.H.V., Hardon, J.J., Tan, G.Y., 1971. Analysis of growth of oil palm (*Elaeis guineensis* Jacq) .1. Estimation of growth parameters and application in breeding. Euphytica 20, 307-315.

Corley RHV, Tinker PB. 2003. The Oil Palm. Blackwell Science, Oxford.

Goodrick I, Nelson PN, Banabas M, Wurster C, Bird MI. 2014. Soil carbon balance following conversion of grassland to oil palm. *Global Change Biology Bioenergy* doi: 10.1111/gcbb.12138

Huth NI, Banabas M, Nelson PN, Webb MJ. (in press) Development of an oil palm cropping systems model: Lessons learned and future directions. Submitted to *Environmental Modelling and Software*

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18, 267-288.

Munday P (2004) Habitat loss, resource specialization, and extinction on coral reefs. Global Change Biology 10:1642-1647

NBPOL (New Britain Palm Oil Ltd.) 2012. *Carbon footprint report 2011*. New Britain Palm Oil Ltd.

Nelson PN, Banabas M, Nake S, Goodrick I, Webb MJ, Gabriel E. (in press) Soil fertility changes following conversion of grassland to oil palm. *Soil Research*

Nelson PN, Gabriel J, Filer C, Banabas M, Sayer JA, Curry GN, Koczberski G, Venter O. 2014. Oil palm and deforestation in Papua New Guinea. *Conservation Letters* 7(3), 188-195. doi:10.1111/conl.12058

Nelson PN, Webb MJ, Banabas M, Nake S, Goodrick I, Gordon J, O'Grady D, Dubos B. 2014. Methods to account for tree-scale variation in soil- and plant-related parameters in oil palm plantations. *Plant and Soil* 374, 459-471. DOI: 10.1007/s11104-013-1894-7 Plus Erratum *Plant and Soil* 378, 415. DOI: 10.1007/s11104-014-2066-0

Nelson PN, Webb MJ, Orrell I, van Rees H, Banabas M, Berthelsen S, Sheaves M, Bakani F, Pukam O, Hoare M, Griffiths W, King G, Carberry P, Pipai R, McNeill A, Meekers P, Lord S, Butler J, Pattison T, Armour J and Dewhurst C. 2010. *Environmental sustainability of oil palm cultivation in Papua New Guinea*. ACIAR Technical Report No. 75. The Australian Centre for International Agricultural Research, Canberra. 66 pp. http://aciar.gov.au/publication/tr075

Nelson PN, Rhebergen T, Berthelsen S, Webb MJ, Banabas M, Oberthür T, Donough CR, Rahmadsyah, Indrasuara K, and Lubis A. 2011. Soil acidification under oil palm: rates and effects on yield. *Better Crops* 95 (4), 22-25.

Pipai, R., 2013. Biological Nitrogen Fixation By Cover Legumes Under Oil Palm Plantations In Papua New Guinea. School of Agriculture, Food and Wine. Faculty of Sciences. The University of Adelaide, Australia.

PNGOPRA 2012. Annual Research Report 2011. Papua New Guinea Oil Palm Research Association: Kimbe.

RSPO (Roundtable on Sustainable Palm Oil). (2013) RSPO principles and criteria for sustainable palm oil production including indicators and guidance. *Roundtable on Sustainable Palm Oil*, www.rspo.org

Tims, S.G.; Everett, S.E.; Fifield, L.K.; Hancock, G.J.; Bartley, R. 2010. Plutonium as a tracer of soil and sediment movement in the Herbert River, Australia. Nuclear Instruments and Methods in Physics Research B 268, 1150-1154

Winn P. 2012. *Up for grabs. Millions of hectares of customary land in PNG stolen for logging*. Greenpeace Australia Pacific. Ultimo, Australia.

10.2 List of publications produced by project

Docherty C. 2013.Good soils have names: Local soil classification and management in Kae, Papua New Guinea. Honours thesis. School of Earth and Environmental Sciences, James Cook University, Australia.

Goodrick I, Nelson PN, Banabas M, Wurster C, Bird MI. 2014. Soil carbon balance following conversion of grassland to oil palm. *Global Change Biology Bioenergy* doi: 10.1111/gcbb.12138

Huth NI, Banabas M, Nelson PN, Webb MJ. (in press) Development of an oil palm cropping systems model: Lessons learned and future directions. *Environmental Modelling and Software*

Nelson PN, Banabas M, Nake S, Goodrick I, Webb MJ, Gabriel E. (in press) Soil fertility changes following conversion of grassland to oil palm. *Soil Research*

Nelson PN, Rhebergen T, Berthelsen S, Webb MJ, Banabas M, Oberthür T, Donough CR, Rahmadsyah, Indrasuara K, and Lubis A. 2011. Soil acidification under oil palm: rates and effects on yield. *Better Crops* 95 (4), 22-25.

Nelson PN and Su N. 2010. Soil pH buffering capacity: a descriptive function and its application to some acidic tropical soils. *Australian Journal of Soil Research* 48, 201-207.

Nelson PN, Gabriel J, Filer C, Banabas M, Sayer JA, Curry GN, Koczberski G, Venter O. 2014. Oil palm and deforestation in Papua New Guinea. *Conservation Letters* 7(3), 188-195. doi:10.1111/conl.12058

Nelson PN, Webb MJ, Banabas M, Nake S, Goodrick I, Gordon J, O'Grady D, Dubos B. 2014. Methods to account for tree-scale variation in soil- and plant-related parameters in oil palm plantations. *Plant and Soil* 374, 459-471. DOI: 10.1007/s11104-013-1894-7 Plus Erratum *Plant and Soil* 378, 415. DOI: 10.1007/s11104-014-2066-0

Pipai, R., 2013. Biological Nitrogen Fixation By Cover Legumes Under Oil Palm Plantations In Papua New Guinea. Masters thesis. School of Agriculture, Food and Wine. Faculty of Sciences. The University of Adelaide, Australia.

Webb MJ, Nelson PN, Rogers LG and Curry GN. 2011. Site-specific fertilizer recommendations for oil palm smallholders using information from large plantations. *Journal of Plant Nutrition and Soil Science* 174, 311-320.