The effect of pruning and nutrient management practices on cacao (*Theobroma cacao*) yields in the Solomon Islands

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Abstract

Cacao (*Theobroma cacao*) is a vital agricultural commodity in the Solomon Islands (SI), yet yields remain low across smallholder farms due to a complex interplay of agronomic, economic and institutional factors. The aim of this study was to investigate and evaluate management practices that have potential to assist cacao growers improve yields. This research involved an initial survey of 60 growers, and assessed the soil and tree nutrient status on selected farms. The effect of a range of different nutrient inputs, including conventional fertilisers and composts, were evaluated using three different field trials. A final grower survey with 14 growers was used to gain a better understanding of the potential influence of cacao tree rejuvenation practices, primarily intensive pruning and grafting, on farm productivity.

The first grower survey in this study aimed to document current farm management practices and assess soil and plant nutrient status across smallholder cacao plantations. The survey showed that cacao yields were low for most farms and identified differences in pruning practices as potential causes of yield variation. Growers who adopted intensive pruning achieved average yields that were 23% higher than those using only standard pruning, and 128% higher than those who did not use any pruning practices. Growers who used both intensive pruning and selected grafting practices appeared to have additional yield benefits. All the growers that used intensive pruning alone or with selected grafting practices had previously received training and tools from support programmes. Overall, most of farms sampled had low soil and leaf nutrient status. Therefore, there is a need to identify cost effective methods to replace nutrient losses that occur over time.

Results from the fertiliser and compost response field trials showed limited and inconsistent results. Only at Site 1, where cacao is grown as a monocrop, was there strong statistical evidence ($p=0.059$) of a cacao yield response to conventional fertiliser addition. The fertiliser treatment applying 100 kg N, 90 kg P and 150 kg K ha^{-1} had 189% higher number of harvested cacao pods compared to the Control (no fertiliser) treatment in the first year of the trial. However, no other treatment effects were observed. High tree variability was one of the factors likely influencing the ability to show more significant effects of nutrient inputs on yields. There was also no consistent influence of conventional fertiliser or compost treatments on soil and cacao leaf nutrient status at any of the trial sites.

This study also highlighted that the cost of conventional fertilisers in the SI is major constraint to their use by growers. In the SI, the cost of bagged fertiliser is more than three times that in

New Zealand. In some cases, growers would need as much as a 300% increase in yield to achieve a break-even return on the cost of fertiliser. This would require unrealistic yield responses to achieve a return on the fertiliser investment. Therefore, fertiliser use will be cost prohibitive for most cacao growers unless fertiliser prices decrease markedly. In addition, because some growers sell their cacao beans for use in single origin chocolate marketed as being organically grown, this is another reason for growers to be careful about using conventional fertilisers. Therefore, the use of improved recycling of tree residues, including pod husks, and the use of organic certified nutrient inputs will be important to help growers who want to maintain organic status. Overall, there is little evidence that conventional fertiliser use would help smallholder growers be more financial sustainable, especially for those with intercropping farm systems. In addition, cadmium (Cd) is becoming an emerging issue in cacao, with access to markets potentially limited due to the presence of elevated levels in cacao beans from some regions in South America (Thomas et al., 2023). Because fertiliser can be a source of Cd, then it is important to ensure that fertiliser use also doesn't increase soil and cacao bean Cd levels. Soil Cd concentrations were low (<0.25 mg Cd kg^{-1}) at both field trial sites tested, for both the Control treatment and 90 kg P ha^{-1} P fertiliser treatment, which is promising as it is associated with lower levels of Cd in dry cacao beans.

The second grower survey investigated the adoption of pruning and grafting techniques among 14 selected growers, evaluated their impact on farm productivity, and explored the potential main factors influencing wider adoption. This survey found that on average, growers that use intensive cacao tree pruning and grafting practices on at least 25% of their farm in the previous 15 years had higher yields than farms only using standard pruning. While further research is needed to provide greater confidence in the size of the yield potential, the analysis revealed that tree rejuvenation practices have potential to improve yields. The potential cost of three strategies to support growers to implement rejuvenation practices were assessed. These included providing clonal seedlings, training and tools for on-farm grafting, or an integrated approach that combines the first two strategies. The integrated strategy showed promise, offering a balance between genetic improvement of trees and grower development, while maintaining cost-effectiveness. However, achieving this will require a national strategy that integrates technical, institutional and economic support mechanisms.

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"Thy Word is a lamp unto my feet and a light unto my path." (Psalm 119:105)

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Chapter 1 Introduction

1.1 Significance of the study

Cacao (*Theobroma cacao*) is an important agricultural export commodity in many topical regions of the world, including Central and South America, Africa, Asia and the Pacific Islands (Franzen & Mulder, 2007; Raju, 2024). Cacao is a perennial crop originated as an understorey tree (Figure 1.1) from tropical rain forests of Central and South America (Linton, 1984). The Latin name for cacao *Theobroma* means ‘food of the gods’, and the beans of cacao plant are used as the main ingredient to produce chocolate (Voora et al., 2019).

Figure 1.1 Cacao tree at 5 years after field planting.

In the South Pacific region, cacao is mainly grown on smallholder farms operated by families to support their livelihoods (Raju, 2024). The SI is the second largest producer of cacao in the South Pacific, after Papua New Guinea, exporting about 5,000 tonnes of dry cacao beans in 2024 (Siliota, 2024). Solomon Island cacao is mostly exported to niche markets in Australia and New Zealand, as well as being exported in bulk to Asia. Cacao is the second largest agricultural export earner for the SI, after coconut (*Cocos nucifera*), and its export value increased substantially from approximate NZ$20 million in 2023 to NZ$55 million in 2024.

This large increase in returns from cacao for the SI was mostly due to a sharp rise in the global price for cacao.

It is estimated that there about 24,000 smallholder families grow cacao in the SI. While cacao is an important source of export revenue for the country, smallholder growers have historically had poor financial returns from growing cacao. This is due to both an extended period of low farmgate prices, prior to 2024, and the on-going challenge of low yields. Some of the common causes of low yields in other cacao growing regions include low soil fertility, old age trees, pest and diseases, and poor tree management practices (Wessel & Quist-Wessel, 2015). In the Pacific region, additional factors identified affecting cacao production include climate related natural disasters, such as cyclones, and socio-economic factors, such as market price (Raju, 2024). Cacao yield is also influenced by the tree propagation practices, such as the use of grafting or choice of seedlings (Asante et al., 2021; CLIP, 2010; Linton, 1984). It is not common for cacao growers in the SI to use fertiliser inputs, to replace loses of nutrient in product removal and other processes, such as leaching and soil immobilisation.

Between 2009 and 2019, cacao tree improvement programmes and projects were implemented in the SI with the aim of increasing yields above the national average cacao annual production of 340 kg dry beans ha^{-1}. While some pilot sites were able to achieve yields as high as 1,400 kg dry beans ha^{-1} (R. Timothy, Pers. Comm., 2020), there was minimal success in improving average yields nationally (MAL, Pers. Comm., 2020; PHAMA, 2016). This may, in part, be due to the small number of growers that were able to participate in these programmes. However, there has been limited research to evaluate the impact of the cacao improvement programmes in SI to assess their effectiveness, and to identify which farm management practices have the most influence on improving yields. This information is important to inform decisions about the benefit of future cacao improvement programmes and to provide advice to growers where they should focus management practices to achieve the best financial returns.

1.2 Research Aims and Objectives

This study aims to provide new knowledge to support cacao growers in SI to improve cacao yields. This involves interviewing growers and monitoring soil and tree nutrient status of gain insights into factors influencing yields. This information is then used to guide the design of subsequent field trials and surveys to assesses the effectiveness of nutrient and tree management practices on improving yields.

The specific objectives are:

1. To provide information on current grower practices, and on soil and plant nutrient status of cacao farms (Chapter 3).
2. To identify local sources of organic wastes that could be used as composts for use on cacao farms (Chapter 4).
3. To quantify the effect of improving the soil fertility of farms, using either conventional fertilises or locally sourced composts, on improving cacao yields (Chapter 4).
4. To identify the potential effect of tree improvement practices on cacao yields (Chapter 5).
5. Evaluate the cost effectiveness of different strategies to support growers implement tree improvement practices (Chapter 5).

Chapter 2 Literature Review

2.1 Introduction

This chapter reviews the literature relevant to this study and is divided into three main sections. Section 2.2 provides an overview of cacao production in the SI, which includes details of agriculture history and importance of cacao, recent developments for cacao production and soils. Section 2.3 covers factors affecting cacao production. Section 2.4 is on nutrient management strategies (or programmes) to improve soil fertility and cacao production.

2.2 Overview of cacao production in the Solomon Islands

2.2.1 The role of cacao in the Solomon Islands

Cacao is a key agricultural commodity in the SI, contributing significantly to smallholder livelihoods and national exports. Alongside oil palm and coconut, cacao is one of the country's major export crops, grown widely by smallholder farmers on land holdings typically less than 2 hectares (CLIP, 2010). Its cultivation provides employment and income for rural communities, where approximately 80% of the population relies on subsistence agriculture and fishing as their primary sources of livelihood (SINSO, 2017; World-Bank, 2020). In 2017, the agriculture sector, primarily driven by smallholder farmers, accounted for NZD $135.6 million in production and contributed 17% of real GDP. Total agricultural exports were valued at NZD $101.5 million that year (SINSO, 2019). Within these exports, coconut was the largest earner, while cacao ranked second, reinforcing its importance as a key cash crop for the sector. Despite its economic importance, cacao production faces constraints due to limited agricultural support services. Only 4% of household agricultural land holdings received assistance such as training, tools, or funding from government and non-government organisations (SINSO, 2019). The lack of access to soil testing and research facilities hampers farmers' ability to improve productivity and manage nutrient deficiencies effectively (Martin, 2000). Strengthening extension services and technical support is therefore essential to enhance cacao yields and sustain smallholder livelihoods in SI.

2.2.2 History and importance of cacao in the Solomon Islands

Cacao crop is commonly grown in the SI in the rural areas. Its seeds and cuttings are used for propagation or grafting. A cacao seedling normally starts branching at a height of 1-2.5 m and fruiting begins between three to five years of age, depending on the soil fertility and other climatic conditions (Tropical-Cacao, 2025, March 2). The fruit produced is called a cacao pod, which contains about 35 seeds that are also referred to as beans (and as wet beans after removal from pods). The beans covered in white mucilage are removed from mature ripe yellow colour pods, fermented and dried, and further processed and value added into cocoa liquor, cocoa butter, cocoa powder and chocolate (Trewren, 1992).

The four main cacao types in the SI are Criollo, Forasterio, Trinitario and Amelonado (Grower survey, Chapter 3; CLIP, 2010; Frazer, 1973). Most seeds were imported into the SI from the Kerevat Agricultural Station near Rabaul in Papua New Guinea (PNG). Cacao plot trials were first conducted at Auki on Malaita Island, followed by Kukum on Guadalcanal Island. After success with good yields and observations on the suitability of the climate and soils, seeds of cacao mentioned varieties, were then distributed to potential farmers on several islands (Urquhart, 1951). The crop has been well distributed throughout the SI and is mostly grown by rural farmers on coastal, alluvial, and low-lying areas, which are regarded as the best sites for cacao, where the climate conditions are also suitable.

In the Pacific Islands region, the other countries that grow the crop commercially are Vanuatu and Fiji (CACAO, 2024; Museum, 2025).

2.2.3 Cacao production in the Solomon Islands

Cacao is a key agricultural commodity in the SI, ranking second in national agricultural income after coconut. Despite its economic importance, cacao production has experienced a notable decline over the past decade, raising concerns about the sustainability of smallholder livelihoods and the effectiveness of sectoral interventions.

In 2011, cacao was cultivated on approximately 16,000 ha, yielding 6,000 tonnes (T) of dry beans, an average of 340 kg ha^{-1} (MAL, 2012; Vadnjal & Pelomo, 2014). By 2020, the area had expanded to 20,000 ha, but national production declined to 4,000 T, reducing average yields to 200 kg ha^{-1} (CBSI, 2020; SINSO, 2019). This figure remained unchanged in 2023, with exports valued at about NZ$20 million (SIG, 2023). While reduced per-hectare yields are a contributing factor, the literature suggests that low market prices may have discouraged harvesting, further exacerbating the decline(SIG, 2024). This trend reflects a diminishing contribution of cacao to agricultural income and rural livelihoods, despite increased cultivation.

To address these challenges, three major programs have provided direct support to cacao smallholders. The Cocoa Livelihood Improvement Program (CLIP, 2009–2012), funded by DFAT, assisted 13,921 enterprises across five provinces. Adoption rates included 40% for Integrated Pest and Disease Management (IPDM), 24% for tool distribution, and 12% for farm rehabilitation (CLIP, 2011–2012). The Rural Development Program (RDP, 2008–2018) improved infrastructure and equipment for smallholders and small and medium enterprises (SMEs), with nearly half of the 37,000 growers who received agricultural advice reporting changes in farming practices (Laven & Hamilton, 2016). The National Cocoa Industry Development Programme (NCIDP, 2011–2019) trained 380 lead growers in IPDM under Participatory Action Research (PAR), and distributed tools, materials, and working capital to approximately 100,000 recipients (F. Wasi, Pers. Comm., 2020). Collectively, these programs contributed to the establishment of an estimated 6.7 million cacao trees nationwide (F. Wasi, Pers. Comm., 2020; Laven & Hamilton, 2016; 2020; SINSO, 2019). However, nutrient management was notably absent from these interventions, representing a critical gap in agronomic support.

In addition to government-led initiatives, several agencies have contributed to cacao sector development. The Pacific Horticultural and Agricultural Market Access (PHAMA) program focused on improving export returns through quality enhancement, traceability, and certification (Laven & Hamilton, 2016). The Australian Centre for International Agricultural Research (ACIAR) facilitated market linkages, genetic resource exchange, and research on intensification and post-harvest practices. The Commodity Export Marketing Authority (CEMA) oversaw processing standards and quality control, though its operational capacity remains limited (R. Timothy, Pers. Comm, 2018). Private sector exporters also played a role by providing services to traders, processors, and farmers aimed at improving bean quality and quantity. While these collaborations have strengthened market access and technical support, the literature reveals limited integration of soil fertility and nutrient management strategies, an omission that may constrain long-term productivity.

Efforts to improve cacao genetics were initiated in 2012, when Trinitario-type cacao clones were imported from Papua New Guinea under CLIP (AusAID-funded). Initial monitoring at Saint Martin School (Catholic Mission) focused on adaptation, yield, and pest resistance. However, the program was discontinued without published results due to funding disparities and political dynamics (Jansen & Maike, 2012). The Ministry of Agriculture and Livestock lacked capacity for follow-up, limiting evidence-based extension. Subsequent ad hoc efforts led to the duplication of some materials from the imported clones to RN Sons farm in 2020 (R. Vava, Pers. Comm., July 18, 2024). While some growers are believed to have adopted these improved cacao clonal materials, formal evaluation remains absent.

Yield comparisons between improved and unimproved farms further highlight agronomic gaps. Improved farms (those receiving training and tools) achieved average yields of 620 kg ha^{-1}, outperforming unimproved farms (320 kg ha^{-1}) and exceeding the targeted yield of 550 kg ha^{-1}. Despite this, national cacao sales declined from 6,000 T in 2011 to 4,000 T in 2021. No formal study has verified the reason for this reduction, though nutrient management was identified as a missing component in previous programs.

Comparative insights from Ghana's cacao sector offer relevant lessons for the SI. Between 2015 and 2019, Ghana's national yields averaged 525 kg ha^{-1}, far below the potential 1,889 kg ha^{-1} (Amponsah-Doku et al., 2022). Contributing factors included acidic soils, low soil organic matter (SOM), and a lack of uniform fertiliser recommendations. Recommended interventions included agroforestry systems, site-specific fertiliser use, and composting cacao pod husks to enhance SOM and nutrient cycling. However, follow-up reports on implementation outcomes were unavailable. These findings underscore the importance of integrating soil health into cacao development strategies, a lesson that remains underutilised in the SI context.

In response to persistent challenges, the SI government launched the Cocoa Sector Intervention Strategy (CSIS) as part of its 100-day plan and 2024–2028 Medium-Term Development Plan. The strategy aims to address genetic variability, aging plantations, and climate change by enhancing productivity, quality, market access, and value addition (MALPRESS, 2024). Local innovation is emerging through Kokonut Pacific Solomon Islands (KPSI), which expanded into value-added cocoa products (e.g., drinking chocolate) with Australian support (Iroga, 2024). Boutique cocoa market development has also gained momentum, with efforts to strengthen supply chains and support growers in meeting international standards (Houanihau, 2025). Despite these promising developments, nutrient management remains absent from current strategic interventions. This omission presents a critical opportunity for future research and policy to address soil fertility constraints and support sustainable cacao intensification.

2.2.4 Soils of Solomon Islands

There have been a number of studies in the SI, assessing the suitability of soil for potential agricultural use. Hansell and Wall (1976) studied distribution of soil to enable effective planning, broad (reconnaissance) surveys of land likely to be of agricultural use and more detailed studies of land already known to have a high agricultural potential. This was initially on Malaita and Guadalcanal Islands and then later extended to other Islands in the country. Of seven soil orders (Alfisols, Entisols, Histosols, Inceptisols, Mollisols, Oxisols and Ultisols) found represented in the SI, Hansell and Wall recognised only 27 ‘great groups’. Amongst them, Guadalcanal has 70% Inceptisols and Malaita has 70 % Ultisols where flood plains, low-amplitude hills in coastal areas are mostly used for growing cacao on these islands. All soils have good properties in terms of drainage from flood plains, depth for root development, clayey textures on upland with undeveloped structures and unimpeded aeration. Conversely, Hansell and Wall also found some Sulfihemists and Acrorthox soils, which were recommended unsuitable for agriculture due to high acidity ($pH < 4$) from the formation of sulfuric acid from pyrite (FeS_2) accumulated in coastal and brackish water environments. These soils are deficient in calcium (Ca), magnesium (Mg) and phosphorus (P), and plants may suffer from toxicity of aluminium (Al), manganese (Mn) and iron (Fe) (Osman, 2018). And out of all the soil types, the Northern plains (floodplains including Ustropepts) of Guadalcanal have the most fertile soils (Hansell & Wall, 1976). Hansell and Wall (1979) indicated potassium (K) deficiencies in soils over calcareous parent materials and limestone and low P availability in soils formed from volcanic rocks. The soil K values in topsoils and subsoils were low (0.3 cmol (+) kg^{-1}) to very low (0.1 cmol (+) kg^{-1}), which limited cacao yields.

2.3 Factors affecting productivity of cacao

There are a range of factors that can impact the productivity of cacao, and a wider knowledge on these factors could assist in the development of a better nutrient management programme. The main factors include climatic and soil conditions and crop establishment, pruning and rehabilitation, and tree size and competition, pest and diseases, tree type, age of growers and cacao trees, and cacao pollination (Akrofi et al., 2015; Baah & Anchirinah, 2011; Dani & Rokhmah, 2022; Gordon, 2011).

2.3.1 Climatic and soil conditions

The most suitable climatic conditions for cacao production occur within 20° latitude of the equator. The crop requires a high annual rainfall of 1,500 – 4,000 mm, daily temperatures of 18 – 32 °C and a sunshine reception of 4.5 - 6.5 hours of direct sunlight per day (MAL, 2012). A preliminary assessment of climate change projections for Guadalcanal Plains in the SI highlighted that the potential for increasing temperatures beyond 32°C, uncertain rainfall projections and higher rainfall, could severely affect cocoa production by 2050 because environmental conditions will become less favourable (CSIRO et al., 2018). The Ministry of Agriculture and Livestock, with the help of the Climate Change Division, were recommended to take a lead role in developing adaptation options in response to the findings. The options include the following: selecting tolerant cacao varieties, changing growing locations to address rising temperatures, and improving pest and disease management.

For the SI, a suitable soil for cacao is a deep topsoil, loamy sands to friable clays, free of large stones, well-drained with no excess water, with high organic content and a pH of 6.0 - 7.5 (Charter, 1953; CLIP, 2010). Soils that are shallow, stony, contain a high clay content or are poorly drained are unsuitable (Tsatsia & Jackson, 2017b). In the Pacific Islands region, Samoa cacao production is on volcanic and stoney soils, which growers prefer to grow them on flat land considering good soil physical characteristics (e.g. soil texture) and nutrient levels (Samoa-Cocoa-Industry-Development-Initiative, 2019).

2.3.2 Crop establishment in the SI

Shade trees are important at the establishment stage, which are normally planted first to establish canopies before planting cacao seedlings (Beer et al., 1998). There are a range of different shade trees, including more permanent species, such as coconut and agroforestry, and temporary trees, such as banana and *Gliricidia* sp. However, the most recommended shade tree for the SI is glyricidia (Trewren, 1992). When intercropped with the permanent trees, the spacing between cacao trees has a density of 400 – 600 trees ha^{-1}. The spacing between cacao trees under temporary trees has the density of 1,110 trees ha^{-1}. For the Amelonado variety of cacao, plant spacing between tree of 3.5 metres intervals is suitable (~ 800 trees ha^{-1}). Temporary shade trees are progressively removed at different cacao growth stages and completely removed when the canopy of cocoa trees is complete (CLIP, 2010).

The best cacao seedlings are planted in the field after successful selection processes involved from best parent tree plants to nursery stages (Asare & David, 2011). Some of the selection criteria often used are high yielding parent trees, resistance to pests and diseases, good beans size from ripe pods, standard nursery methods and conditions, and strong and healthy germinated seedlings (SKIA, 2019).

Maintenance of cacao involves a range of measures that ensure good establishment and growth of the seedlings. One is ‘ring weeding’, which involve weeding in a ring between 60 – 100 cm around the base of young seedlings on regular basis every 6 – 12 weeks. In addition, undergrowth is cut to allow easy access and prevent competition from weeds (CLIP, 2010).

2.3.3 Pruning and rehabilitation

Pruning is an important practice because cacao trees produce excess branches and leaves, which compete with other trees (David, 2005). Pruning also keeps cacao trees in good shape to capture most of the sunlight and is used to maintain a good height and increase production with an adequate number of pods bearing branches (Hamilton & Grange, 1938). Pruning also helps to reduce pests and diseases by removing dead, weak, damaged, diseased and insect infected branches, and promotes good air movement through the trees (Hansell & Wall, 1976). There are five major steps involved to prune a tree (SKIA, 2019). They are formation pruning, sucker pruning, sanitary pruning, structural pruning and yield-stimulating pruning. Yield-stimulating pruning, which consists of sanitary pruning and structural pruning is recommended to be applied to a tree at least twice a year (Karun & Hubballi, 2019). In section 2.2.3 describes how growers in the SI were provided with tools and able to learn pruning practices as part of Integrated Pests and Diseases Management (IPDM) through Participatory Action Research (PAR).

A well pruned mature cacao tree produces 20 – 30 pods where a pod has an average of about 40 g dry beans (Cocoa-Life, 2024). A low yield of 10 pods or less per tree per year is yielded when cacao trees are old or poorly managed or affected by pests and diseases. For example, a one ha plantation farm of 800 trees producing 10 pods, each containing 40 g dry beans, produces a total yield of 320 kg ha^{-1}, in comparison to a dry bean yield of 960 kg ha^{-1} from 30 pods per tree. Cacao rehabilitation or rejuvenation of trees is an approach recommended mainly for old (i.e. over about 30 year old) cacao trees, which are overgrown (CLIP, 2010). Wood and Lass (2001) defined cacao rehabilitation as "the process of restoring yield by improved cultivation and management of existing mature cocoa trees". Fongers and Visser (2015) defined rehabilitation as an application of good agricultural practices and good quality inputs to improve farm productivity. Thus, rehabilitation involves practices such as under-brushing, pruning of old cacao trees and shade trees, pest and disease control, sanitation, cleaning of blocked drainage ditches and applying inorganic or organic fertiliser and replacement planting as appropriate (David, 2005). As part of the CLIP, growers in the SI were introduced to grafting techniques through on-farm demonstrations (Section 2.2.3). These demonstrations enabled growers to use scion wood from their most productive local cacao trees to graft onto existing rootstocks, thereby improving overall farm productivity (R. Timothy, Pers. Comm., 2020). The intention behind this approach was to offer growers a practical and cost-effective alternative to imported clonal materials. By equipping them with the skills to propagate high-performing local varieties, CLIP encouraged farmers to make informed decisions about replacement planting and yield improvement strategies based on their own resources and economic considerations. Besides pruning of cacao trees, pre-harvest practices such as pruning and thinning of shade trees plays an important role in influencing yield of cacao fruit in cacao agroecosystems. Thinning is a shade control method that is progressively and selectively done to shade trees in cacao plantation farms (Trewren, 1992). Along with the use of fertiliser inputs (25 kg N ha^{-1}, 10 kg P ha^{-1}, 20 kg K ha^{-1} and 4 kg Mg ha^{-1}) with the pre-harvest practices, Mendoza-Meneses et al. (2023) observed effects on changes in total yield from 472 (± 52) to 520 (± 105) kg and modifications in other aspects such as increase in size of the pod and the cacao bean. The yield values were not clearly specified to be either in ha or not.

2.3.4 Tree size and competition

Although pruning is viewed a vital yield-enhancing practice for cacao farming, some researchers have found inconsistency on its effects on yield (Ampofo, 1986; Bahaudin et al., 1986; Balasimba, 2007; Govindaraj & Jancirani, 2017; Leiva-Rojas et al., 2019; Thomas & Balasimba, 1992). The adoption rate of the practice becomes low as advisory services have only provided general and standard instructions, which are not addressing the specificity of farm situations (Obeng Adomaa et al., 2022). On crop development, pruning directly increased flushing activity, whilst for yield it was mediated by the interaction with tree size and competition. Tree size and competition effects increased flower number and cherelle numbers. Cherelle refers to a young cacao pod (CLIP, 2010). In the latter effect, pruned trees under high competition encountered increased cherelle wilting due to competition for nutrients, which resulted in similar numbers of large and harvested pods on the stem in pruned and unpruned trees (Valle et al., 1990). Tosto et al. (2022) found that the predicted net effect of pruning on pod number harvested greatly varied from -58% for small trees under low competition to +150% for large trees under high competition. Individual-level analysis to quantify pruning effects was seen as important and more attention to individual tree characteristics is recommended in training and practice of pruning.

2.3.5 Pests and Diseases

Cacao production in the SI has been affected by major pests of weevil borers (*Pantorhytes sp., Acalolepta mixtus*), termites and amblypelta, and major diseases of black pod (*Phytophtora sp.*), canker (*Phytophtora sp.*), root rot (*Phellinus noxius*), thread blight (*Ceratobasidium koleroga*) and pink disease (*Erythricium salmonicolor*) (CLIP, 2010).

Tsatsia and Jackson's (2017b) indicated that black pod fungal disease causes annual losses of 20-30% of the pods and 10% of the trees from canker worldwide. Pacific Island countries, with the absence of fungicide usage and higher rainfall periods, experience losses of at least 40% of the pods (Tsatsia & Jackson, 2017a). Furthermore, other factors such as precipitation, cacao variety, poor or lack of adaptation management strategies of the trees are also believed to be other key determinants of crop losses (Asante et al., 2021). However, their effects may possibly be minimised by improved agronomic management strategies. Newhook and Jackson (1977) study on soil-baiting confirmed the presence and distribution of *P. palmivora* through insect vectors, rain splash and humid conditions in cacao plantation soils in the SI. Soil-baiting is a laboratory and field technique used to detect or isolate soilborne pathogens, especially fungi like Phytophthora and Pythium, that cause root rot and other plant diseases (Burgess et al., 2020). Hence, both studies revealed a poor pest and disease control practices that can be resolved by pruning, shade thinning, general cleaning and phytosanitary measures (Tsatsia & Jackson, 2017a).

Friend and Macfarlane (1974) reviewed two longicorn beetle species known as *Glenea aluensis* Crab (Lever, 1968) and *Megacersium horni* Heller (Duffy, 1963), which were the only two species that were found in the SI. These beetles are also called ‘stem borers’ because they feed on cacao stems and destroy the plant. An outbreak of *M. horni* (Heller) on an Aruligo plantation in Guadalcanal was reported in 1972, which was resolved through pruning of infested branches every three to four days for one month, followed by regular fortnightly inspection and pruning tied to normal management procedures. It totally eradicated the pest and stopped it from spreading. Rats also are serious pest, which make holes in mature pods to eat the mucilage where infestations can cause high losses of pods (Stapley, 1972). There are other reported pests and diseases in the SI, but no records were provided on their level of damage (CLIP, 2010; Tsatsia & Jackson, 2017a). In the Pacific Islands region, Samoa has black pod, mealy bug (*Planococcus pacificus*), cocoa pod borer (*Conopomorpha cramerella*) and Rose beetle (*Adoretus versutus*) (Taylor et al., 2016). Papua New Guinea was affected by cacao pod borer (McQuillan, 2016). And Vanuatu has black pod, bark canker, root rot (not specified) and rats (SPC, 2011).

2.3.6 Tree types, age of growers and cacao trees

The main cacao types grown worldwide are *Forastero*, a vigorous and most widely grown variety producing around 80% of the world’s cocoa production; *Criollo*, a higher quality type that produces less than 1% of the production; and *Trinitario*, a hybrid, which produces about 5% of the world total production (PHAYANAK, 2020; Umaharan, 2018). In addition, there are a few sub-types including *Amelonado* (1,200 kg dry beans ha^{-1} yr^{-1}) (Linton, 1984). Afoakwa (2014) and Minimol et al. (2019) comparatively reviewed the characteristics of the three main cacao types and potential yields under coconut shading. Forastero is more resistant to diseases and produces a high yield of typically > 1,000 kg dry beans ha^{-1} yr^{-1} (Garnsworthy, 2010). It can be quite bitter, acidic, and sometimes it is called a 'bulk cocoa' as some manufacturers combine it with other cacao beans to enhance the flavour. Criollo is rarer and grown far less commonly around the world because it produces lower yields (typically about 500 kg dry bean ha^{-1} yr^{-1}) than the other types and is prone to fungi diseases and pests (MR.-POPPLE'S-CHOCOLATE, 2024). Trinitario as a hybrid, has the aromas and fine flavours from Criollo and the hardiness, high yields (typically about 800 kg dry bean ha^{-1} yr^{-1}) and resistance to diseases from Forastero (MERIDIAN CACAO, 2025) . Hence, the above mentioned are the four main cacao types in the SI, but there are no records on yields or area per cacao type.

Most cocoa farmers in major producing countries are over 50 years old (Fairtrade, 2024; Rikolto, 2023), which can affect their physical ability and productivity. Old-aged trees (> 30 years) also limit cacao production. These are overgrown trees, which occupy good land but produce few pods and often have black pod disease (Binam et al., 2015; CLIP, 2010). The peak of production is at 18 years after planting and having a high proportion of older trees contributes to a marked reduction of potential yield of cacao in farms. A national cocoa strategy (MAL, 2012) involving replanting and increase planting area targeting 10,000 T by 2020 for SI was implemented but unsuccessful.

2.3.7 Cacao pollination

Pollination in cacao is a critical yet challenging process that directly affects fruit set and yield, particularly under smallholder intensification (SI) systems. Unlike many tree crops, cacao is strictly entomophilous, relying on tiny insects such as biting midges (Forcipomyia spp.) and thrips (Thysanoptera) for pollination (Gómez, 2024; Lander et al., 2025; McAlister, 2017). These insects thrive in cool, moist microhabitats like rotting leaf litter, banana pseudostems, empty cacao pods, and bromeliads (Mowbray, 2025). However, SI practices such as pruning and sanitation, though beneficial for disease control, can inadvertently raise temperatures and degrade these habitats, reducing pollinator abundance and leading to lower pollination rates and yields (Lander et al., 2025). Despite a cacao tree is producing thousands of flowers annually, only about 10% are successfully pollinated, leaving the vast majority unproductive (Falque et al., 1995; Klein et al., 2007; de Almeida & Valle, 2007). To mitigate these limitations, management strategies that maintain leaf litter and understory biomass, preserve soil organic matter, provide moderate shade, and reduce chemical inputs have been recommended to support pollinator populations and stabilize microclimates (Groeneveld et al., 2010).

Additionally, hand pollination has proven effective in supplementing natural pollination, increasing yields by up to 20% in trials conducted across Brazil, Ghana, and Indonesia (Oxford, 2025). These findings underscore the importance of integrating ecological management practices into SI systems to enhance pollination success and ensure long-term productivity.

2.4 Soil fertility and nutrient management requirements for cacao

In cacao systems, the successful growth and production of cacao is stimulated by important nutrients that are required based on their functions. van Vliet and Giller (2017) highlighted that nitrogen (N), P and K were the nutrients that are needed by cacao in large quantities and the nutrients that have the main influence on yield, whilst sulphur (S), Ca and Mg were of lesser importance for crop yield. Nitrogen is important for the vegetative growth of the cacao trees, where it boosts the seasonal development of branches and leaves.

At the production stage, N influences yield by increasing the number of flowers and pods, and by extending leaf life (Weinstein et al., 2024). In cacao systems, nutrient loss occurs through exports from harvesting and leaching through soil, which limits production. Phosphorus is also a major nutrient important for cacao crops for root development, wood growth, flowering and cherelle formation (Ling et al., 1990). Phosphorus exists in the soil as orthophosphates and organic forms. Depending on the parent material from which the soil has developed, and the extent to which weathering and leaching have taken place, the total P in surface soils ranges from 0.005 to 0.15%.

Potassium is another important nutrient for crop production, and cacao requires relatively large amounts, similar to requirements for N (McLaren, 1996; Snoeck et al., 2016). In cacao, K is important for its physiological development (pod development and maturation). Potassium is taken up by plants as the K^+ ion form rapidly during vegetative growth stage and is mobile within the plant, which allows it to be translocated from older leaves to younger growing points. Sulphur has also been recognised as an essential plant nutrient that is required by plants in similar amounts as P (McLaren, 1996, p. 2). Sulphur is important for chlorophyll formation, particularly its involvement in protein synthesis. It exists in the soil mostly in organic forms and the main form taken up by plants is as the sulphate ion (SO_4^{-2}). Sulphur can also be supplied in rainfall for farms close to the coast.

Other micronutrients, such as Mn, Fe, copper (Cu), zinc (Zn), boron (B) and molybdenum (Mo), have no appreciable impact on cacao yield but are required in small amounts and their availability is affected by soil pH (Lockard & Asomaning, 1964). Like most crops, soil fertility plays an important role in cacao production and, therefore, it is important to identify the soil nutrient status that are required for optimum productivity.

2.4.1 Soil fertility and fertiliser use

Low soil fertility is one factor influencing declining cacao productivity (Hartemink, 2005). The estimated annual amounts needed to build up the frame and the canopy of the trees before pod production starts are 212 kg N, 23 kg P, 321 kg K, 140 kg Ca, 71 kg Mg, 7.1 kg Mn and 0.9 kg Zn ha^{-1} yr^{-1} (based on 1,075 trees ha^{-1}) for 3 years (Thong & Ng, 1978). The optimum soil test values of cacao are pH (H_2O) 6, 2.5% organic carbon (OC), 0.3% total N, 15 mg kg^{-1} available P (Olsen), > 0.65 cmol (+) kg^{-1} K, 11 cmol (+) kg^{-1} Ca, 2.45 cmol (+) kg^{-1} Mg (Snoek et al., 2016).

In large tropical climate countries such as Ghana, cacao was originally mainly grown by small-scale growers on fertile virgin forest soils and had little or no fertiliser use. Over time, the decline in productivity on the farms was caused by the removal of essential plant nutrients, through harvesting of pods and beans over long periods without replenishment with fertiliser application, resulting in declining soil fertility. Many cacao growers in Ghana have inadequate or lack of prudent soil fertility management practices and lack of suitable advice (Kongor et al., 2018).

In the SI, some previous work on the development of the crop has focused on areas that previously were forested land with good natural fertility and suitable geographical locations. Consequently, these crops had high cacao yields of 600 – 1000 kg dry beans ha^{-1} yr^{-1} with the support of good management practices and choice of cacao types (CEMA, 2012; Fleming & Fleming; M. Pelomo, Pers. Comm., 2021). The commercial farms (fertilised) under optimal conditions produced 1,000 – 2,500 kg dry beans ha^{-1}. However, in many other older cacao growing areas, yields have not been sustained, which is likely to be influenced by a decline in soil fertility in the humid tropical climatic conditions (Gallup & Sachs, 2000).

Fertiliser use

In the SI, cacao production without fertiliser use is common with smallholders, due to fertiliser use being cost prohibitive. Therefore, nutrient inputs are largely limited to the availability of local sourced organic materials (CLIP, 2010). However, there are no research outputs reported in the literature on the use of organic fertilisers for cacao in the SI.

While fertiliser use improves yield, van Vliet et al. (2015) noted that fertiliser response will depend on soil fertility as original soil fertility is repeatedly not accounted for. Also, research results from research institute trials with optimum management conditions provided an overestimation of the impact of fertiliser application for the average smallholder farms (Appiah et al., 2000). Also, the interactions between nutrients provided unclear data, as it is sometimes not clear whether results are influenced by one nutrient or more than one nutrient (Ahenkorah & Akrofi, 1968).

Cacao physiology, fertiliser, and shade effects

As an understorey species, the use of fertiliser (101 kg N ha^{-1} yr^{-1}, 46 kg P ha^{-1} yr^{-1}, 121 kg K ha^{-1} yr^{-1} and 34 kg Mg ha^{-1} yr^{-1} by average) with shaded Amelonado trees over a 16 year period achieved an average yield of 1,330 kg ha^{-1} yr^{-1} (Ahenkorah et al., 1974). In fertiliser absence, although the average yield is low (970 kg ha^{-1} yr^{-1}), it is still higher than the national average yield (300 kg ha^{-1} yr^{-1}). The higher yields observed in the study is, in part, likely be due to more optimal management conditions on the research site. However, this study shows that a dry bean yield increase of 360 kg ha^{-1} yr^{-1} was achieved from fertiliser addition.

Murray (1975) stated that cacao yield rapidly increases with increasing light intensity (50% optimum) at aged 3 and is higher (1,000 kg ha^{-1} yr^{-1}) with fertiliser addition compared to unfertilised trees (550 kg ha^{-1} yr^{-1}). Changes occur as trees mature in terms of the interaction between light intensity and fertility. For instance, cacao needs some shade at young age for fertiliser to be most effective whilst fertiliser application effectiveness in the absence of shade increases as trees mature (Linton, 1984). At 75-100 % light intensity, the yield of fertilised cacao decreased due to an increase in nutritional requirements with age and/or possibly environmental factors that determine nutrient uptake (Murray, 1975). Apart from that, the fertiliser effect lasted longer for nonshaded cacao and is more economically worthwhile, compared to shaded cacao (Asomaning et al., 1971). For instance, under shade conditions the yield response to fertiliser diminishes over time, whereas in full sun the yield responses continue to increases (Ahenkorah et al., 1974). However, a study realises that results on yields for fertiliser application in the cacao production systems in West Africa were highly variable, which ranged from no effect to doubling of the yield (Goudsmit et al., 2023). Goudsmit et al. then worked on fertiliser effects on cacao pod development, pod nutrient content and yield under the systems who found that increase in soil nutrient availability did not change the number of pods produced annually per tree. But increased pod size, which increased the estimated annual dry been yield from 2260 kg ha^{-1} to 2930 kg ha^{-1}. This was due to the number of pods developed during high peak harvest season were heavier due to the bean weight within the pods were relatively higher.

2.4.2 Integrated effects of light and nutrient availability on cacao growth

Cacao trees (*Theobroma cacao* L.) are shade-adapted perennials whose physiological performance depends on canopy structure, light availability and soil nutrition. As understory species, cacao achieves optimal photosynthetic rates at intermediate irradiance (~400 µmol m^{-2} s^{-1}), while excessive shade reduces light interception and carbon assimilation efficiency (Arévalo-Gardini et al., 2021). Conversely, high light exposure can lead to photoinhibition and increased respiratory costs, particularly in upper canopy leaves with shorter lifespans (Miyaji et al., 1997). Studies on agroforestry systems show that balanced canopy density improves biomass and nutrient uptake, especially N, P and K, compared to unshaded monocultures (Isaac et al., 2007). Furthermore, controlled experiments demonstrate that higher light intensities and elevated CO_2 enhance root and shoot biomass, leaf area, and nutrient use efficiency across cacao genotypes (Baligar et al., 2021). These findings highlight the critical interplay between light, canopy architecture, and nutrient dynamics in optimising cacao growth and yield.

2.4.3 Soil fertility and quality assessment on cacao soils

Assessing the fertility and quality of soils used for growing cacao is important for improving cacao production. It reveals nutrient depletion issues, limiting factors, and the level of management, which helps cacao growers to improve. In the SI, in the three island provinces (Guadalcanal, Malaita, and Makira) that are major producers of cacao, there have been no soil assessments carried out for many years due to lack of research and extension support.

Nutrient status of cacao farms

Some previous studies that involved chemical analysis of soil profiles of some soils in the SI (Wall et al., 1979; Wall and Hansell, 1973) and highlighted the success of cacao grown under coconuts in Malaita as an introduced system suitable for rural growers. This intercropping system (cacao-coconut agroforestry) has not only benefited growers in terms of maximising land use on available land, but the mature coconut trees provided shade for cacao trees in which they collaboratively build up soil organic carbon (OC) content through plant residues from fallen branches, leaf litter and harvested fruits for nutrient cycling (Utomo et al., 2016). In the meantime, Wall et al. (1979) reported low levels of soil K in available, and reserves forms in soils for cacao at the Dala Experimental Station in Malaita. And highest yields of 550 kg ha^{-1} dry bean had been achieved with the K addition, in which the amount applied was not specified. However, the yields response was not large enough to cover the cost of the added K fertiliser. Unfortunately, the full details of this trial are not available. This work and the references are all around 50 years old, which indicates that the agriculture sector has been largely ignored by the research sector, and growers have quite different approaches to production now.

Nutrient stock and cycling in cacao ecosystems

Nutrient cycling in cacao ecosystems plays a vital role in sustaining productivity, especially under SI systems. Young (1976) highlighted that most N is concentrated in the topsoil (4,800–18,750 kg ha^{-1}), with less than 10% stored in above-ground vegetation. Annual litterfall contributes 20–45% of vegetation N and only 2–3% of soil N per season, indicating limited replenishment through natural cycling. Phosphorus availability is constrained by low soil pH, and although total P in vegetation ranges from 7–55 kg ha^{-1}, only 10–40% of available soil P is replenished via litter. Potassium, predominantly stored in plant biomass (especially xylem sap), is heavily depleted through harvests, with 86% of K is lost in unreturned husks (van Vliet et al., 2015), and topsoil exchangeable K ranging from 100–550 kg ha^{-1}.

Partial nutrient balances show negative trends in the absence of inorganic fertilisers, particularly for K. For every 1,000 kg of dry beans harvested, 20 kg N, 4 kg P, and 10 kg K are removed, while husks, if returned, can restore 15 kg N, 2 kg P, and 50 kg K. However, studies like Aikpokpodion (2010) in Nigeria reveal chronic deficiencies in Mg and P, and suboptimal K levels in foliage despite moderate soil K, suggesting that natural recycling via litter is insufficient to meet crop demands.

For SI systems, these findings underscore the need for deliberate nutrient management. Continuous nutrient mining without replenishment leads to soil degradation and declining yields. Therefore, integrating organic matter inputs (e.g. husk return), monitoring soil pH and nutrient levels, and applying targeted fertilisers are essential to maintain balanced nutrient cycling and ensure long-term sustainability in intensified cacao production. Over time, these nutrients will need replenishing to ensure balanced nutrient cycling and sustainable production.

2.4.4 Diagnosing nutrient requirements for cacao improvement.

Soil testing

Soil testing is an important tool for helping to identify if nutrient limitations in the soil may influence crop yields. Cacao trees can grow in soil with a pH ranging from 4.6 to 7.5 in the top 20 cm. However nutrient availability is generally most favourable in the soil pH ranging from 6 to 7.5 (Foth, 1990; Wood, 1985). Generally, between soil groups and geographically in the SI, the soil pH previously tested on some soils (~0-30 cm depth) varies from 3 to 8.5 (average 5.8), which were influenced by parent material, age and climate (Lee, 1969; Wall et al., 1979).

Most soils where cacao is grown in SI are within pH 5-6.9, with the optimum pH range being 6.0 to 7.5 (Wood, 1985).

Soil testing for TN method has been common on cacao soils. The average soil TN optimum level for cacao is considered > 0.2% N, and values below the lower limit are likely to be deficient in N (Snoek et al., 2016). At any one time, an estimated > 95% of TN will be in organic forms which are not immediately available to plants, however, as TN increases the potential supply of inorganic N should increase. However, the quantity of mineralised N will also be influenced by other soil factors, such as the C:N ratio of the soil.

The soil available P range of adequate to optimum available P for cacao is considered to be 12 – 25 mg L^{-1} P (Olsen P), and values below the lower limit indicate P deficiency (Snoeck et al., 2016). Based on the above research on cacao soils, testing for both total P and available P (Olsen P or Bray P1 extraction) have been used.

About 90 – 98% soil K is found in soil minerals, such as feldspars and micas. The average soil K range of adequate to optimum for cacao is 0.2 – 1.2 cmol (+) kg^{-1}, and values below this limit are considered to be deficient in K (Snoeck et al., 2016) .

According to van Vliet et al. (2015), S deficiencies have been reported across Africa, more commonly on sandy soils. However, less information is available on its requirements and application for cacao. For the SI, S deficiencies were reported on Ustropepts soils (former grassland) (Wall and Hasell, 1973). There are no reports on the S situation in general for the SI agriculture. The average total soil S optimum level for cacao is 0.05% - 0.1%. But for available S, sulphate-S or extractable organic S are the main methods. For many crops, S deficiency is unlikely when soil sulphate-S values are > 10 mg S kg^{-1}.

Plant testing

Plant testing can be useful for monitoring the nutritional status of crops and help to identify or confirm soil deficiencies. Snoeck et al. (2016) pinpointed the importance of combined soil and plant tests to predict cocoa productivity. However, there is limited information available with regards to plant testing of cacao in the SI. Critical plant test nutrient ranges for cacao developed in other countries can be used to guide nutrient requirements in cacao growth in the SI (Bryson et al., 2014). However, further research is required to refine plant testing requirements for that farm systems and environmental conditions that are specific to the SI.

2.4.5 Fertiliser application and management

Fertiliser management is dependent on crop requirements, soil nutrient status and whether the expected yield response to fertiliser use provides a sufficient economic return to cover the cost of nutrient inputs (i.e., an economic response). Nutrient sources include both imported manufactured fertiliser and local organic amendments, such as mulches, animal manures, composts and food processing by-products.

Inorganic fertiliser application by time and farm conditions

For the inorganic fertiliser as an option, proper timing for application (mainly N, P and K fertilisers) is important because it has a significant effect on crops by increasing yields, reducing nutrient losses, increasing nutrient efficiency and preventing damage to the environment (Sela, 2020). However, for the performance of inorganic fertiliser will be influenced by how well plantations are managed, including pruning, pest and disease control, and weed management. The fertiliser application is best before a light rain, whilst a hot and dry period or heavy rainfall are not suitable conditions for improving fertiliser use efficiency (CLIP, 2010; FAO, 2020).

Appiah et al. (2000) conducted four year trials on the effects of fertilisers on cacao (Amazon, Hybrid, Amelonado) yields on twenty small-holder farms (9 to 27 year-old trees) in Ghana. These farms had at least a minimum level of farm maintenance, such as pruning, control of weeds, pests and diseases, and shade control. Prior to the fertiliser application, the nutrient contents were considered lower than optimal for cacao cultivation, which resulted in nutrient depletion in the crop. A combination of triple superphosphate and muriate of potash, providing 56 kg P ha^{-1} yr^{-1} and 63 kg K ha^{-1} yr^{-1}, was applied to half of the demarcated 1.6 ha plots of selected farms leaving the other half unfertilised (no N was applied). The time of application was between March and May each year before the rainy seasons. Generally, in all farms, the fertilised plots showed an increase in yield due to increase in the number of mature pods per tree, compared to the unfertilised plots during the trial period. In the fertilised plots, gross yields were 807 kg ha^{-1} (61.7% increase) in the 1st year, 1033 kg ha^{-1} (99.8% increase) in 2nd year, 1124 kg ha^{-1} (116% increase) in 3rd year, and 1457 kg ha^{-1} (106% increase) in 4th year.

For P fertiliser application in Brazil or Malaysia, no fertilisers are necessary for mature cacao if available P was above 15 mg kg^{-1} (Olsen P). And generally, in Amazonia and Bahia of Brazil respectively, 39 kg ha^{-1} P is recommended for soil Olsen P levels below 6 ppm and rates of 20-26 kg ha^{-1} P for Olsen P levels of 7-15 ppm (Snoeck et al., 2016). For mature Amelonado cacao variety in Nigeria, at soil Olsen P values below 10 ppm, 22 – 26 kg ha^{-1} P is recommended for the crop (Wood & Lass, 2001).

For K fertilizer application, Snoeck et al. revealed K is often supplied as KCl, and it is best during pod set and development with split applications. According to recommendations for mature cacao in Amazonia and Bahia, below 0.3 cmol(+) kg^{-1} would require 50 kg ha^{-1} K and 75 kg ha^{-1} K, respectively beyond 0.3 cmol(+) kg^{-1} no K fertiliser input is required (Snoeck et al., 2016).

The average recommended nutrient rates for cacao producing trees under coconut on volcanic soils in the SI are 67.2 kg ha^{-1} yr^{-1} N, 38.4 kg ha^{-1} yr^{-1} P and 63.6 kg ha^{-1} yr^{-1} K. All rates are applied for limestone originated soils and alluvial soils except for P due to its high presence in the soils (Linton, 1984).

Organic fertiliser practice

For smallholders in the SI, the use of manufactured fertilisers is limited due to fertiliser being cost prohibitive. In additional, some chocolate manufacturers market their chocolate as 'organic', therefore, growers wanting to produce their cacao 'organically'.

However, the government policy (Solomon Islands Cocoa Industry Policy and Strategies 2012-2020) on organic production for cacao was not clearly specified. Most cacao growers rely on local soil amendments, which are mainly from decaying materials from leaf litter, harvested cacao pods and pruned parts of cacao trees (Applied-Agricultural-Resources, 2014).

For organic fertiliser as an option, CLIP (2010) and van Vliet et al. (2015) mentioned use of leaf litters, pruned materials and harvested pods (burnt or composted), which are placed in rows between cacao trees (Boyer, 1973; Fontes et al., 2014; Thong & Ng, 1978). Important sanitation is followed to ensure pest or disease issues are not carried over. A few other sources of organic fertilisers that are good for cacao are used such as peat, animal manures, basalt and palm oil wastes (Adejobi et al., 2014; Cooke, 1982; Shamshuddin et al., 2011; Sharifuddin & Zaharah, 1991).

Cacao plant residues are used as organic fertiliser to improve soil fertility, in particular dried, ground cacao pod husks have high concentrations of nutrients (Moyin-Jesu, 2007). Agbeniyi et al. (2011) reported that application of the cacao pod husks produced 471 kg ha^{-1} dry beans in comparison to zero application in which they yielded only 240 kg ha^{-1}. Hence, at the selling price of NZD$1.39 kg^{-1} for cacao dry beans, the profitability of cacao husk application increased (Gross revenue – total cost; NZD$655 – 121) and is higher compared to zero application (NZD$334 – 141).

In the SI, there are local food processing companies (IFC, 2016; SIG, 2020; SolBrew, 2023; A. Thomas, 2011) and farms (IFC, 2016; MAL, 2011, 2012), which produce by-products and organic wastes (in tonnes), which are potential nutrient sources for use by growers. Most companies operate on Guadalcanal Island but the amounts they produce each year are not known. These products may be a more cost-effective way for famers to replace nutrient losses and maintain soil fertility, compared to purchased chemical fertilisers. And growers can receive premium prices for 'organically produced' pods, which are preferred by some chocolate manufacturers. These materials include fish wastes (e.g. fish meal), oil palm wastes (e.g. empty fruit bunch ash; 0.02% N, 0.02% P and 2.7% K), spent grain (0.78% N, 0.008% available P and 0.008% K), cacao pod husk ash (0.09% N, 0.05% P and 0.43% K), saw dusts (0.42% N, 0.001% available P and 0.0005% K) and poultry manure (0.086% N, 0.016% P and 0.046% K) (Ahuja et al., 2020; Moyin-Jesu, 2007; Ndubuaku & Kassim, 2003). In a greenhouse pot trial in Nigeria, cacao seedlings obtained the highest response (plant height, root length, number of leaves and leaf area) to cacao pod husk ash and oil palm empty fruit bunch ash at 4,000 kg ha^{-1} rate compared to control and NPK fertiliser (20:10:10) (Akanbi et al., 2014). Poultry manure was applied to 6 months old cacao seedlings in Nigeria under shade at 556 kg ha^{-1} for 32 weeks and obtained the highest yield response (height, stem diameter, leaf number and leaf area) compared to chemical and zero fertilisers (Ndubuaku & Kassim, 2003). On okra crop, received decomposed cacao husk, saw dust and spent grain in Nigeria at 24,000 kg ha^{-1} per four crops and achieved higher pod weights (754, 551 and 1483) gross plot kg ha^{-1} than zero fertiliser (19 gross plot kg ha^{-1}). Hence, the use of available organic materials to replenish lost nutrients has potential as an option for cacao growers, but growers need good advice on amounts to be applied, their availability and the costs.

Also, the use of legumes as a cover crop is common for plantation farms on crops such as cacao, banana, coffee, rubber and oil palm in the tropical regions (Baligar & Fageria, 2007). Cover cropping using legumes is practiced in the Pacific region. In the wet subtropics of Australia, a study on the use of Pinto peanut (*Arachis pintoi*) and poultry litter in two coffee plantations sites, produced 4-5 t ha^{-1} biomass of the legume over 12 months period, which fixed 146 kg N ha^{-1} yr^{-1} and lowered emissions of 0.38 kg N_2O-N ha^{-1} yr^{-1} and 2.26 kg N_2O-N ha^{-1} (Rose et al., 2019). The use of Pinto peanut cover crop treatment was found to be a lower emission factor than for poultry litter. Hence, integration of cover crop legumes into coffee plantations was suggested to offset a portion of external N inputs, while lowering N_2O emissions. There was no mention of impacts on coffee yields. However, Wendling et al. (2016) affirmed that the major part of the accumulated nutrients by the cover crops is subsequently released to the main crop through biomass decomposition and the mineralisation of the residues. This includes N fixation by legumes. In Fiji, Lal (2021) used mucuna (*Mucuna pruriens*) as a green manure crop intercropped with taro plus 120 kg N and 120 P kg P ha^{-1} fertiliser treatments. The corm yield increased by 21%, 16 t ha^{-1} higher than the yield of 13 t ha^{-1} for the same fertiliser treatment without mucuna. In the SI, legumes such as tropical kudzu (*Pueraria phaseoloide* spp.), calopo (*Calopogonium mucunoides* spp.), centro (*Centrosema pbescens* spp.), glyricidia (*Gliricidia sepium*), leucaena (*Leucaena leucocephala*) are common in pastures, coconut and oil palm plantations. Other legumes that are not common, the sensitive plant (*Mimosa pudica* L.), which is mostly regarded as weed due to its thorns, but it basically controls weeds (Sefa, 2012) and *Mucuna* spp., which has been planted within plantations in Samoa (SIFLORA, 2025).

Disadvantages of fertiliser use

In SI systems for cacao production, the use of fertilisers, while essential for maintaining soil fertility and crop yields, can present significant challenges. Conventional fertilisers, when used excessively or over long periods, can disrupt soil microbial activity, reduce soil organic matter, and increase soil acidity (Dar et al., 2016; Dinesh et al., 2010). These changes degrade soil quality and can negatively affect cacao growth and productivity. Moreover, fertilisation contributes to the accumulation of heavy metals in the soil, which can be absorbed by cacao plants and accumulate in beans, posing health risks and potentially making cocoa non-compliant with international trade standards (Anyimah-Ackah et al., 2019). Additionally, the high salt content in some fertilisers can alter soil structure and chemistry, leading to reduced plant growth and lower yields (Akhtar & Alam, 2021; Pirhadi et al., 2018). These drawbacks highlight the need for balanced and context-specific nutrient management strategies in SI cacao systems to safeguard both productivity and environmental sustainability.

2.5 Summary

Cacao is a vital cash crop for smallholder growers in the SI, yet productivity remains low despite ongoing improvement programs that offer training, tools, and planting materials. Climate variability, including irregular rainfall and prolonged dry periods, directly affects flowering and pod development. Pests and diseases, such as black pod and cocoa pod borer, continue to reduce yields, while shade management in agroforestry systems influences both productivity and resilience. Socio-economic challenges, including limited farmer knowledge, weak extension services, insecure land tenure, labour shortages and volatile market prices, further undermine production. Infrastructure constraints, particularly poor roads and transport, increase post-harvest losses, while policy gaps and inconsistent governance limit coordinated sectoral development.

One major gap in improvement programs is the lack of focus on soil fertility and nutrient management, which are essential for healthy plant growth and sustainable yields. Without proper nutrient replenishment, cacao trees struggle to thrive, especially in soils that have been depleted over time. Soil fertility in cacao-growing areas has declined due to several factors, including nutrient loss from harvesting, surface runoff, and the absence of fertiliser use. Although fertilisers are available locally, their high cost makes them inaccessible to most growers. As a result, soils are not being replenished adequately, which limits the potential for improved cacao production.

Compounding this issue is the lack of recent research on the nutrient status of soils in cacao plantations across the SI. Minimal monitoring and outdated data mean that growers and agricultural advisors lack the information needed to make informed decisions. Additionally, imported clonal cacao materials have not been formally evaluated, and promising trials, such as those conducted at Saint Martin School, have not been followed up, further hindering progress.

To address the challenges related to soil fertility, it is essential to conduct a comprehensive survey of cacao growers, along with soil and leaf sampling and analysis across major cacao-producing regions. These steps will help identify current nutrient levels, highlight specific limitations, and guide future interventions. Since much of the existing research is based on international studies, there is a pressing need for locally relevant data. Understanding and maintaining soil fertility, while also addressing climate, pest, market, and institutional constraints, is key to ensuring that cacao production systems in the SI achieve sustainable and economically viable yields.

Chapter 3: Survey of Cacao Growers on Guadalcanal and Malaita Islands

3.1 Introduction

Cacao is the second largest economic crop grown in the SI, after coconut. Cacao is mostly grown by smallholder growers for dried bean exports to niche markets in Australia and New Zealand, as well as being exported in bulk to Asia. Between 2009 and 2019, cacao tree improvement programmes and projects (MAL, 2019; PHAMA, 2016), described in Chapter 2, were implemented with the aim of increasing yields above the national average cacao annual production of 340 kg dry beans ha^{-1}. However, during this period, average cacao production declined to approximately 200 kg dry beans ha^{-1}. While the underlying causes of declining yields have not been clearly identified, the absence of soil and agronomic improvement practices in development programmes is acknowledged as a possible contributing factor. Lower cacao productivity may also have been influenced by some growers choosing not to harvest all or some of their cacao crop, due to low farm-gate prices (Babalola et al., 2017). Global price volatility of cacao has been a significant challenge globally, due to its influence on the prices that growers receive. Between 2015 and 2023 the global market price fluctuated between NZ\$3.25-4.60 kg dry beans^{-1} (Shahbandeh, 2025; Trading-Economics, 2025; Voora et al., 2019). This resulted in the farm-gate prices paid to growers in the SI dropping to as low as NZ\$1.50 kg dry beans^{-1}. Hence, these low prices are likely to have resulted in some growers choosing not to harvest their crops (Babalola et al., 2017), contributing to lower harvested yields and exports (Trading-Economics, 2025).

Between 2023 and 2024, the global annual average price for cacao has increased substantially to about NZ\$11.70.00 kg dry beans^{-1}, and the forecast for 2025 remains at NZ\$12.00 kg dry beans^{-1} , which is high compared to historic prices (Trading-Economics, 2025). These higher prices have been caused by unfavourable weather conditions in some of the main cocoa-producing regions, such as Ghana and Côte d'Ivoire, which has decreased yields. In addition, outbreaks of black pod disease and swollen shoot virus have reduced cacao production, resulting in global supply not keeping up with demand (Gimenez et al., 2025). Other factors influencing higher prices include inflation and increases in production costs (Miranda, 2025), as well as speculation and investment in cocoa futures (Trading-Economics, 2025). Higher global prices in recent years has resulted in SI growers receiving prices of up to NZ\$7.40 kg^{-1} dry beans (Kale, 2023), which has incentivised many growers in the SI to revive abandoned cacao plantations (Mamu, 2024).

Recent renewed interest in cacao production in the SI, influenced by better economic returns, highlights the importance of growers having access to information and support to assist with improving the productivity of their farms. Further information is required to identify the farm practices that have the most influence on improving cacao yields, particularly those related to soil and nutrient management. To better understand the research needs, a grower survey was conducted on the Guadalcanal and Malaita islands, which are two important cacao growing regions of the SI. The objective of the survey was to collect data on farm management practices, and soil and plant nutrient status, on smallholder cacao plantations. The information obtained was used to identify causes of limitations to cacao production in the SI and inform the research objectives presented in the subsequent chapters of the thesis.

3.2. Methods

The survey involved collection of data through interviews with growers, and collection of soil and cacao leaf samples for nutrient analysis. The approach was influenced by previous cacao growers' studies (Arthur et al., 2017; Kongor et al., 2019; Lirag, 2021; Nelson et al., 2011).

3.2.1 Grower survey 1

A cacao grower survey was conducted in March 2021 on 60 plantation farms in two major cacao producing provinces of the SI, namely Guadalcanal (Figure 3.1) and Malaita Islands (Figure 3.2), 30 farms respectively. A research assistant was appointed to conduct the survey on the ground to assist the researcher, due to border closures and travel restrictions caused by the Covid-19 pandemic.

Grower selection and engagement

The participating cacao growers were randomly selected through consultations with extension officers of the Ministry of Agriculture, SI, by considering two factors. One factor was agricultural support, with approximately half of selected growers receiving assistance through government or Non-Governmental Organisations (NGOs) improvement programmes and the other half were growers who had not received assistance. The second factor was location, with growers being selected from the two major cocoa producing regions with the longest history of production, with approximately half from Guadalcanal Island and the other half from Malaita Island. Initially 100 potential growers were selected from the regions based on the above factors and were sent information sheets and consent forms to seek their formal acceptance and engagement in the survey. A final list of 60 cacao growers was selected, representing a range of horticultural systems from minimal to more intensive levels of management.

Grower survey research mechanism

A semi-structured research questionnaire was prepared containing research questions (Appendix I). Prior to the actual survey, the questionnaire was pretested on a smaller group of growers to help improve the questions used. The research assistant conducted face-to-face grower interviews. The advantage of this approach is that the rates of response are typically high, and it provides an opportunity for more complex questions to be asked and for questions to be clarified. The growers were interviewed using their preferred language (i.e., Pidgin English, Doku, Dee, Gae, Baelelea, Toabaita or English).

Ethical approval (#4000023988) for the survey was granted via the Massey University's Low Risk Notification process. The research was undertaken in accordance with Massey's Code of Ethical Conduct.

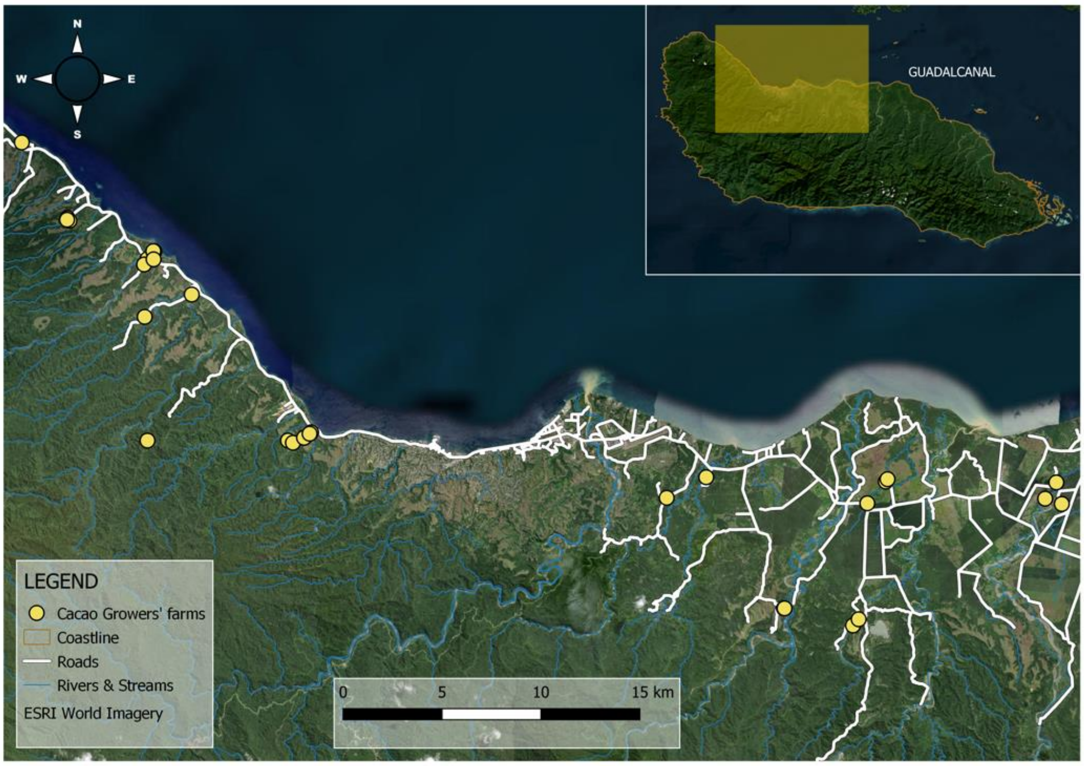


Figure 3.1 Surveyed Cacao Growers' farms on Guadalcanal Island (ESRI-World-Imagery, 2023)

Figure 3.2 Surveyed Cacao Growers' farms on Malaita Island (ESRI-World-Imagery, 2023)

3.2.2 Yield data collection

The yield data was collected from the cacao growers based on their estimates of average annual bean weight. This data was collected through face-to-face interviews with the growers using a questionnaire sheet (Appendix I).

3.2.3 Soil and foliar survey

The 60 survey farms were categorised into three distinct types of common land: coastal land, low-lying land along rivers, and sloping land. The coastal and low-lying land types are important for growing cacao in the SI, due to accessibility, highly suitable soil types (alluvial soils) and flat topography. For the purpose of soil collection and analysis, a random sample of 20 farms was selected from the total surveyed farms, with 10 farms being from each island (Guadalcanal and Malaita). This involved selecting 3-4 from each land type from each island. Half of the farms selected for soil sampling were randomly allocated for leaf sampling, resulting in a collection of 10 samples (5 from each island).

At each farm, a composite sample was collected, comprising at least 10 soil cores (0-15 cm depth) was taken at a distance of approximately 1.25 m from the base of the trees. For each farm selected for foliar tissue sampling, a composite leaf sample was collected from 15 trees consisting of 4 to 8 leaves, with each leaf selected from the fourth position from different locations (north, south, east and west) in the upper canopy of each tree (Figure 3.3). The 'fourth position' in leaf sampling refers to the fourth fully expanded leaf from the top of the plant. The soil cores and the leaf samples were collected approximately every 10m along a diagonal transect. The samples were brought to SPE Analytical and Scientific Laboratory, in Honiara, for sample preparation and analyses. Soil chemical properties analysed include pH, total C, total N, Olsen P, and exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}), cation exchange capacity (CEC) and electric conductivity (EC). The foliar tissue chemical analyses include total N, C, S, P, K, Ca and Mg, and trace elements. The nutrient status was assessed by comparing the values of the tested chemical properties with their respective optimum values. To identify potential relationships between nutrient status and cacao yields, the main chemical properties were correlated with cacao yields of the surveyed farms.

The SPE Analytical and Scientific Laboratory operates with quality control practices such as standardised sample handling procedures to ensure traceability and reduce contamination, routine calibration of laboratory instruments (supported by ACIAR and Griffith University) alongside consistency checks using control samples and repeated measurements. The laboratory follows internationally recognised analytical methods such as atomic absorption spectroscopy, to maintain comparability with global standards. And staff oversight was led by a qualified soil scientist.

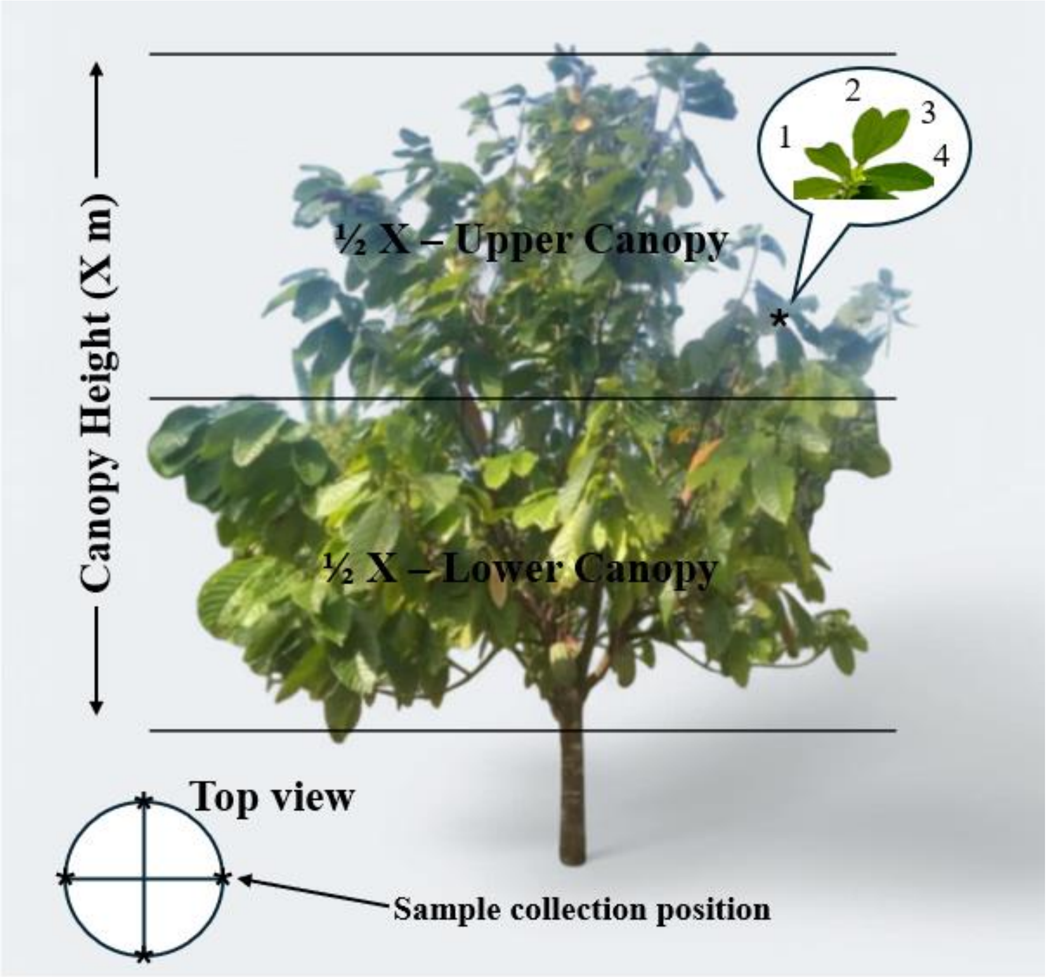


Figure 3.3 Example of the canopy structure of a cacao tree.

Soil analyses

Sample preparation
Soil samples were air dried and passed through a 2 mm sieve to prepare them for analysis.

pH analysis
Soil pH was determined in a 1:5 soil to water ratio by weighing 5 g of air-dried soil adding 25 ml deionised water. The mixture was thoroughly stirred and left for approximately 16 hours before stirring again and reading pH with a hand-held portable multi-meter (EcoTester).

Total Organic Carbon

Soil total organic carbon was determined by the loss on ignition method (Schumacher, 2002). A total of 6 g of oven dried soil was ignited, at 375 °C in a Muffler furnace, for 16 hours and the difference between the soil mass before and after ignition was considered as the organic matter content of the soil sample. The organic matter content was divided by 1.72 to provide the total organic carbon values.

Total Nitrogen

Soil total N was determined by a LECO Trumac Analyser at the Environmental Analysis Laboratory, Southern Cross University. This analysis involves weighing 1 g of air-dried soil in sample boats and the sample is combusted in a high-temperature furnace, converting N compounds into measurable gases, using thermal conductivity or infrared detection.

Inorganic N

Soil samples (air dried) were weighed (3 g) into centrifuge tubes, 30 ml of 2M KCl was added and shaken for 1 hour in an end-over-end shaker. The solutions were centrifuged and filtered, and extracts were analysed for inorganic N on an auto analyser as NH_4^+-N and NO_3^--N.

Olsen P

Olsen P was determined using the sodium bicarbonate ($NaHCO_3$) extraction method, in which 2.5 g of air-dried soil was shaken end-over-end with 50 mL of 0.5 M $NaHCO_3$ (pH 8.5) for 30 minutes at 25 °C, using a soil:solution ratio of 1:20. Extractable P was then measured colorimetrically by the phosphomolybdate blue method of Murphy and Riley (1962), with absorbance read at 880 nm using a Hach DR3900 spectrophotometer.

Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and CEC

Exchangeable cations and CEC analyses were determined by the Ammonium Acetate Extraction Method (Rayment & Lyons, 2011a) followed by atomic absorption spectrophotometry (AAS) analysis of the exchangeable cations. A 1 M ammonium acetate solution was prepared at pH 7 for all soil samples. In summary, air-dried 5 g of air-dried soil was weighed, packed into a sample extraction set-up, and extracted by leaching with 4 x 50 ml ammonium acetate solution. The leachate was collected in a 250 ml volumetric flask and made up to a total volume 250 ml with double reverse osmosis (RO) water for the analysis of Ca, Mg, K and Na.

Plant foliar tissue analyses (macro- and micro-nutrients)

Plant samples were oven-dried at 70ºC and ground to a fine powder prior to analysis. Plant N and S concentrations were determined using a LECO Trumac Analyser. Phosphorus, K, Ca and Mg were determined by inductively coupled plasma mass spectrometry (ICP-MS) following nitric acid digestion.

3.2.4 Pests and diseases survey

On the 60 farms, growers walked research representatives through their blocks to identify pests and diseases using questionnaires and photo guides to match common symptoms (Appendix I). Severity and frequency were assessed using scoring sheets.

3.2.5 Data analysis

Grower survey data were analysed in Microsoft Excel using descriptive statistics (means, medians, standard errors, percentages, and ranges). Correlation and linear regression were applied to examine relationships between variables. Box plots were generated to display the median, interquartile range, whiskers, mean and outliers.

3.3 Results and Discussion

3.3.1 Description of surveyed farms

Farm size, land tenure and cropping system.

The farms surveyed have a combined total land area of 89 ha used for cacao production, with an average farm size of approximately 1.5 ha (Table 3.1). All the sites are located at an elevation of < 200 m. Most of the land in the SI is customary owned, and this is reflected in the ownership types of the surveyed farms, with 92% being on land under customary ownership and only 8% leased from the Crown. Customary land is tribally owned, and all tribal members have access to it and its use is governed by tribal leaders. Main decisions for land development are made through tribal meetings. Crown lease refers to long-term lease of government owned land, which is a common type of land tenure with church missions.

The two main types of cacao systems used by the growers surveyed are intercropping with coconuts (95%) or mono-cropping (5%). Cacao is commonly intercropped with coconut trees for permanent shading, and typically involves cacao trees being planted at approximately 3 m x 3 m spacing in between mature coconut trees that are spaced at 10 m x 10 m. Mono-cropping of cacao is not common and is limited to higher altitudes or narrow valleys, where cacao can obtain temporary shading in naturally forested areas during the early stages of growth.

3.3.2 Average yields

Overall, annual estimated cacao yields of the farms in the survey were moderately low, and there was a high level of variation between farms. The average dry bean yield for surveyed farms was 350 kg dry beans ha^{-1} yr^{-1} and individual farm yields, estimated by the growers, ranged from 149 - 720 kg dry beans ha^{-1} yr^{-1}. The average yields for survey farms on Malaita Island of 413 kg dry beans ha^{-1} yr^{-1}, which was 20% higher than for Guadalcanal Island (Figure 3.4). Malaita Island also had the largest range in values from 267 to 720 kg dry beans ha^{-1} yr^{-1}. However, the middle 50% of farms (i.e. between upper and lower quartiles) on Malaita Island had a smaller yield range compared to Guadalcanal Island, being 349 – 433 kg dry beans ha^{-1} yr^{-1} and 248 – 400 kg dry beans ha^{-1} yr^{-1}, respectively. Overall, Guadalcanal had a higher proportion of farms with very low yields, with about a quarter farms achieving < 250 kg dry beans ha^{-1} yr^{-1}, compared to no farm on Malaita Island.

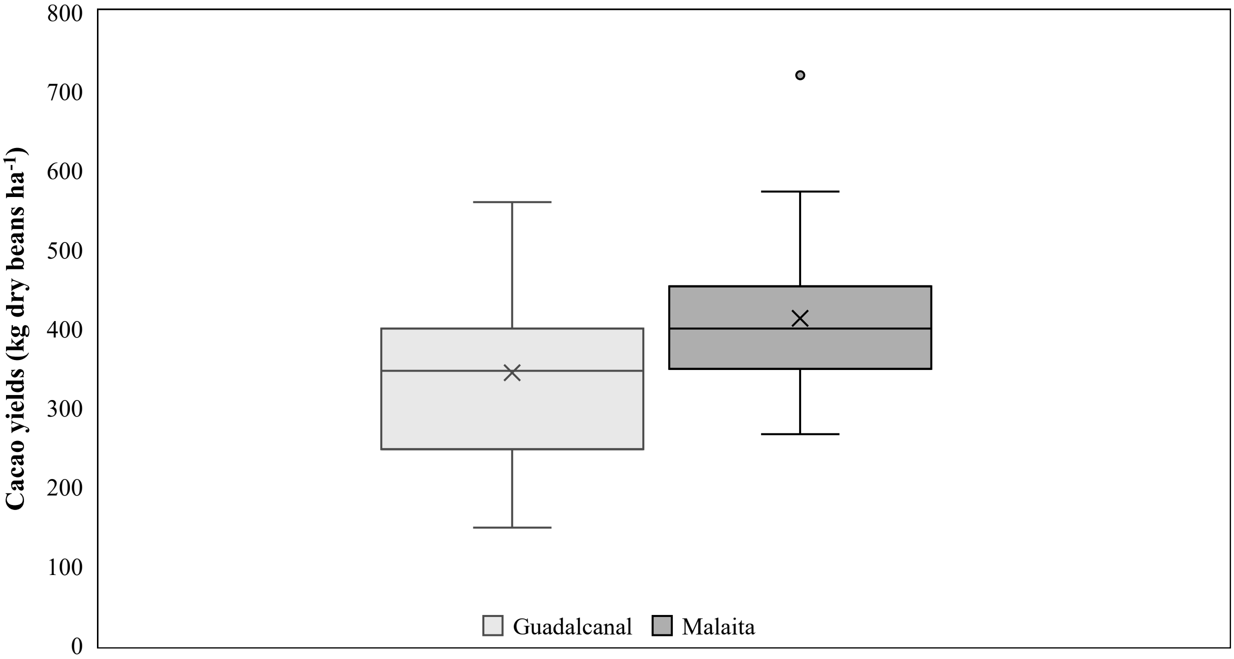


Figure 3.4 Cacao yields for the 60 surveyed farms on Guadalcanal and Malaita Islands.

3.3.3 Potential factors influencing yield variation

i. Cacao types

Forastero, Trinitario and Amelonado are the three main cacao types identified by the surveyed growers. Trinitario is a hybrid of Criollo and Forastero cacao, while Amelonado is a sub-type of Forastero cacao. Recent research by Dillon et al. (2023), on cacao genetic resources in SI (Guadalcanal, Makira, Malaita, Western and Santa Isabel), confirmed that the majority of samples collected were Amelondao cacao, but there was also a high proportion of samples with substantial Criollo content, indicating Trinitario cacao.

Of the total combined area of 89 ha for the 60 farms in the survey, approximately 73% of the area was identified by the growers as growing Amelonado cacao, while Trinitario and Forastero made up 18 and 9% of the area, respectively. All the surveyed farms included Amelonado cacao, and most farms had a combination of cacao types. Only about 20% of the combined total area of the farms in the survey, which was 19 out of 60 farms, grew only Amelonado cacao. This type of cacao is the most commonly recommended by the Ministry of Agriculture and Livestock due to its improved resistance to pests and diseases and because it has a relatively high yield potential (up to ~1,200 kg dry beans ha^{-1} yr^{-1}) when grown under shade with fertiliser inputs and standard management practices (CLIP, 2010). However, in the current survey, the average yields reported by growers for each of the three types were similar, being 305, 366 and 351 kg dry beans ha^{-1} yr^{-1} for Forastero, Trinitario and Amelonado cacao, respectively. The absence of a clear yield advantage for Amelonado cacao, especially compared to Trinitario, for the farms surveyed may be due to other factors, such as inconsistent use of pruning practices and the absence of fertiliser inputs, which could limit yields to levels well below the potential of this variety. In addition, the record of the types of cacao grown will be based on each grower's recollection of the original types planted. However, over time, as growers replace trees with seedling grown from seed, the genetics and yield potential is likely to have changed.

ii. Farm topography

The majority (56.7%) of the survey farms were located on flat topography, along the coastal areas, plains and rivers, with another 30% of farms having rolling topography and only 13.3% being located on easy hill (Table 3.1). The estimated average cacao yields for farms on flat and rolling land were similar, being 385 and 395 kg dry beans ha^{-1} yr^{-1}, respectively. There was a tendency for farms on easy hill topography to have lower yields, with an estimated average yield of 335 kg dry beans ha^{-1} yr^{-1}. Half of the farms on easy hill topography had yields in the lowest quartile of yields (< 320 kg dry beans ha^{-1} yr^{-1}) in the survey. In comparison, none of the on-farm sites located on easy hill topography had yields in the highest quartile (> 440 kg dry beans ha^{-1} yr^{-1}). This indicates a lower likelihood for higher yielding farms being located on easy hill land. Growing cacao on easy hill topography may limit productivity in a number of ways. Firstly, hilly terrain may provide unfavourable habitats for pollinators like midges (Osama, 2025). In addition, hill environments may exhibit sub-optimal temperature or humidity conditions for cacao growth. Furthermore, plantations located in the hills are often farther from growers' homes, reducing the time and frequency with which they can manage their trees.

Table 3.1 Potential factors influencing cacao yields between survey farms.

Potential Factors	**Percentage of farms**	**Average cacao yield** (kg dry beans ha^{-1})
Topography of farm		
Flat (0-3 degrees)	56.7%	385 (± 24.1) *
Rolling (4-9 degrees)	30.0%	395 (± 22.9)
Easy hill (10-15 degrees)	13.3%	335 (± 25.0)
Duration that farm has grown cacao		
< 35 years	83.3%	402 (± 16.6)
35 years or greater	16.7%	278 (± 27.3)
Received training/tools for pruning, grafting and/or phyto-sanitation		
No	60.0%	334 (± 14.4)
Yes	40.0%	452 (± 27.2)
Use of pruning & grafting practices on their farm		
No pruning or grafting	6.7%	187 (± 20.8)
Standard pruning	55.0%	346 (± 12.1)
Intensive pruning	33.3%	426 (± 15.8)
Intensive pruning & selected grafting	5.0%	720 (± 80.0)
Use of phytosanitation practices on their farm		
No	13.3%	338 (± 42.8)
Yes	86.7%	388 (± 16.8)

* Values in parentheses are standard error of the mean

iii. Duration that the farm has grown cacao

The average duration that the survey farms have grown cacao is 27 years, and there was a large range in duration from 6 to 45 years. According to CLIP (2010), the highest yields for cacao trees are typically between 10 and 25 years of age and are expected to decline as trees age further. However, the survey results did not conform with this observation, with cacao farms that where 10 to 25 years old (392 kg dry beans ha^{-1} yr^{-1}) having similar average yields to those that are 25 to 45 years old (379 kg dry beans ha^{-1} yr^{-1}) (Figure 3.5). However, the duration that a farm has been growing cacaos does not necessarily provide a direct indication of tree age, because it is common practice for growers to replace old and damaged trees with new seedlings grown from seeds over time. In addition, some farms use grafting practices to improve the yield potential of older trees. For example, the highest farm average yields (up to 720 kg ha^{-1} yr^{-1}) were for farms that have grown cacao for more than 30 years, but which had used grafting to improve trees approximately 9 years before the survey was undertaken. ICRAF (2014) states that grafting on mature cacao trees doubles cacao yield within two years because the propagation technique shortens the period between flowering and fruiting.

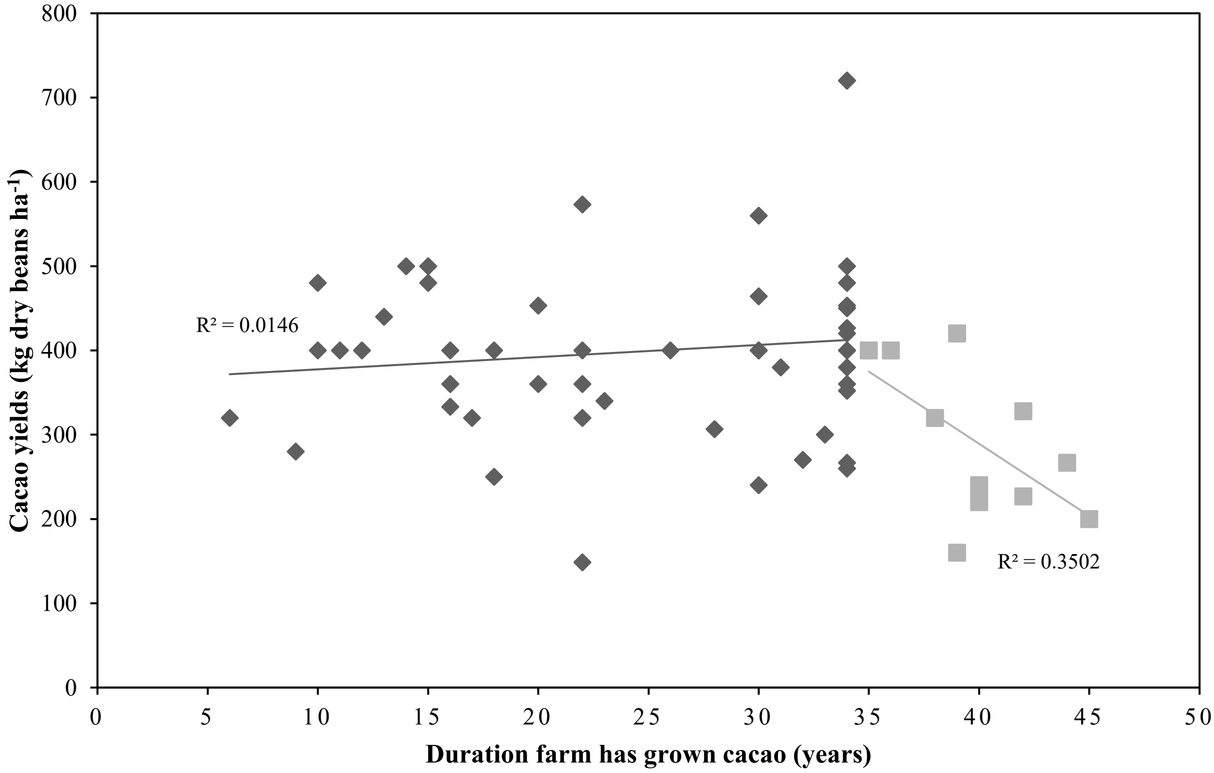


Figure 3.5 Relationship between the duration each farm has been growing cacao and estimated cacao yields.

While there is clearly no significant relationship between duration of cacao growth on a farm and yield up to about 35 years, there is some indication of lower average yields for farms that had been growing cacao for longer than 35 years (Figure 3.5). These farms, which represent 16.7% of the surveyed farms, had average cacao yields of 278 kg dry beans ha^{-1} yr^{-1}, which is 31% lower than the average yield for farms that have grown cacao for less than 35 years (Table 3.1). In addition, just over half of these older farms had yields within the lowest quartile of yields in the survey. In comparison, none of the farm that had grown cacao for 35 years or longer had yields in the highest quartile of yields. This supports a lower likelihood for higher yields being achieved by the oldest farms. Cacao farms older than 35 years likely face declining yields due to tree aging, pest and disease build up, outdated genetic stock, and reduced management efficiency. Canopy overgrowth and accumulated soil pathogens may further limit productivity. Also, the economic lifetime of cacao trees is between 30 and 40 years where productivity declines and yields are low (Wessel & Quist-Wessel, 2015).

iv. Grower support programmes

About half of the surveyed growers have received a least one type of support, such as advisory services (47%), training and demonstrations (43%), tools and materials (37%) and financial support (2%). Also, some growers received more than one type of support. These types of assistance were received mainly through: Solomon Islands National Cocoa Development Program (SINCDP), Cocoa Livelihood Program (CLIP), Rural Development Program (RDP), Participatory Action Research (PAR) and Insect, and Pests and Diseases Management (IPDM), and Commodity Export Marketing Authority (CEMA). Most of these programmes finished in 2018 and only a small number of growers receive on-going support from the Solomon Islands government.

One of the main types of support that growers received was with training and/or tools to assist with pruning and grafting practices and with phyto-sanitation. Of the growers surveyed, only 40% had received these types of training and/or had received tools to help with these practices. On average, farms that received training and/or tools to assist with pruning and grafting practices and with phyto-sanitation had an estimate average yield of 452 kg dry beans ha^{-1} yr^{-1} (Table 3.1) This compares to an average yield of only 334 kg dry beans ha^{-1} yr^{-1} for growers that did not receive this assistance. Farms that received support made up 80% of farms in the highest quartile of yields, but only 20% of the lowest quartile of yields. This highlights that there is a higher likelihood for the growers to have higher yields if they received training and/or tools to assist with pruning, grafting and phyto-sanitation. This is likely to be the influence this type of support has had on growers' ability to implement more intensive pruning practices on their farms. For example, of the growers that received support, 91.7% used either intensive pruning or intensive pruning plus select grafting on their farms. This compares to only 8.3% of farms that had not received support. The majority of these growers who did not receive support practiced only the standard pruning practices. The potential benefit of more intensive pruning practices to improve cacao yields is discussed in more detail in the following section.

v. Pruning and grafting practices

Pruning is a key tree management technique practiced by growers, which has many benefits, such as shade control, growth control, phytosanitation for pests and diseases control, shaping plant growth, ensuring easy access for harvesting, and keeping the pods lower in the tree for easier picking (Kongor et al., 2018). The grower survey identified differences in grower behaviour in relation to pruning and grafting practices conducted in their cacao plantations, which are also likely to have had an influence on yields. The grafting practices involved are side-grafting and top-grafting, which were taught through cacao grower group leaders at on-farm demonstrations under development programmes. Hence, the four categories of farm tree management practices on cacao were: no pruning; standard pruning; intensive pruning and intensive pruning plus selected grafting. Pruning techniques are selected and applied based on what is observed on the trees by growers. In the survey, 'standard pruning' is the removal of approximately 10% of total secondary branches to all tree ages usually over harvest times (Uma et al., 2018). Intensive pruning refers to removal of approximately > 30% of total secondary branches.

Over half of the growers surveyed used standard pruning practices and a third of growers used intensive pruning on their farms. Only 5% of growers used both intensive pruning plus selected grafting on farm. Only a small proportion of the growers (6.7%) used no pruning or grafting on their farms. There was a trend of increasing average yields with the adoption of pruning practices. Farms that did not use pruning had a very low average yield of 187 kg dry beans ha^{-1} yr^{-1}. In comparison, farms that use standard pruning or intensive pruning had average yields of 346 and 426 kg dry beans ha^{-1} yr^{-1}, respectively. Farms where both intensive pruning and select grafting were used showed the higher average yield of 720 kg dry beans ha^{-1} yr^{-1}. Of the farms within the lowest quartile of yields, the majority (86.7%) either did not regularly prune or used standard pruning. In contrast, the majority (86.7%) of the farms within the highest quartile of yields used either intensive pruning or intensive pruning plus grafting. This indicates a higher likelihood of growers having higher yields when involved in more intensive pruning, with potentially additional benefits from also conducting selected grafting.

Pruning and shade management is best carried out shortly after the major and minor cacao flushes, or peak production periods. A cacao flush refers to a production period for young shoots and leaves. The surveyed growers identified that the period between July and September was a better time for pruning than between October and December. However, success can vary with seasons and geographical location depending on prevailing winds and weather patterns (CLIP, 2010). During pruning, the healthy pruned materials are placed on the ground near trees to decompose and recycle nutrients. Phyto-sanitation is applied which involves removing and burning infected plant parts or entire plants outside plantations. Hence, these practices are intentionally conducted to improve tree performance and yields.

Newly grafted plants are identical to the original or parent plant with high yielding characteristics (Christophe et al., 2018). To differentiate, side-grafting is an older vegetative propagation technique that has been improved over time, and involves the use of a stalk shoot that is inserted into a second plant, whereas bud-grafting is a more recent propagation technique, in which a bud of one plant is inserted into a second plant (Baharuddin et al., 2022; Bilderback et al., 2014). The use of both techniques aims to achieve the same goal by acquiring the same characteristics for the grafted plant as the source plant (CLIP, 2010). Hence, improved practices, including grafting techniques, are intentionally conducted to improve productivity of cacao farms (AMARTA, 2010). In SI in general, the adoption of grafting practices across all cacao varieties was low and there were no records kept of the number of trees grafted by trained growers (R. Vava, Pers. Comm, March 18, 2024). The yields declined from 2013 – 2019 as the government support to follow up on set development strategies towards farm productions was limited and inconsistent.

vi. Pest, diseases and weed management

There were five main pests and four main diseases identified by surveyed growers (Section 3.2.3) as causing damage to their cacao trees and/or crop (Table 3.2). The main pests identified were wood borer, pod borer, termites, amblipelta, and rats. The impact of damage was mostly ranked as 'low' for all pests, with only 8% or less ranked as 'medium' and no pest damage was ranked as 'high'. Of the three pests that damaged cacao pods, rats were the most common cause of damage (85% low, 8% medium), followed by pod borer (23% low, 3% medium). Wood borer was the most common cause of tree trunk damage (63% low, 8% medium). Similarly, the impact of all diseases was mostly ranked 'low', with only 3% ranked as 'medium', and no disease damage was ranked as 'high'. With respect to specific damage to cacao pods, black pod disease was the most common cause of damage (97% low, 3% medium). Damage to branches was mostly caused by pink disease (23% low) and damage to roots was mostly caused by root rot (13% low).

Growers generally practiced phyto-sanitation between July and December, likely helping in pest and disease control. The majority (86.7 %) of growers adopted phyto-sanitation practices on their farms (Table 3.1). However, the yield benefit was modest, with farms using phyto-sanitation achieving an average yield only 14.8% higher than the average value (338 kg dry beans ha^{-1} yr^{-1}) compared to farms that did not regularly use this practice.

For weed management, the surveyed growers identified two manual weed control methods. The majority (50%) of growers practiced manual slashing, which refers to cutting of grasses using brush knives. The other 30% did hand weeding (ring and strip) in their cacao farms. Ring weeding is applied at 1 m around the base of each tree and strip weeding is at 1 m each side of trees in the row. Manual slashing offers quick control but allows regrowth. In contrast, hand weeding removes weeds from the root, requiring more labour but providing longer lasting control. These methods were applied at least once every 1 – 2 months per year. The other 20% of growers did not practice weed management regularly, which may be due to limited weed growth under their fully established cacao tree canopies. None of the surveyed growers used herbicides due to their high cost.

Table 3.2 Pests and disease management on surveyed cacao farms on Guadalcanal and Malaita Islands.

Parameter		**Presence and level of damage**			**Main seasons of the year when damage is observed**				**Phyto-sanitation time**			
		Low	Medium	High	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Pests	Wood borer (trunk)	63 %	8 %	-	-	10 %	62 %	-	-	-	(22/3) %	(63/0) %
	Pod borer (pod)	23 %	3 %	-	-	12 %	12 %	3 %	-	-		
	Termites (trunk)	40 %	8 %	-	-	3 %	45 %	-	-	-		
	Amblipelta (pod)	5 %	2 %	-	-	7 %	-	-	-	-		
	Rats (pod)	85 %	8 %	-	-	93 %	-	-	-	-		
Diseases	Black pod (pod)	97 %	3 %	-	-	12 %	-	88 %	-	-	(20/0) %	(67/0) %
	Canker (pod)	3 %	-	-	-	-	-	2 %	-	-		
	Root rot (roots)	13 %	-	-	-	2 %	15 %	-	-	-		
	Pink disease (branches)	23 %	-	-	-	3 %	-	-	-	-		

“-“indicate no data or not relevant

3.3.4 Soil and plant testing, and fertiliser management

The grower survey revealed that soil or plant testing had not been conducted on any of the surveyed cacao plantations since their establishment. All growers considered that they were growing cacao ‘organically’, with no inputs of manufactured fertiliser or sprays, and that their trees were naturally grown. The majority (85%) of the surveyed growers stated that they relied on cacao tree residues (prunings and leaf litter) as the only nutrient sources on their farms, whilst the remaining growers did not answer this question. Tree residue management normally involves moving the pruning and leaf litter (excluding pod husks) about 1 m away from a tree base between July and September, which represents the annual period of limited cropping. It is also the drier period of the year, which is preferred for this practice, not only because of the risk of spreading pests and diseases is higher during the wet period, but also to increase air flow and sunlight (Hartemink, 2005; Nair, 2010). The leaf litter is a part of nutrient stock that recycles essential nutrients (N, P and K) for uptake by lateral roots (Garden-Island-Chocolate, n.d.). These roots usually grow up to about 120 – 150 cm from the trunk of an adult cacao plant, about 15 – 20 cm below the soil surface. Although, cacao plantations use tree residues as a valuable resource, there is limited information on the actual amounts of nutrients recycled (Sari et al., 2022).

Typically, the empty pod husks (harvested pods after beans removal) are left in piles to decompose within the plantations after harvest and are not normally redistributed back near the trees. The reasons for these practices are to keep the plantation farms clean and tidy by leaving pod husks at certain spots to decompose. This attracts insects, such as midges, bugs, and flies to aid pollination (Toledo-Hernandez, 2021), which is good for pod formation on cacao trees. Growers may also have a lack of knowledge on the importance of the empty cacao pod husks in nutrient cycling within their plantation farms to sustain production, as in some cases pod husks are removed for other uses (Hougni et al., 2021). For example, the survey identified that 5% of growers removed the empty pod husk materials, either decomposed or fresh, from their farms for uses such as pot mix ingredients for vegetable gardening and ornamental plants, and livestock feed. In a recent PhD study, the amounts of nutrients in empty pod husks have been estimated at 5.3 - 15.7 kg N ha^{-1} and 14.1 - 38.6 kg K ha^{-1} for every 500 kg dry beans ha^{-1} harvested (Hartemink 2005). Therefore, the use of pod husks can help recycle key nutrients to help maintains soil fertility. However, Hougni’s (2023) observed that substantial amounts of K can be rapidly leach from pod husks, while other nutrients, like Ca, Mg, P, and N, are released more slowly. Rainfall intensity and husk decomposition stage significantly influence nutrient release rates. Consequently, if pod husks are left in piles to decompose before returning to the trees as a compost, then much of the K they contained can be lost. To optimise K recycling from pod husks they should be returned immediately after harvest, but any pod husks showing signs of disease should be disposed of.

Soil types and parent materials

The 20 cacao farms that were included in the soil testing survey have soil types that belong to either the Alfisol, Entisol or Inceptisol soil orders, which are three of the seven soil orders in the SI described by Wall and Hansell (1974). The chemical characteristics of the soils in the SI are inherited from two major groups of soil parent materials: volcanic deposits and derived sediments with low silica, moderate alkali and high magnesium oxide (MgO) content; or marine sediments of varied origin, having high contents of calcium carbonate and moderate to high levels of phosphate (P_2O_4) (Wall et al., 1979). Due to multiple overlapping geological, environmental, or climatic processes, regions across SI may have more than one parent material that influence soil properties (Gray & Murphy, 1999). However, the sampled farms have similar properties in relation to the most common parent materials found on Guadalcanal and Malaita Islands (Phillips, 1992; Wall et al., 1979). Of the 10 farms sampled on Guadalcanal Island, 90% have soils formed from riverine alluviums, which are mostly composed of volcanic materials, such as basaltic volcanics and non-calcareous volcanic sediments (Figure 3.6, Albert et al., 2017; Lee, 1969; Trustrum et al., 1989). These soils are fertile and ideal for agriculture (Adams, 2023). In contrast, on Malaita Island (Figure 3.7), all 10 sampled farms are mostly composed of coral, calcareous and limestone materials, which are typically found on coastal areas (MMERE, 2025; SIART-PMU, 2024).

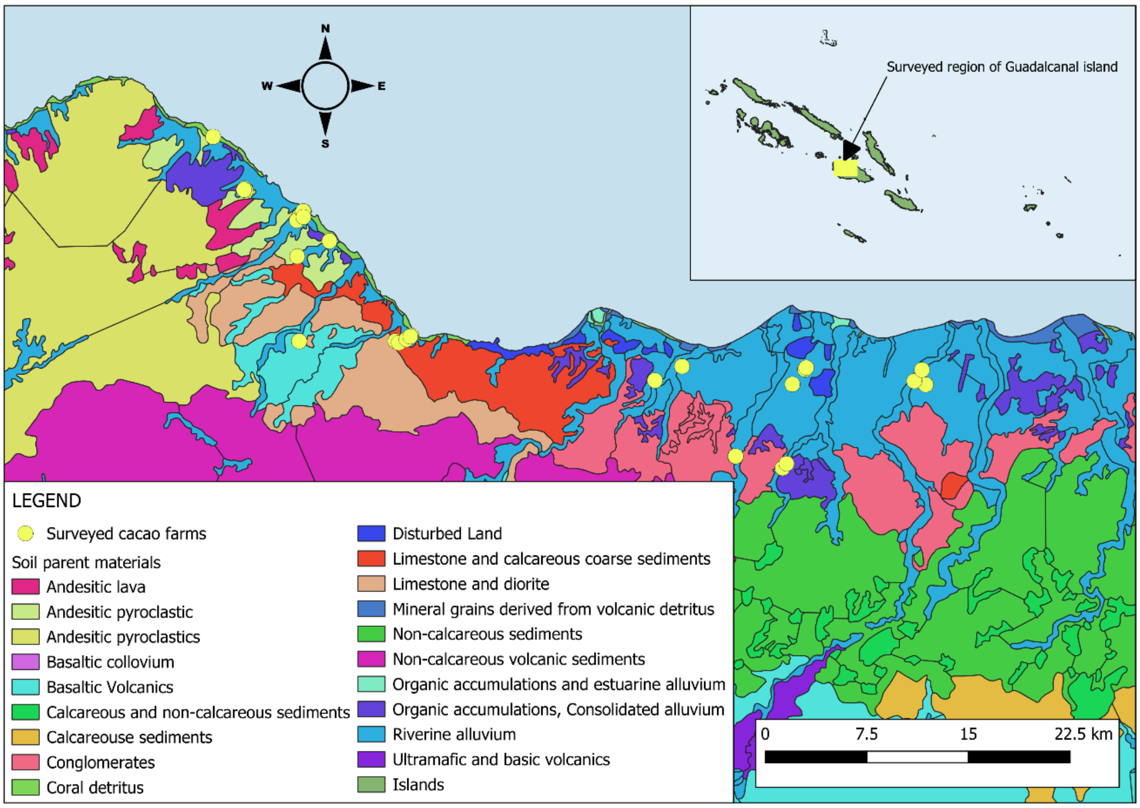


Figure 3.6 Summary of soil parent materials for cacao farms on Guadalcanal (Wall et al., 1979).

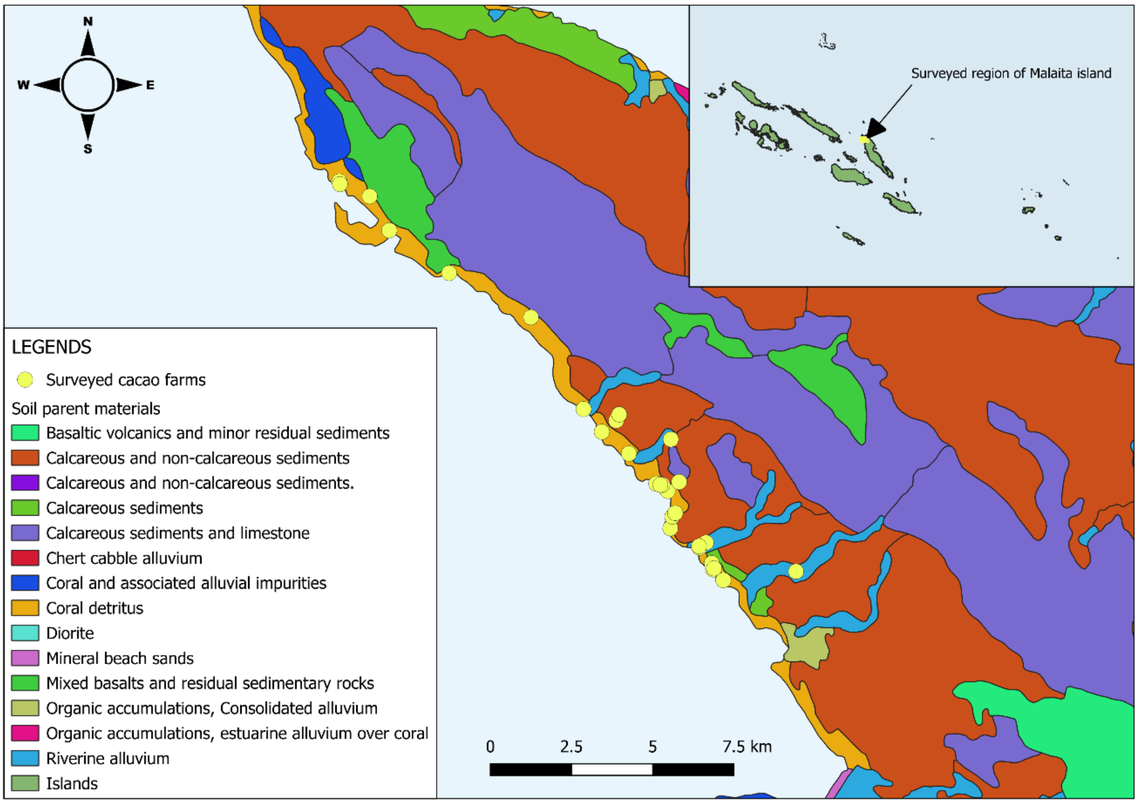


Figure 3.7 Summary of soil parent materials for cacao farms on Malaita (Wall et al., 1979).

Soil fertility status

Table 3.3 shows the results for soil parameters for the 20 farms that had soil samples collected, which are compared to the considered optimum level of cacao growth and yield (Mannan, 2025; Snoek et al., 2016). The soil pH values for the 20 surveyed farms sampled ranged from 5.6 to 8.3, with an overall average of 7.1. At least 35% of the farms tested had soil pH levels within the optimum range of 6.0-7.5. Maintaining optimal soil pH is important for improving the availability of key plant growth nutrients, like P and exchangeable cations. Across the 10 farms sampled on each island, the average soil pH was 6.7 on Guadalcanal and 7.4 on Malaita. The higher pH values for soils on Malaita Island will be influenced by the soil parent materials, being mostly coral, and other calcareous materials. These parent materials also influence the higher Ca content of this soil, which is discussed later in this section.

For the total 20 farms sampled, the soil C content values ranged from 1. 7 – 7.5%, with an overall average of 4.3%. Most (70%) of the farms tested had soil C levels that were higher than 2.5%, which is considered for a minimum level for sustainable cacao production (Doe et al., 2022). Carbon levels provide an indication of the amount of soil organic matter in soils, which is an important store of key nutrients like N, P and S. Soil C also contributes to a soil's CEC, which is important for the retention of exchangeable cations. Soil organic matter also improves the water holding capacity of soils. The average soil carbon levels for the 10 farms on Guadalcanal Island was 3.0%, which was lower than the average of 5.5% on Malaita Island. The higher C content of the soils on Malaita will be influenced by many of the soils being formed from basaltic parent materials, which contain minerals that enhance soil organic matter formation.

Total N ranged from 0.10 – 0.48%, with an overall average of 0.3%, which just meets the minimum optimal level (≥ 0.3%), indicating good stores of soil N, which will predominately be in organic forms. At least 40% of the farms tested had total N above the threshold. Malaita on average has measured higher soil N levels (0.33%) than Guadalcanal (0.19%). Carbon-to-Nitrogen Ratio (C:N) for the 20 sampled farms ranged from 5.20 – 24.5. Guadalcanal and Malaita had average C:N ratios of 17.41 and 17.35, respectively.

Table 3.3 Soil (0-15 cm) chemical analysis and optimum nutrient ranges of 20 sampled cacao survey farms, Solomon Islands.

Parameters	**Guadalcanal**	**Malaita**	**Range**	**Optimum nutrient values***
Soil pH	6.7	7.4	5.6 – 8.3	6.0 – 7.5
% C	3.0	5.5	1.7 – 7.5	≥ 2.5
% N	0.19	0.33	0. 10 – 0.48	≥ 0.3
C:N	17.41	17.35	5.2 – 24.5	
Available N (mg kg^{-1})	19.4	35.4	5.70 – 46.1	20.0 – 50.0
Available (Olsen) P (mg kg^{-1})	3.6	12.2	1.0 – 40.9	≥ 15.0
Ca (cmol (+) kg^{-1})	21.3	50.6	7.70 – 63.0	≥ 11.0
Mg (cmol (+) kg^{-1})	4.6	4.6	0.9 – 14	≥ 2.5
K (cmol (+) kg^{-1})	0.5	0.3	0.1 – 1.1	≥ 0.7
Na (cmol (+) kg^{-1})	0.2	0.1	0.1 – 0.4	NA
CEC (cmol (+) kg^{-1})	26.5	55.6	8.93 – 72.5	≥ 14.1
EC (mS cm^{-1})	0.11	0.18	0.04 – 0.64	< 2.0

*Sources of optimum nutrient values are Mannan (2025) & Snoek et al. (2016)

Nitrogen is important for vegetative growth improvement and uptake of available P for pod production (Sharma et al., 2017). Soil available N of the sampled farms ranged from 5.7 – 46.1 mg kg^{-1}, with an overall average of 27.4 mg kg^{-1}, which is within the considered optimal range (20 – 50 mg kg^{-1}). Soil available N is determined by method described in Section 4.2.7 of Chapter 4. Most (70%) of the farms sampled had available N levels within this optimum range. The average for the farms sampled on Guadalcanal was 19.4 mg kg^{-1}, which was lower than the average for the farm on Malaita of 35.4 mg kg^{-1}. This difference in available N may reflect the differences in the stores of total N between farms sampled on the two islands, with the farms sampled on Malaita having high total N levels on average. Higher total N levels may indicate that a soil has a higher ability to supply plant available N via organic matter decomposition (Guinto & Catto, 2016; Hill-Laboratories, 2025). These average soil available N concentrations, when converted to the amounts of N on a per hectare basis, equate to approximately 29 and 53 kg N ha^{-1} for Guadalcanal and Malaita Islands, respectively. Soil available N is very dynamic, as it can change relatively quickly over time due to changes in plant uptake or other losses, such as leaching, volatilisation and denitrification. Therefore, a single soil test provides only an indication of the supply of N that plants can access at a point in time but is typically insufficient to provide a measure of available N over a season. In these plantation farms, all the N added to the soil is provided by natural sources, such as prunings and leaf litter decomposition, which is made available through mineralisation. Therefore, the pattern of available N will be strongly influenced by soil conditions that influence mineralisation, such as soil temperature and moisture, as well as loss processes, such as leaching. Consequently, without the use of N fertiliser inputs, their ability to ensure adequate N supply at critical phenological stages of cacao production is limited.

Soil available P, as measured with the Olsen P test, showed a very wide range from 1.0 – 40.9 mg P kg^{-1} for the farms sampled, with an overall average of 7.9 mg P kg^{-1}. Only about 5% of the sampled farms had available P above the considered optimum of $\geq$ 15.0 mg P kg^{-1}, while 75% of farms samples had low Olsen P of < 10 mg P kg^{-1}. The farms sampled on Guadalcanal had a very low average Olsen P of only 3.6 mg P kg^{-1}. In comparison, the average for Malaita of 12.2 mg P kg^{-1} was closer the optimum value. Overall, these results indicate that P availability is potentially a limiting factor for cacao tree development and production for the majority of farms sampled, especially on Guadalcanal. Phosphorus plays a crucial role in enhancing root growth for nutrient and water uptake, supports flower initiation and pod development, aids in energy transfer as adenosine triphosphate (ATP) for metabolic processes, strengthens plant defences against pathogens, and contributes to bean production and quality (Snoek et al., 2016). In soils with lower available P, cacao forms associations with arbuscular mycorrhizal fungi (AMF), which enhance P uptake (Paguntalan et al., 2020). Arbuscular mycorrhizal fungi establish symbiotic relationships with cacao roots, extending their hyphal networks into the soil to access P beyond the plant's direct reach. This helps facilitate P absorption, reducing dependency on sources of P inputs, stimulates root branching for nutrient access, supports beneficial microbial populations and improves resilience to drought and nutrient limitations (Paguntalan et al., 2023).

Soil exchangeable K ranged from 0.1 to 1.1 cmol (+) kg^{-1}, with an overall average of 0.4 cmol (+) kg^{-1}. Only about 15% of the sampled farms had levels that were at or above the considered optimum of 0.7 cmol (+) kg^{-1}. This indicates soil available K levels could potentially be limiting cacao tree growth and yield on the majority of sampled farms. The farms sampled from Guadalcanal on average had higher exchangeable K levels compared to Malaita, being 0.5 and 0.3 cmol (+) kg^{-1}, respectively. Potassium is an important nutrient for cacao growth, yield and overall health. It improves seed development in terms of better bean size and weight, improves water retention and stomatal function of trees to withstand drought stress, strengthens plant defences against fungal infections and pests, supports chlorophyll production and efficient energy transfer and ensures proper fruit development and reduces premature pod drop (Akane, 2017; Kaba et al., 2022).

Soil exchangeable Ca ranged from 7.70 – 63.0 cmol (+) kg, with an overall average of 35.9 cmol (+) kg^{-1}. Most (95%) of the farms sampled had Ca levels at or above the considered optimum (≥ 11.0 cmol (+) kg^{-1}). Soil exchangeable Mg ranged from 0.9 – 14 cmol (+) kg, with an average of 4.6 cmol (+) kg. The majority (65%) of sampled farms also had soil with Mg concentrations at or above the considered optimum (≥ 2.5 cmol (+) kg^{-1}). The soil CEC of the sampled farms ranged widely from 8.93 – 72.5 cmol (+) kg^{-1}, with a high average of 41.1 cmol (+) kg^{-1}. The farms from Malaita had an average CEC that was more than double the value from Guadalcanal, being 55.6 and 26.5 cmol (+) kg^{-1}, respectively. The higher CEC values where for soils with pH levels > 7. This is likely to have overestimated their CEC values due to additional Ca being released from soil parent materials, during extraction with 1 M ammonium acetate, as a result of the solution pH of 7 being lower that the soil pH.

With the soil pH of most farms being close to neutral, the CEC would predominantly consist of basic cations, with negligible exchange acidity. Soil exchangeable Ca made up most of the cations, consisting of 62.0 – 98.0% of soil CEC. Exchangeable Ca made a larger proportion of exchangeable cations in soils from Malaita compared to Guadalcanal, being 90.8 and 79.5%, respectively. Calcium is often the dominant exchangeable cation in soils (Kongor et al., 2019), and the higher Ca content of soils from Malaita will be influenced by the soil types there, which are mostly formed from coral sands, calcareous and limestone materials. Soil exchangeable Mg contributed between 1.5 – 36.0% of cation charge on the CEC of the soils sampled. Whereas this range was only 0.2 – 4.3% for exchangeable K.

Electrical conductivity (EC) of the farms samples was low, 0.11 and 0.18 mS cm^{-1} (range of 0.04 - 0.64 (mS cm^{-1}), for Guadalcanal and Malaita respectively. Low EC indicates that soil salinity is unlikely to be a problem on any of the farms sampled on both islands. Soil salinity is a unique challenge in some coastal parts (low-lying land type areas) of the SI for cacao as it is influenced by coastal proximity, climate change-induced seal-level rise for saltwater intrusion, and shifting rainfall patterns (J. Prior, Pers. Comm., 2015; Soil-Science-Australia, 2022). The effects of salinity on cacao are stunted root growth, low yields, nutrient imbalance, leaf burn and wilting and soil structure degradation (CLIP, 2010; Tropical-Cacao, 2024; YARA, 2025). Soil EC can also be used to provide an indicator of nutrient availability, soil texture and available water capacity for these areas (USDA-NRCS, 2014). Very low EC may indicate low levels of available nutrients, which may be the case for the case for some of the farms sampled.

Plant analysis

The leaf sample nutrient results for the ten cacao survey farms sampled are summarised in Table 3.4. These results are compared with ranges that are consider optimum are cacao growth and yield (Aikpokpodion, 2010; Nelson et al., 2010. Foliar N content of the sampled farms ranged from 1.65 – 2.26%, with overall average of 1.87%, which is below the optimum value of 2.00% established by Wessel (1985). Only 20% of the farms sampled had leaf N concentration above the threshold level. Both Guadalcanal and Malaita had similar averages of 1.82 and 1.91% N, respectively. For cacao trees, N is important for leaf formation and canopy development, ensuring healthy growth, supporting chlorophyll production by improving plant’s ability to convert sunlight into energy. This contributes to strong root systems to improve nutrient and water uptake, aids in flower and fruit development to leading to higher yields (Akane, 2017; Borges, 2022).

Leaf P content ranged from 0.13 – 0.25% with an overall average of 0.2%, which meets the optimum level of 0.20% (Aikpokpodion, 2010; Wessel, 1985). At least 60% of the sampled farms are above or equivalent to the threshold level. The P leaf levels were higher on average for samples from Malaita (0.23%) than from Guadalcanal Island (0.17%). This reflects the differences in average Olsen P for the two islands, also being lower on Guadalcanal. These results highlight that P availability could be limiting factor for cacao productivity, especially on Guadalcanal. While there is the potential for mycorrhizal symbiosis to help to improve tree P status when soil P availability is low, there is no research on this in the SI. Phosphorous is used for new root formation, seed production, fruiting and flowering (Nathaniel, 2025).

The K content of leaf samples ranged from 0.94 – 2.32%, with an overall average of 1.71%, which is below the optimum of 2.00% (Aikpokpodion, 2010; Wessel, 1985). Only 10% of the farms had K levels above the optimum. On average the K leaf levels were higher on Malaita compared to Guadalcanal, being 1.78 and 1.63%, respectively. These results highlight, along with the soil test results, that insufficient K could also be a limiting factor. Limited K uptake or shortages can delay the transition from juvenile to mature stages, affecting flowering and overall yield (Weinstein et al., 2025). And the differences in yields possibly related to other factors such as tree age (Snoek et al., 2016). And K generally helps strengthen stems for quick growth and disease resistance (Xiao-yan et al., 2006). The levels of Ca and Mg in all leaf samples collected were above the considered optimums of 0.40 and 0.45%, respectively.

Table 3.4 Leaf nutrient analysis for the 10 sampled cacao survey farms on Guadalcanal and Malaita, Solomon Islands.

Parameters	Guadalcanal	Malaita	Range	Optimum nutrient values*
Nitrogen (%)	1.82	1.91	1.65 - 2.26	2.00 – 2.50
Phosphorus (%)	0.17	0.23	0.13 - 0.25	0.20 – 0.30
Potassium (%)	1.63	1.78	0.94 - 2.32	2.00 – 2.50
Calcium (%)	1.56	1.47	0.84 - 2.17	0.40 – 1.50
Magnesium (%)	0.69	0.65	0.52 - 0.89	0.45 – 1.00
Sodium (%)	0.02	0.02	< 0.01 - 0.02	NA

*Sources of optimum nutrient values are Aikpokpodion (2010) & Nelson et al. (2010)

3.3.5 Relationships between soil and leaf nutrient status and cacao yields

There were no strong relationships observed between farm cacao yields and either soil or leaf N, P or K status for the survey farms sampled (Table 3.5). While the relationship with Olsen P was the strongest ($R^2 = 0.31$), this was predominately due to the farm with the highest yield having an Olsen P level that was well above the values of the other farms sampled. This farm had an Olsen P of 40.9 mg kg^{-1}, whereas the other 19 farms sampled had Olsen P values of 15 mg kg^{-1} or less. When this farm was removed from the regression analysis then there was no longer evidence of a relationship ($R^2 = 0.04$). Manso et al. (2025) also observed that the relationship between cacao pod numbers and either soil nutrient content or leaf nutrient levels were weakly correlated ($R^2 = 0.32$ and 0.20, respectively).

Table 3.5 Relationship between soil and leaf nutrient levels and cacao yield.

Analysis type	Nutrient	R^2 value
Soil (n=20)	Total N (%)	0.08
	Olsen P (mg kg^{-1})	0.31
	Exchangeable K (cmol (+) kg^{-1})	0.08
Leaf (n=10)	Nitrogen (%)	0.05
	Phosphorus (%)	0.08
	Potassium (%)	0.00

Even though soil and leaf N, P and K levels were low on the majority of farms sampled, it is interesting that there were no correlations observed between yield and nutrient status. One potential reason for this is that the presence of multiple nutrient limitations could restrict the ability for a relationship between yield and any one of the individual nutrients to be observed. In other words, if N, P and K are all limiting on many of the farms, then just improving the level of one of these nutrients will unlikely have an appreciable influence on yield. In addition, with the yields being low on most of the sampled farms, then there is also limited potential to show the effect of nutrient status changs across a wider range of yields.

Based on the soil test optimums, presented in Table 3.3, nine of the twenty farms soil sampled had below optimum total N (TN), Olsen P and Exchangeable K levels. Another ten farms had below optimum levels of two of these nutrients and only one farm had a limitation of only one nutrient. This farm, which also had the highest yield, had above optimum TN and Olsen P levels, but below optimum exchangeable K level. In addition, the leaf testing results showed that of the ten farms sampled, three had below optimum levels of N, P and K, five farms had below optimum levels of two nutrients and only two farms had below optimum levels of only one nutrient. These leaf nutrient results also support that there is the potential for multiple nutrient deficiencies. Therefore, any nutrient response trial used to evaluate fertiliser nutrient requirements, needs to ensure that adequate rates of all of the main plant growth limiting nutrients are applied. Also, applying a range of different combinations of N, P and K will help to establish which of these nutrients are more limiting and to identify the rates of each required to optimise yield.

3.4 Summary

Overall, cacao yields were low for the majority of the 60 farms in the survey, with there being large variations in yields between farms. Growers indicated that Amelonado is the main cacao types grown on the surveyed farms, followed by Trinitario and Forastero. The average yields reported for each of these cacao types were similar, with no clear yield advantage for the Amelonado cacao, even though it has a higher yield potential. The average yield reported in this survey for Amelonado was less than a third of its yield potential. The grower survey highlighted that pruning practices appeared to have an association with some of the yield variation observed. Growers who adopted intensive pruning achieved average yields that were 23% higher than those using only standard pruning, and 128% higher than those who did not use any pruning practices. Growers who used both intensive pruning and selected grafting practices appeared to have a further yield advantage. All the growers that used intensive pruning alone or with selected grafting practices had previously received training and tools, for pruning and grafting, from support programmes. In contrast, of the growers who either only used standard pruning or no pruning or grafting practices, the majority had not received any form of support. This demonstrates the importance of these types of support programmes to assist farmers implement improved practices and the benefit they can potentially have for improving yields. Further research is required to more specifically assess the effects on the use of pruning and grafting practices on cacao yields, which is the focus of the research described in Chapter 5 of this thesis.

The soil test results for the 20 survey farms sampled from Guadalcanal and Malaita Islands, indicated that both plant available P and K are potentially limiting plant growth on the majority of farms. Soil available P was particularly low on the farms sampled on Guadalcanal. While soil available N at the time of sampling was adequate for most of the farms sampled, this doesn’t provide a good indication of the supply of plant available N over the entire growing season. Total N, which provides an indication of the soil store and longer-term supply of N for plant growth, was below the considered ideal level on the majority of farms sampled. The leaf test results for the ten survey farms sampled indicated below optimum leaf N and K levels for the majority of farms, and below optimum for leaf P level for four farms on Guadalcanal Island. Overall, most of the farms sampled had low soil and leaf nutrient status for either two or three key plant growth limiting nutrients. None of the farmers in the survey use conventional fertiliser, which in part is likely due to the historic low returns for cacao on a per hectare basis. With the more recent increase in cacao prices, then the use of fertiliser inputs becomes more economically feasible and, therefore, needs further research. This is the focus of the research described in the following chapter.

Chapter 4: Fertiliser and Compost Response Trials

4.1 Introduction

The cacao grower survey and soil and leaf testing results presented in Chapter 3 identified pruning practices and nutrient management as potential factors influencing low cacao yields in the SI. Growers primarily rely on leaf litter, pruned materials and the empty cacao pod to recycle nutrients within their cacao plantations. As it is not common for growers to use conventional fertilisers, there is typically no significant new inputs of nutrients to replace losses, other than though rainfall, which can be a source of sulphur. Conventional fertilisers allow nutrients to be applied in mostly plant-available forms, but there are a number of implications with their use (Hoffmann et al., 2020; Rowell, 1994). For example, conventional fertilisers can be cost prohibitive, or may not be permitted on farms that are selling their cacao beans as being 'organically grown' (Djokoto, 2016). In addition, cadmium (Cd) is becoming an emerging issue in cacao, with access to markets potentially limited due to the presence of elevated levels in cacao beans from some regions in South America (Thomas et al., 2023). Because fertiliser can be a source of Cd, it is important to ensure that fertiliser use does not increase soil and cacao bean Cd levels.

A potential alternative to conventional fertilisers as a nutrient source, is the use of composts made from locally available organic wastes (Mulia et al., 2017). Information is needed to assess the potential benefit of these locally made composts for managing nutrients. They also need to be compared with other options for nutrient addition, such as conventional fertilisers or legume green manures crops. Studies in other countries (Agbeniyi et al., 2011; Mulia et al. 2017) have demonstrated that organic wastes, such as composts or cacao pod husks, can improve cacao tree growth, flowering and dry bean yield. However, it is important for farmers to have evidence that fertiliser and other soil amendments are tailored to their soil and climate environments to ensure that they are only applied at rates required to achieve optimum returns. Unfortunately, there is minimal research conducted in the SI on fertiliser requirements for cacao or the benefits of using composts as a nutrient source. Therefore, the objectives of the research presented in this chapter were to identify local sources of organic wastes that could be used as composts for use on cacao farms; and to quantify the effect of improving the soil fertility of farms, using either conventional fertiliser or locally sourced composts, on improving cacao yields.

4.2 Methodology

4.2.1 Field trial sites

This study involved three field trial sites that were located on two plantation farms (Sape farm and Tarou farm) on Guadalcanal Island (Figure 4.1). At two sites (Site 1 at Sape farm and Site 2 at Tarou farm) conventional fertiliser field trails were conducted (hereafter referred to as ‘conventional trials’). A third field trial was conducted at Sape Farm (Site 3), which compared organic nutrient inputs, legume cover crops and conventional fertiliser (hereafter referred to as ‘combined fertiliser trial’). The two farms selected for the conventional trials were both well maintained and used good management practices, including pruning and phyto-sanitation for pest and disease control. Both farms were also located close enough to Honiara, the capital city of the SI, to allow good accessibility to enable regular monitoring and sampling. The Sape farm using was predominately a cacao mono-cropping system (10-30% shading), while the Tarou farm had a more typical cacao intercropping system with coconut (70-80% shading).

Figure 4.1 Map of field trial experimental sites 1, 2 and 3 on Guadalcanal Island (Imagery, 2023).

4.2.2 Climate

Over the duration of the study (2021-2023), the two farms used for field trial sites showed a similar pattern of monthly rainfall on average (Figures 4.2 and 4.3). However, the quantity of rainfall was higher at the Tarou Farm, which had an annual average value of 2579 mm (monthly range of 76 – 540 mm). In comparison, the annual average rainfall at the Sape Farm was 2325 mm (monthly range of 50 – 347 mm). In general, at both farms the average monthly rainfall was lower for the months from May to October/November and higher from December to April.

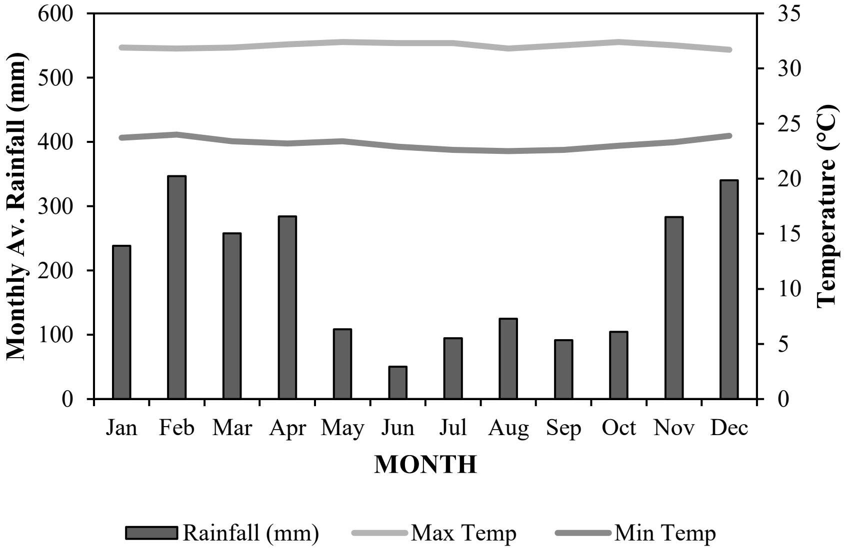


Figure 4.2 Average monthly rainfall and temperatures for Sape Farm (SI-Meteorological-Service, 2024).

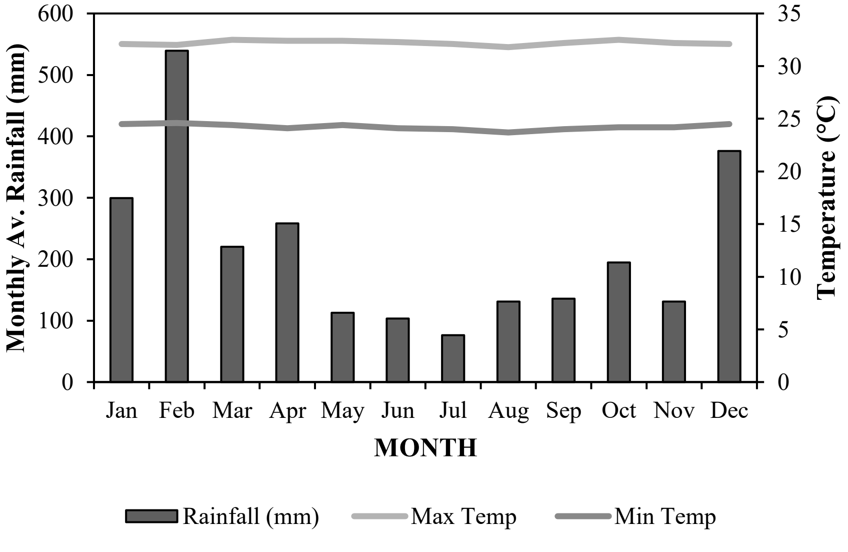


Figure 4.3 Average monthly rainfall and temperatures for Tarou Farm (SI-Meteorological-Service, 2024).

There was minimal variation in monthly average minimum and maximum temperatures over the year. Monthly temperatures were similar for both farms, with minimum and maximum monthly temperatures ranging from 23.7 to 24.6 °C and 31.8 and 32.5 °C, respectively, for the Tarou Farm, and from 22.5 to 24 °C and 31.7 to 32.4 °C, respectively, for the Sape Farm. The trial sites experienced moderate to severe impacts from cyclones between 2021 and 2023, particularly from Cyclones Judy, Kevin, Lola, and Jasper. These events brought heavy rainfall, flooding, and strong winds that damaged young cocoa trees, disrupted flowering and pod development.

4.2.3 Site description and soil information

Trial site characterisation

Trial site characterisation included a description of the soil and landscape (Table 4.1). Site-specific information was obtained during the Grower Survey (Chapter 3), which involved field observations of soil profiles to assess soil texture, colour, and drainage using standard methods outlined by Manaaki Whenua – Landcare Research (2019), Munsell (1905), and Thien (1979). Topography and elevation were determined using a clinometer and a hand-held Garmin GPS unit.

Sape farm (Sites 1 & 3)

These sites are located on the same farm, with a cacao plantation established 20 years ago (as of 2025) under a monocropping system. The surrounding landscape consists of drier grassland with native ferns, situated on flat alluvial plains at an elevation of 12–13 m. The soils are classified as Ustropepts, a subgroup of the Inceptisol order, derived from volcanic alluvium. Soil profiles show brownish loams and clays, which are deep and well-drained, indicating favourable conditions for root development and water movement. Soil classification and parent material identification were guided by the work of Hansell and Wall (1974).

Tarou farm (Site 2)

This site features a 34-year-old (as of 2025) cacao plantation intercropped with coconut, surrounded by regrowth vegetation, mixed-crop gardens, and boundary fruit trees. It is located on flat alluvial terraces at an elevation of 31 m. The soil is classified as a Eutropept, also within the Inceptisol order, and shares the same volcanic alluvium parent material as Sape Farm. The soil texture is described as brown loam, which are shallow but well-drained, suggesting moderate rooting depth and good drainage. Soil classification was also based on Hansell and Wall (1974).

Table 4.1 Trial site characterisation.

Site characteristics	*Sape Farm (Sites 1 & 3)*	*Tarou Farm (Site 2)*
Plantation age	20 years	34 years
Soil Classification*	Ustropept Subgroup of Inceptisol Order	Eutropept Subgroup of Inceptisol Order
Soil texture	Brownish loams and clays	Brown loams
Elevation	12-13 m	31 m
Topography	Flat alluvial plains	Flat alluvial terraces
Drainage	Deep and well drained	Shallow and well drained
Current vegetation	Cacao monocropping system, drier grassland with ferns/naturally grown trees.	Regrowth, gardens boundary fruit trees, shade trees and coconut-cacao intercropping
Parent material	Volcanic alluvium	Volcanic alluvium

*USDA Soil Taxonomy

4.2.4 Trial establishment and maintenance

At each field trial site, a set of either 55 (conventional trials) or 60 trees (combined fertiliser trial) in the same area of each farm was selected, excluding any obvious unhealthy trees. The selected trees were marked with barricade tape, and received standard pruning methods, which are described in Chapter 2 (Section 2.3.3) and Chapter 3 (Section 3.3.3). Pruning was carried out to ensure trees were well maintained and in a good condition before the research started. Once a month, or during harvesting, the trees were maintained by also using structural pruning and sanitary pruning for yield improvement. Weeds were removed by hand and using a bush knife.

4.2.5 Experimental design and treatments

Conventional trial

The two conventional trials, conducted from September 2021 to October 2023 at Sites 1 and 2, involved a randomised complete block design. The design involved five replicate trees per treatment (Table 4.2). The rate of N, P and K applied were split in two applications in the first year (1st October 2021 followed by 1st April 2022). No fertiliser was applied in the second year of the trial. The trial design was selected to assess responses in yield to increasing rates of each nutrient. This involved four different rates of each nutrient combined with the other two nutrients applied at their highest rates. The rates were determined based on providing a wide range of nutrient additions, up to levels that would be considered to be high inputs. This approach was used in order to help identify potential optimum rates of each nutrient. Each tree was tagged using a label with a code that included the treatment and replicate number.

Table 4.2 Rates of N, P and K applied in conventional fertiliser treatments.

Treatment #	**Nutrient rate** (kg ha^{-1} yr^{-1})		
T1	Control (no fertiliser addition)		
T2	0 N	90 P	150 K
T3	50 N	90 P	150 K
T4	100 N	90 P	150 K
T5	150 N	90 P	150 K
T6	150 N	0 P	150 K
T7	150 N	30 P	150 K
T8	150 N	60 P	150 K
T9	150 N	90 P	0 K
T10	150 N	90 P	50 K
T11	150 N	90 P	100 K

Combined fertiliser trial

The combined fertiliser trial, conducted from October 2022 to April 2024 at Site 3, also involved a randomised complete block design. There were five replicates (1 tree per replicate) of twelve treatments involving selected organic composts, legume ground cover and conventional fertiliser treatments (Table 4.4). Trees were tagged with labels to identify treatments. All of the compost treatments were applied at a rate of 10 m^3 ha^{-1}, based on previous studies (Fungenzi et al., 2021; Quaye et al., 2021). Nutrient application rates varied between compost treatments because of the different nutrient composition of the composts. Treatments involving compost alone (T3–T5) delivered substantial nutrient inputs, with Pig Manure compost (T3) contributing the highest N (410 kg ha^{-1}) and P (150 kg ha^{-1}), while Zai Na Tina compost (T5) provided the highest K (987 kg ha^{-1}). Treatments combining compost with legumes (T6–T8) potentially enhanced N availability through biological N fixation, although exact contributions depend on legume performance. Conventional fertiliser treatments (T9–T12) were used as a comparison, either with or without legumes. All treatments involved a single application applied in the first year of the study (1st October 2022) except for the conventional fertiliser, which was applied as split application like in other two trials, with a second application on 1st April the following year). No compost or fertiliser treatments were applied in the second year. The rates of composts were determined based on the nutrient contents of the selected materials (Table 4.3). Pueraria (*Pueraria montana*) and peanut (*Arachis hypogaea*) legumes were selected because they are locally available, are a good source of biologically fixed N, and are shade tolerant (CLIP, 2010; Wong et al., 1985).

Table 4.3 Nutrient contents of selected composts.

	Concentration of nutrients in compost				
Compost type	**N%**	**P%**	**Ca%**	**Mg%**	**K%**
Zai Na Tina	0.8	0.25	1.16	1.09	2.47
Pig Manure	2.1	-	1.38	1.22	0.61
Cacao Pod Husk	1.7	0.38	1.13	0.55	0.65
	Quantity of nutrient applied in 10 m^3 of compost*				
	N (kg ha^{-1})	**P (kg ha^{-1})**	**Ca (kg ha^{-1})**	**Mg (kg ha^{-1})**	**K (kg ha^{-1})**
Zai Na Tina	40	12.5	58	55	124
Pig Manure	105	-	69	61	31
Cacao Pod Husk	85	19.0	57	28	33

Based on an assumed typical dry matter content of 500 kg m^{-3}.

Table 4.4 Organic amendments, legume and conventional fertiliser treatments.

Treatment #	Details
T1	Control (no organic compost, legume or fertiliser addition)
T2	Legumes only (0.5 kg Pueraria seed & 10 kg Peanut seed ha^{-1})
T3	Pig manure compost only (10 m^3 ha^{-1})
T4	Cacao pod husks compost only (10 m^3 ha^{-1})
T5	Zai Na Tina compost only (10 m^3 ha^{-1})
T6	Pig manure compost (10 m^3 ha^{-1}) + legumes (T2)
T7	Cacao pod husk compost (10 m^3 ha^{-1}) + legumes (T2)
T8	Zai Na Tina compost (10 m^3 ha^{-1}) + legumes (T2)
T9	NPK fertiliser only (100 N, 90 P, 150 K; kg ha^{-1} yr^{-1})
T10	NPK fertiliser (T9) + legumes (T2)
T11	NPK fertiliser only (150 N, 90 P, 150 K; kg ha^{-1} yr^{-1})
T12	NPK fertiliser (T11) + legumes (T2)

4.2.6 Treatment materials and application

Conventional trials

The conventional fertilisers used in the trial were urea (46% N), triple superphosphate (20.5% P), and potassium chloride (50% K). All fertiliser treatments were weighed, according to their rates, into labelled sealable plastic bags. In the field, each trees label was cross-checked to ensure correct allocation of fertiliser treatments, which were mixed and applied by hand. Two split applications were applied only during the first year of the trial, in October 2021 and again in April 2022. At each application, half of the annual fertiliser rates for each treatment was applied. At the first application, treatments were applied in a narrow (20 mm wide and 20 mm deep) trench in a ring approximately 1 meter away from the tree base. The use of a trench to apply fertiliser was to reduce the risk of losing the fertiliser in runoff doing the subsequent rainy season (Nov-May). After the rainy season, the second application of fertiliser treatments were applied in a 50 cm wide band in a ring about 1 m away from the tree base. After application, all treatments were covered with thin layer of litter.

Combined trial

i. Selection of organic materials for composting

The identification and sourcing of organic materials involved two sets of activities, which were conducted between July and December in 2021. The first activity was a collection of data through a question-and-answer sheet (Appendix II) or from the Ministry of Agriculture and Livestock, on food processing by-products, livestock manures, farm residues and composts from local food processing companies and farms. The second activity involved collection, composting and chemical analysis of the organic materials selected. Participating organisations and farms were selected as a sample population representing food processors and farms. They identified the most available organic materials produced by answering the questionnaire provided. Formal agreement for participation was made upon receipt of the information sheets and consent forms.

All identified materials were selected according to different criteria. Food processing by-products were obtained from four food-processing companies, which were selected through consulting Central Bank of Solomon Islands reports. These companies were Solomon Breweries Ltd, Guadalcanal Plains Oil Palm Ltd (GPPOL), Sol-Tuna Ltd, and National Fisheries Developments Ltd (NFD). These are the major food processors that regularly produce high volumes of by-products suitable for agricultural use. Solomon Breweries Ltd produces a spent grain by-product derived from malting barley, which is commonly repurposed as livestock feed and compost due to its high protein and fibre content (Mussatto, 2014). Guadalcanal Plains Oil Palm Ltd produces palm expeller, oil palm husk ash, and oil palm empty fruit bunches (EFB), all of which have documented benefits for mulching, soil conditioning, and livestock nutrition (Lim & Rahman, 2011; RSPO, 2011). Sol-Tuna Ltd and National Fisheries Developments Ltd produce fishmeal from fish processing by-products such as offal, bones, and scales. These materials are widely recognised for their value in aquaculture feed and organic fertiliser production (López-Mosquera et al., 2011; Nurfy & Junianto, 2021; Tri-

Marine-Group, 2019). The oil palm empty fruit bunches, oil palm expeller, spent grain and fish meal were excluded for use in making composts in this study due to prohibitive costs.

Livestock manure was obtained from four semi-commercial piggery farms. The farms are Prosperity Piggery, Saga Piggery, FW Piggery and Taiwanese Technical Mission farm. These farms had herds of between 50 and 100 fattened pigs each (4 – 5 months after weaning), used common feed sources (such as millrun, made from wheatmeal; food scraps and vegetable market waste) and their locations were accessible for manure collection. Only decomposed dried pig manure was used as organic fertiliser.

The evaluation of cacao crop residues was undertaken on both the Sape and Tarou cacao farms. On these farms the empty cacao pod husks were stored out in the open and allowed to decompose in compost nets to make a compost.

The commercially made organic compost was obtained from Zai Na Tina Organic Farm. This compost producer was selected based on its leading role in organic farming activities in the SI. Zai Na Tina has been producing a compost called “ZNT compost”, which is made from city food market wastes.

Legume seeds were locally available. Pueraria was collected from Zai Na Tina Organic Farm and peanuts were purchased from a vegetable market in the outskirts of Honiara city. The seeds were tested by placing them in container of water to assess their quality. The float test offers a quick field method to assess seed quality. Seeds were placed in water for 5–10 minutes; viable seeds typically sink, while non-viable or damaged seeds float. This method helps reduce poor germination in cocoa cover cropping and is supported by seed viability guidelines (NCSU, 2015).

ii. Composting

The composting process was conducted using cocoa pod husks and pig manure. Prior to composting, cocoa pod husks were mechanically chipped to enhance decomposition. The selected organic materials were arranged in piles either within a dry shed or in shaded outdoor areas, protected from direct sunlight. These piles were manually turned using a spade three to four times per week to ensure aeration and uniform breakdown (Figure 4.4). Composting was carried out over a minimum period of two months. Upon completion, the matured composts were weighed, bagged, and stored in a dry location until field application. The nutrient concentrations and quantities of the composts (Table 4.3) were determined using the analytical procedures outlined in Section 4.2.9 of this chapter.

Figure 4.4 Simon Sefa turning over the pig manure compost. Photo credit, the author.

iii. Application of treatments

The treatments were weighed into labelled sealable plastic bags for the conventional fertilisers or labelled large bags (25 – 35 kg) for organic composts. The labels on the bags were cross-checked against labels on the treatment trees to ensure treatments were allocated correctly. All treatments were applied, during fine weather conditions, within a 50 cm wide band in a ring located approximately 1 m away from the tree base (Figure 4.5). The conventional fertiliser treatments were applied in two split applications (October 2022 and April 2023). They were thoroughly mixed in buckets before application. The legume ground cover treatments were applied directly as seeds, following the work of Quaresma et al. (2017), but the selection was based on most locally available legumes. Pueraria was sown at 0.5 kg ha^{-1} once at the commencement of the trial, whilst peanuts were sown at 10 kg ha^{-1} in split applications at every three months. Legume residues were left on the soil surface and were not incorporated, typical of the groundcover management approach.

Figure 4.5 Field support worker applying the Zai Na Tina compost treatment.

4.2.7 Soil sampling

Soil sampling occurred 7 months before the commencement of the conventional trials (Site 1 & 2) and 19 months before the start of the combined trial (Site 3). Site 3 was located next to Site 1 on the same farm and, therefore, is expected to have similar initial soil fertility.

Site 1 and 2

In March 2021, prior to the start of the field trials, a soil corer was used to collect a soil sample from both Site 1 and 2. Each sample was single bulk soil sample with up to 10 soil cores (0-15 cm depth), collected approximately 1.25 m from the base of trees. This soil sampling was used to assess the initial soil fertility of both sites prior to fertiliser treatment applications. At each site in October 2022, a soil auger was used to collect four soil cores (0-15 cm soil depth) from each of the five replicate trees for each treatment, from a sampling zone that was between 1 and 1.5 m from the base of each tree. This sampling zone covers the area where previous treatment fertiliser applications occurred in the trial. This sampling method provided a bulk soil sample of 20 soil cores for each treatment (Figure 4.6). This second soil sampling was used to assess the effect of fertiliser application on soil fertility. An auger was used instead of a soil corer at the second sampling because the soil corer that was initially used for the study was stolen.

Site 3

Site 3 was located on the same sample farm as Site 1, therefore, the initial soil sample collected in March 2021 at Site 1 was also used to provide an indication of initial soil fertility at Site 3. Treatment application at Site 3 occurred in October 2022, and it was soil sampled in March 2023 using a soil auger to collect 20 cores per treatment, as described previously. The soil samples were air-dried, sieved (2 mm) and shipped to Massey University's biosecurity facility in the Soil Science Chemical Laboratory, where the samples were analysed (Figure 4.7).

Figure 4.6 Field support worker soil sampling next to one of the treatment trees at Sape farm.

4.2.8 Soil analysis

The soil chemical properties analysed include pH, total N, inorganic N, Olsen P and exchangeable cations (K, Ca, Mg and Na) (Blakemore et al., 1987). This was to determine the effect of different fertiliser treatments on the soil nutrient status. Selected soil chemical properties and farm cacao yields from the field trials were examined using linear regressions to determine the relationship between soil fertility status and cacao yields.

Figure 4.7 Deborah assisting in analysis of total cations of leaf samples at Massey University.

Soil pH

Soil samples (air-dried) were weighed (10 g) into 100 ml beaker with 25 ml distilled water (1:2.5 soil: water ratio) added, stirred vigorously, and left to stand overnight. The next day, a pH meter calibrated with buffer solutions (pH 7 and 4) was used to measure soil pH. The electrodes of the pH meter were thoroughly washed with deionized water prior to each measurement. Duplicate samples were tested at intervals to mitigate the risk of analytical errors.

Olsen P

Based on the methodology outlined by Olsen et al. (1954), soil samples (1 g, air-dried) were weighed into centrifuge tubes. A 20 ml volume of 0.5 M sodium bicarbonate (pH 8.5) was added to the soil in each tube and the suspension was shaken using an end-over-end shaker for 30 minutes. The extraction was centrifuged using a Sorvall RC5C with SS-34 centrifuge equivalent rotor 5,000 rpm for 3 minutes and then filtered through Whatman No. 42 filter paper under suction into a standard test tube. Using a pipette, 4 ml filtrate was transferred into a 50 ml volumetric flask with 32 ml distilled water and 10 ml Murphy and Riley solution. Distilled water was further added up to 50 ml mark on the flask, closed with stopper, shaken thoroughly, and left for 30 minutes for colour development. Using a UV/Visible spectrometer at 712 nm and a 4 cm cell, absorbance was recorded (Blakemore et al., 1987).

Sulphate S

Sulphate S was determined by weighing 10 g of air-dried soil and was combining with 50 mL of 0.25 M potassium chloride (KCl) and shaking for 3 hours at room temperature. The resulting suspension was filtered to obtain a clear extract. The Sulphate S concentration of extracts was then determined using the turbidimetric method, in which $BaCl_2$ was added to precipitate $BaSO_4$ and the turbidity was quantified using a spectrophotometer (modified version of Rayment and Lyons, 2011; Method 10D1).

Soil P retention

Phosphorus retention (P-retention) was determined by weighing 1 g of air-dried soil a 100 mL polyethylene bottle. A 0.02 M phosphate solution was prepared using potassium dihydrogen phosphate (KH_2PO_4), and 20 mL of this solution was added to each sample, giving a soil-to-solution ratio of 1:20. The samples were shaken end-over-end for 16 hours at laboratory room temperature (approximately 20–22°C) to allow equilibration between the soil and the phosphate solution.

Following shaking, the suspensions were centrifuged and filtered through Whatman No. 42 filter paper. The concentration of phosphate remaining in the filtrate was measured colorimetrically using the yellow vanomolybdate method at 470 nm. The amount of phosphate adsorbed by the soil was calculated as the difference between the initial and final phosphate concentrations. P-retention was expressed as the percentage of added phosphate retained by the soil.

Inorganic N

Soil samples (air dried) were weighed (3 g) into centrifuge tubes with 30 ml of 2M KCl added and shaken for 1 hour in an end-over-end shaker. The soils were centrifuged down using a Sorvall RC5C with SS-34 centrifuge equivalent rotor at 5000 rpm for 3 minutes and the supernatant was filtered through Whatman No. 41 filter paper into sample vials. Reagent blanks were used in each set.

Extracts were analysed for inorganic N on an auto analyser as NH_4^+-N (as an indo-phenol Prussian blue complex) and NO_3^--N (as a red azo complex).

Exchangeable cations

At pH 7 cation exchange properties were quantified using 1M ammonium acetate solution (Blakemore et al., 1987). Soil samples (1 g, air-dried) were mixed with 3 g of acid-washed silica sand and packed into semi-micro leaching tubes with macerated filter paper at the bottom. Blank samples made with acid-washed sand and standard soils of known CEC were run alongside samples for quality control.

Each leachate was measured for pH and recorded. A 2 ml aliquot of concentrated 26,000 ppm Strontium chloride – Caesium chloride (Sr and Cs) solution was pipetted into each leachate, stirred thoroughly, and measured on a MP-AES machine for exchangeable K, Ca and Mg. Exchangeable Na was not measured. The charge for the exchangeable basic cations were combined with estimates for exchange acidity displaced from the soil to determine soil CEC.

Total cadmium

Total cadmium (Cd) concentrations in soil samples were determined using graphite furnace atomic absorption spectrometry (GFAAS), employing an Agilent 280Z AA spectrometer equipped with Zeeman background correction. This technique was selected for its high sensitivity and suitability for trace metal analysis in complex matrices.

Reagents used included concentrated nitric acid (HNO_3, 65–70%, analytical grade) and a Cd standard solution (1000 mg L^{-1}). Platformed graphite furnace tubes were used for sample injection, and the instrument was fitted with either a Cd-specific hollow cathode lamp (HCL) or an electrodeless discharge lamp (EDL). All sample preparation and digestion procedures were conducted using polypropylene tubes and acid-washed plasticware to minimise contamination.

Soil samples were first air-dried. A subsample was oven-dried at 105 °C to determine dry matter content. For digestion, 1.00 g of sieved soil was weighed into polypropylene tubes, and 10.0 ml of concentrated HNO_3 was added. Samples were predigested overnight at ambient temperature to initiate breakdown of organic matter. Reflux caps were then fitted, and the tubes were heated on a graphite block or hotplate at 120–140 °C for two hours. Heating was carefully controlled to maintain a steady simmer and prevent evaporation to dryness. Following digestion, samples were quantitatively transferred and diluted to a final volume of 25.0 ml with deionized water. A fixed 1:10 dilution was prepared for instrumental analysis by combining 1.00 ml of digest with 9.00 mL of 1% HNO_3.

Analysis was conducted at a wavelength of 228.8 nm, with Zeeman background correction enabled and a default slit width of approximately 0.5 nm. A 20 µL aliquot of each sample or standard was injected into the platformed graphite tube without the use of chemical modifiers. Calibration standards were prepared in 1% HNO_3 to match the analytical matrix, with concentrations of 0, 0.5, 1, 2, and 5 µg L^{-1} Cd. Calibration linearity was verified prior to sample analysis, and any samples exceeding the upper calibration limit were appropriately diluted and reanalysed.

Quality control procedures included the digestion and analysis of triplicate reagent blanks. Mean blank values were subtracted from sample responses and used to estimate limits of detection (LOD) and quantification (LOQ). In cases where elevated background absorption or matrix interference was observed (such as high salt loads), a 1:20 dilution was considered to mitigate signal suppression. For future analyses requiring enhanced thermal stability and improved robustness, the use of a palladium (Pd) or Pd/Mg chemical modifier may be introduced to support higher pyrolysis temperatures.

4.2.9 Leaf sampling and analysis

Each sample consisted of 4-8 leaves (fourth position) from the top half of the tree canopy for each tree (see method described in Section 3.2.2 of Chapter 3). Leaf samples were prepared (dried, chopped, grounded, sieved, and packed) and shipped to Massey University Biosecurity Facility for chemical analysis.

The herbage samples were chemically analysed for Total N and P (Kjeldahl digestion) and total K, Ca, Mg and Na (Nitric acid digestion) concentration. This was to determine the effect of different fertiliser treatments on plant uptake.

Total N and P

The digest mixture was prepared by adding 250 g of K_2SO_4 and 2.5 g of selenium powder to 2.5 L of H_2SO_4 in a 5 L Pyrex beaker with heating over a gas ring burner until clear.

Oven dried herbage samples were weighed to 0.1 g on a 4 decimal place balance and transferred into 50 ml marked digestion tubes. Digest mixture (Kjeldahl Digestion – 4 mL) was added to each tube and heated in Al block at 350 °C for 4 hours. The tubes were cooled and diluted to 50 ml with deionised water and thoroughly mixed in a vortex mixture. Blanks and standard herbage samples were included in each digestion set. An auto analyser was used to analyse samples for total N and P according to the method described for the soil samples.

Total K, Na, Mg and Ca

Oven dried herbage samples were weighed to 0.1 g on a 4 decimal place balance and transferred into 25 ml marked digestion tubes with blank and standard herbage samples included in each digestion set. Concentrated nitric acid (4 mL) was added to each tube in a fume cupboard and a small glass funnel was placed on top. Overnight, the tubes were digested at 150 °C. Next morning, the funnel was removed to allow the solution to evaporate as the temperature slowly increased to 230 °C until it was dry (approximately 4 hours heating). Tubes were removed from the block while warm and 5 ml of 2 M HCl was added. The solution was mixed using vortex, which was repeated after 2 hours to ensure dissolution of dry samples from inner walls of tubes and left to dissolve overnight. Strontium chloride-caesium chloride (Sr and Cs – 1 mL of 26,000 ppm) was added to each tube using a pipette and thoroughly stirred. Deionised water was added to each tube to bring the final volume up to the 25 mL mark. And samples were measured on Microwave Plasma Atomic Spectrometry (4210 MP-AES, Agilent, USA) machine for total K, Ca, Mg and Na.

4.2.10 Harvesting

Harvesting of cacao pods (Figure 4.8) was conducted monthly, from October 2021 to September 2023 for Sites 1 and 2, and from October 2022 to April 2024 for Site 3. The research support team harvested the cacao from each trial site, with specific sample times based on mutual agreement with each grower. Only the number of pods harvested per trial tree was recorded as the yield data. The bean yield was not measured due to time constraints. During the initial stages of this study, Covid-19 travel restrictions meant that much of the field work relied on field support workers. This limited the amount of time available, especially as there were three different trial sites to set up and maintain. While the trial sites were selected because they had initially low signs of disease, some damaged pods (such as black pod or pest damage) were observed during harvesting. There were no chemical pest and disease control measures used during the trial.

Figure 4.8 Field support workers harvesting cacao at Trial Site 1 on the Sape farm.

4.2.11 Tree trunk size and spacing measurements

At all three trial sites, tree trunk circumference was measured on all trial trees in February 2025. Three tree trunk circumference measurements were taken at heights of approximately 0, 50 and 100 cm above ground level of each tree using a measuring tape. The average of the three measurements was used as the value recorded for each tree. Measurements were also recorded of the distances between trees to provide the average tree spacing, which was used to determine the average tree planting density.

4.2.12 Data analysis

All statistical analyses were conducted using Genstat (version 19). An Analysis of Variance (ANOVA) was performed to test treatment effects on measured variables. Where significant differences were detected, mean separation was carried out using Duncan's Multiple Range Test (DMRT) at P = 0.05. For parameters based on repeated or subsampled measurements, plot means were calculated from multiple replicates prior to analysis. All graphs were produced using Microsoft Excel.

4.3 Results and Discussion

4.3.1 Initial soil fertility for trial sites

The soil test results for the samples collected in March 2021 from two farms used for the field trials in this study are presented in Table 4.5.

Overall, the soil test results indicate that soil pH was unlikely to be a limiting factor at the trial sites. The soil pH for Site 1 of 6.7 was near the middle of the optimum range, whereas the Site 2 value of 6.0 was at the lower end of the optimum range. Soil total C was the same for both at 2%, however total N differed. Total N at Site 1 was only 0.1% and was a third of the value for Site 2. This meant the C:N ratio of the soil at Site 1 was higher than Site 2. The soil inorganic N concentration was 36 and 15 mg N kg^{-1} for Sites 1 and 2, respectively. These values are equivalent to approximately 54 and 22 kg N ha^{-1} in the top 15 cm of the soil profile. While the quantity of available N in the soil was low at Site 2 at the time of sampling, soil inorganic N is highly variable with time and, therefore, a single test is not able to provide an indication of the supply of N over the growing season. Also, inorganic N is highly mobile and moves down the soil profile with drainage. Therefore, there is potential for cacao trees to also access inorganic N from below the top 15 cm of the soil profile.

Soil Olsen P was low for both sites, being 6 and 4 mg P kg^{-1}, for Sites 1 and 2, respectively. These values are well below the considered optimum of $\geq$ 15 mg P kg^{-1}. This highlights that soil available P could be a limiting factor for cacao growth and yield at both sites.

The soil CEC capacity of Site 1 was 24 (cmol(+) kg^{-1}), which was less than half of the value for Site 2 of 53 (cmol(+) kg^{-1}). Consequently, the levels of exchangeable Ca, Mg, K and Na were all higher at Site 2. The exchangeable K levels were 0.27 and 0.88 (cmol(+) kg^{-1}) for Sites 1 and 2, respectively. Only values at Site 1 were below the considered optimum of $\geq$ 0.7 (cmol(+) kg^{-1}), indicating that soil K availably at this site could be a limiting factor for cacao growth and yield.

The soil sulphate S was notably high at both sites, being 32 and 34 mg kg^{-1}, for Sites 1 and 2. These values are above 10 mg S kg^{-1}, which is the optimum value for many crops. These high values are likely to reflect mainly natural inputs of S, such as via rainfall and sea spray during cyclones, which are typically high along coastal areas.

Table 4.5 Soil test (0-15 cm) results for Sape and Tarou farms sampled in March 2021.

Soil analysis	***Sape Farm (Sites 1)[#]***	***Tarou Farm (Site 2)***	***Optimum values****
Soil pH	6.7	6.0	6.0-7.5
Total C (%)	2.0	2.0	≥ 2.5
Total N (%)	0.1	0.3	≥ 0.3
C:N ratio	20	7	12 – 25
Inorganic N (mg N kg^{-1})	36	15	20 – 50
Olsen P (mg P kg^{-1})	6	4	≥ 15
Sulphate S (mg S kg^{-1})	32	34	≥10^
Phosphorus retention (%)	15	10	NA
CEC (cmol(+) kg^{-1})	24	53	≥ 14.1
Exchangeable Ca (cmol(+) kg^{-1})	20.0	46.0	≥ 11
Exchangeable Mg (cmol(+) kg^{-1})	2.9	5.2	≥ 2.5
Exchangeable K (cmol(+) kg^{-1})	0.27	0.88	≥ 0.7
Exchangeable Na (cmol(+) kg^{-1})	0.31	0.37	NA
Electrical conductivity (mS cm^{-1})	0.05	0.07	< 2.0

*Source of optimum nutrient values is Snoek et al. (2016) ^Common optimum for many crops
#Site 3 was located next to Site 1 on the same farm.

4.3.2 Conventional Trials

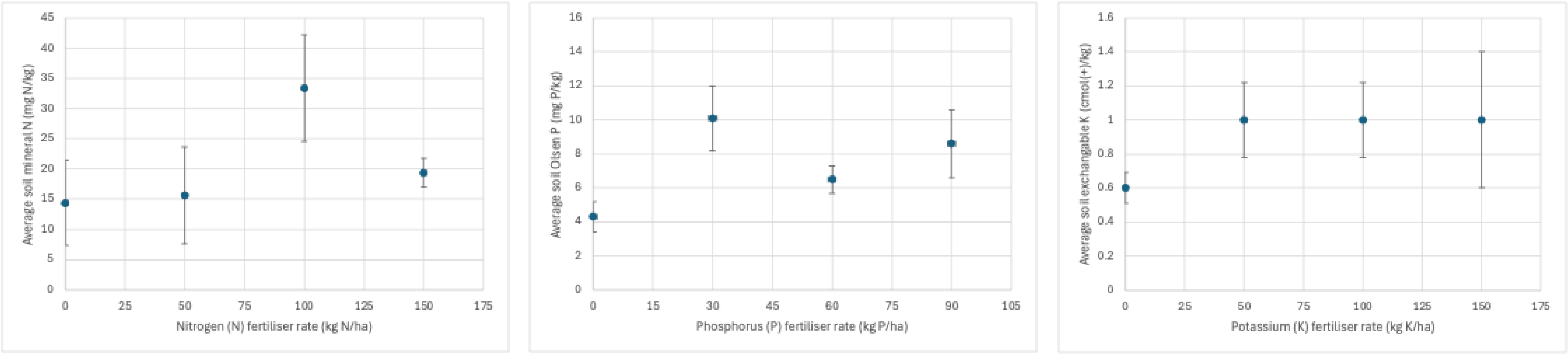
Effect of treatments on soil fertility

The effects of the conventional fertilisers on soil fertility at Sites 1 and 2 were assessed using soil test results from samples collected in October 2022, which was about one year after the start of conventional trials and six months after the second split application of fertiliser. At Site 1 (Figure 4.9a), there was some evidence that the 100 kg N ha^{-1} rate of N fertiliser resulted in a higher soil mineral N compared to the Control (no fertiliser) treatment. The increase in soil mineral N concentration for the 100 kg N ha^{-1} rate of N fertiliser equated to about 30 kg N ha^{-1}, which was 130% higher than the Control treatment value. However, the effect of N fertiliser treatments on soil mineral N was not consistent, with there being only an insignificant minor increase in soil mineral N for the highest rate of N fertiliser (150 kg N ha^{-1}) compared to the Control treatment. In comparison, at Site 2 (Figure 4.10a) only the 150 kg N ha^{-1} rate of N fertiliser showed evidence of increasing soil mineral N compared to the Control treatment. However, the difference was small, being equivalent to about 8 kg N ha^{-1}, which was 28% higher than the Control treatment average. Nitrate is typically the main form of soil mineral N in soils, which is highly mobile in soil and easily lost via leaching and denitrification. Therefore, the extended period between the previous N fertiliser application and when soil samples were collected would have contributed to differences between treatments being less evident, compared to soon after fertiliser application.

For both trial sites (Figures 4.9b and 4.10b), the average Control treatment Olsen P values at the October 2022 soil sampling were very low, being about 4 mg P kg^{-1}, which was similar to their original site Olsen P values measured a year earlier. At both sites, there was evidence that the fertiliser added treatments increased Olsen P levels, however, there was no consistent relationship between the amount of P added and increase in Olsen P. The highest rate of P fertiliser added (90 kg P ha^{-1}) increased Olsen P to an average concentration of approximately 9 and 7 mg P kg^{-1} at Site 1 and 2, respectively. These Olsen P levels are still low and below the considered optimum for cacao of 15 mg P kg $^{-1}$. This indicates that Olsen P may still be limiting cacao yields at these sites, even at the highest rate of P fertiliser added. However, high variation in Olsen P values between replicate treatments indicate that the field procedure used (e.g. fertiliser application and soil sampling methods) could have had an influence on the results obtained, which is discussed later in this section.

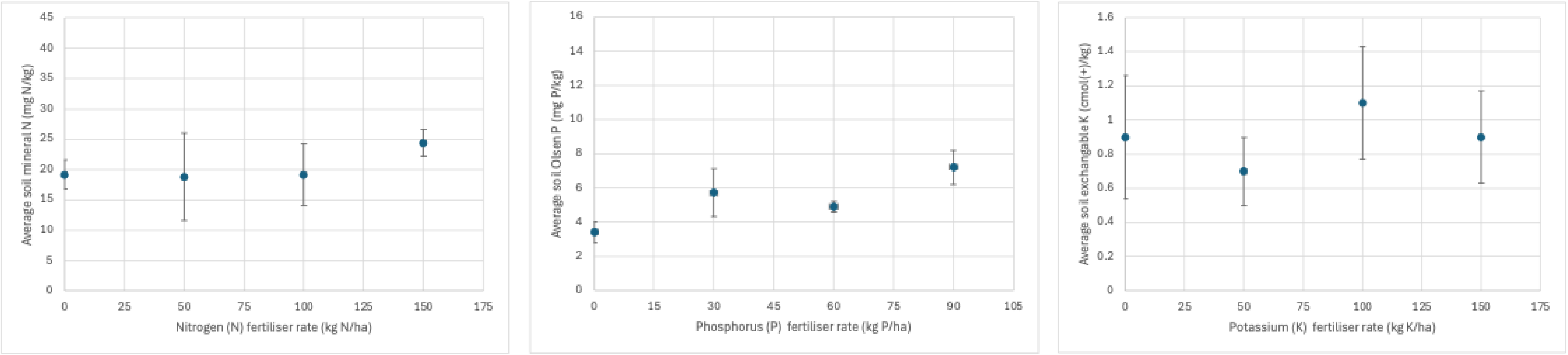
At Site 1 (Figure 4.9c), K fertiliser addition increased soil exchangeable K compared to the Control treatment, but there were no differences between the rates of K fertiliser applied. All three rates of K (50, 100 and 150 kg K ha^{-1}) resulted in average soil exchangeable K levels of 1.0 cmol(+) kg^{-1}, compared to 0.6 cmol(+) kg^{-1} for the Control. Therefore, the lowest rate of K was sufficient to increase the soil exchangeable K concentration to an optimum level of > 0.7 cmol(+) kg^{-1}. In contrast, at Site 2 (Figure 4.10c) the Control treatment had a soil exchangeable K concentration that met the optimum level of 0.9 cmol(+) kg^{-1} and K fertiliser addition did not have a consistent effect on appreciably improving soil K status.

Overall, the soil test results were highly variable between treatment replicates, especially for mineral N and exchangeable K. This may, in part, be due to these two nutrients being more mobile in the soil compared to P. However, there was also high variation in Olsen P values between replicate treatments. This indicates that field procedures may also have contributed to the variation observed, as P is relatively immobile in soils and not easily lost in processes like leaching. Other causes of variability include the way that fertiliser was applied in bands around each tree. In particular, the first application of fertiliser was applied in a very narrow band, which could have created greater spatial variability and, hence, large variation in test values. In addition, due to theft of the original soil corer, the soil samples at this sampling time were collected using a soil auger. When using a soil auger, it is more difficult to ensure that the soil profile is sampled evenly and that the whole sample is collected. This can especially be an issue for nutrients like P, which are less mobile will be mostly reside near the surface of the soil following fertiliser application.



(a) **(b)** **(c)**

Figure 4.9 Average soil mineral N, Olsen P and exchangeable K at each rate of fertiliser at Site 1 (*Error bars represent standard error of the means*).



(a) **(b)** **(c)**

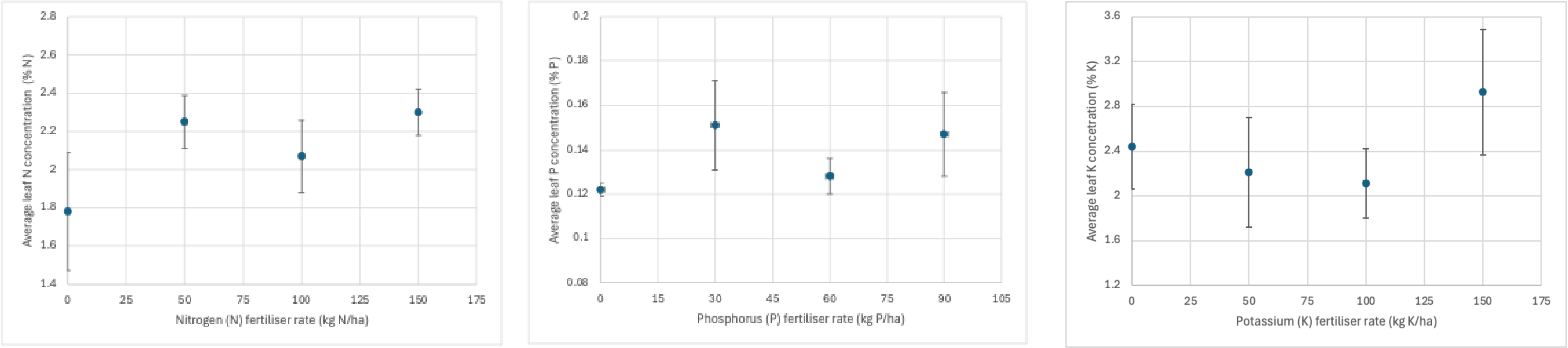
Figure 4.10 Average soil mineral N, Olsen P and exchangeable K at each rate of fertiliser at Site 2 (*Error bars represent standard error of the means*).

Effect of treatments on leaf nutrient concentrations

The effects of the conventional fertilisers on leaf nutrient concentrations at Sites 1 (Figure 11a) and 2 (Figure 4.12a) were assessed using leaf test results from samples collected in October 2022, which was the same time that soil samples were collected. To compare the overall effect of N, P and K fertiliser addition, the average leaf nutrient concentrations are presented for all treatments with the same rate of each nutrient. At both trial sites there was evidence that N fertiliser addition increased cacao leaf N status, especially for the highest rate of N. The 150 kg N ha^{-1} treatment resulted in an average leaf N concentration of 2.3%, which was 28% higher than the Control treatment values of 1.8%. However, all rates of N addition achieved average leaf N concentrations above the considered optimum level of > 2.0%. At Site 2 the 150 kg N ha^{-1} treatment resulted in an average leaf N concentration of 2.4%, which was 20% higher than the Control treatment values of 2.0%. Also at this site, all rates of N addition had average leaf N concentrations > 2.0%. Overall, these results support that N fertiliser addition at both sites increased the N status of the cacao trees. However, the improvement was greater at Site 1, where the Control treatment trees had lower N levels.

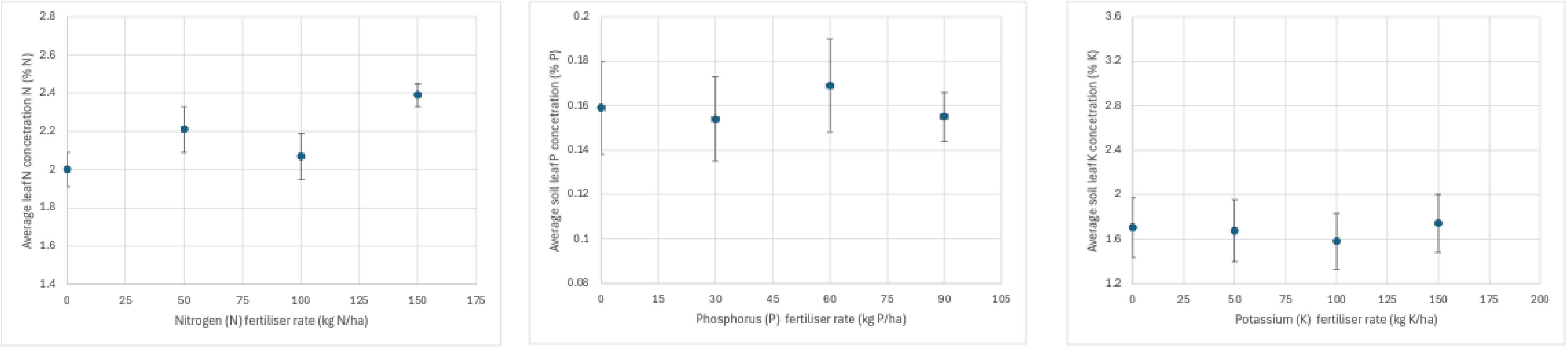
There was some evidence of P fertiliser addition increasing leaf P concentration at Site 1, but not at Site 2. At Site 1 (Figure 11b) the average leaf P concentration for the Control treatment was 0.12%, which increased to 0.15% for the 30 kg P ha^{-1} P fertiliser treatments. However, the response in leaf P concentrations from higher rates of P fertiliser was variable and showed no further consistent increases. At Site 2 (Figure 12b) the average leaf P concentration for the Control treatment was 0.16%, and there was no appreciable further increase from any of the rates of P fertiliser addition up to the highest rate. The average leaf P concentrations for all treatments at both sites remained below the considered optimum of 0.20%.

At both sites there was limited influence of K fertiliser addition on leaf K concentrations. Only the 150 kg K ha^{-1} rate of K fertiliser resulted in an average leaf K concentration notably higher than the Control treatment value of 2.4% K. However, the higher variation in K concentrations at each level of K fertiliser applied, limited the ability for interpretation of the data to establish evidence of a significant different. There appeared to be a site difference in leaf K status, with the Control treatment being 2.4 and 1.7% K at Sites 1 (Figure 11c) and 2 (Figure 12c), respectively. The average leaf K concentrations for all treatments at Site 1 were above the considered optimum of 2.0%, but not at Site 2. What is difficult to explain is that prior to fertiliser application, Site 1 had a lower soil exchange K level status than Site 2. Therefore, leaf K concentration did not consistently reflect soil K status.



(a) **(b)** **(c)**

Figure 4.11 Average leaf N, P and K concentrations at Site 1 (*Error bars represent standard error of the means*).



(a) **(b)** **(c)**

Figure 4.12 Average leaf N, P and K concentrations at Site 2 (*Error bars represent standard error of the means*).

4.3.3 Combined Trial

Effect of treatments on soil fertility

The Combined trial at Site 3 assessed the effects of various sources of nutrient inputs, including legume ground covers, composts and conventional fertiliser treatments. The effect of treatments on soil fertility was assessed using soil test results from samples collected in March 2023, which was six months after the commencement of treatments. However, this was just prior to the second split application of conventional fertiliser.

Overall, there was insufficient statistical evidence to support a significant effect of any of the treatments relative to the Control treatment (Table 4.6). The average Olsen P of the four 90 kg P treatments (only 45 kg P applied before soil test) was 12.2 mg P kg^{-1}, which was double soil test value for the control treatment of 6.1 mg P kg^{-1}. All other treatment averages were lower. The exchangeable K value for the two Zai Na Tina compost treatments was on average 1.3 cmol(+) kg^{-1}, compared to 0.9 for the Control treatment. But high variability between replicate values limited the ability to support a significant difference.

Variability within soil fertility treatments arises from several interacting factors. Organic inputs like composts can have inconsistent nutrient compositions depending on their source materials and decomposition processes, leading to uneven nutrient release (Geisseler et al., 2021). Finally, variability can stem from differences in application methods and timing, affecting how uniformly nutrients are distributed and absorbed. As previously discussed, the use of a soil auger rather than a soil corer to collect soil samples may have contributed to some of the variability in soil test results observed.

There was also high variability in leaf nutrient concentrations between treatment replicates, which also contributed to there being insufficient statistical evidence to support a significant treatment effect (Table 4.7). Given low initial soil fertility and the wide range of treatments used, it is uncertain why greater differences in plant nutrient status were not observed. But the observed high replicate variation supports the need to increase the number of replicates used in future evaluations.

Table 4.6 Soil test (0-15 cm) results for the treatments from the Combined trial at Site 3.

		Mineral N	Olsen P	Exchangeable cations		
				K	Ca	Mg
		(mg kg^{-1})	(mg kg^{-1})	(cmol(+)kg^{-1})	(cmol(+) kg^{-1})	(cmol(+)kg^{-1})
T1	Control	39.2 ± 17.9	6.1 ± 1.6	0.9 ± 0.6	10.4 ± 3.3	0.8 ± 0.4
T2	Legumes only	29.6 ± 2.8	11.3 ± 3.1	0.6 ± 0.4	7.9 ± 0.8	0.3 ± 0.0
T3	Pig manure compost	28.4 ± 3.6	8.3 ± 2.4	0.3 ± 0.1	6.7 ± 0.4	0.3 ± 0.0
T4	Cacao pod husk compost	28.8 ± 1.7	7.9 ± 1.2	0.4 ± 0.1	7.7 ± 0.7	0.3 ± 0.0
T5	Zai Na Tina compost	41.4 ± 11.0	8.2 ± 3.1	0.5 ± 0.2	6.9 ± 0.6	0.3 ± 0.0
T6	Pig manure compost + legumes	23.8 ± 2.9	4.9 ± 1.3	1.2 ± 0.9	11.1 ± 3.9	0.8 ± 0.4
T7	Cacao pod husk compost + legumes	38.0 ± 6.2	9.7 ± 2.0	0.5 ± 0.2	7.0 ± 0.7	0.4 ± 0.0
T8	Zai Na Tina compost + legumes	31.2 ± 7.1	6.1 ± 0.8	2.0 ± 1.0	15.4 ± 4.6	0.9 ± 0.4
T9	Fertiliser (N100P90K150)	25.4 ± 6.0	17.8 ± 4.5	1.0 ± 0.5	9.9 ± 3.0	0.7 ± 0.4
T10	Fertiliser (N100P90K150) + legumes	32.0 ± 6.6	16.3 ± 5.2	1.2 ± 0.7	10.7 ± 3.8	0.8 ± 0.4
T11	Fertiliser (N150P90K150)	20.8 ± 4.3	6.4 ± 0.9	0.8 ± 0.3	6.6 ± 0.7	0.4 ± 0.0
T12	Fertiliser (N150P90K150) + legumes	44.6 ± 4.6	8.2 ± 2.1	0.5 ± 0.2	6.9 ± 0.6	0.3 ± 0.0
	P-value	*NS*	*NS*	*NS*	*NS*	*NS*

Values are means ± standard error. *NS* denotes not significant.

Table 4.7 Leaf test results for the treatments from the Combined trial at Site 3.

		Nutrient Content (mean)				
		N%	**P%**	**Ca%**	**Mg%**	**K%**
T1	Control	1.77 ± 0.27	0.13 ± 0.04	1.26 ± 0.30	0.66 ± 0.15	1.83 ± 0.93
T2	Legumes only	1.82 ± 0.12	0.15 ± 0.02	1.29 ± 0.23	0.67 ± 0.11	0.70 ± 0.11
T3	Pig manure compost	1.72 ± 0.23	0.15 ± 0.08	1.40 ± 0.13	0.78 ± 0.17	1.34 ± 1.02
T4	Cacao pod husk compost	2.01 ± 17	0.14 ± 0.05	1.25 ± 0.17	0.61 ± 0.16	0.99 ± 0.88
T5	Zai Na Tina compost	1.9 ± 0.23	0.13 ± 0.02	1.35 ± 0.31	0.73 ± 0.11	1.29 ± 0.86
T6	Pig manure compost + legumes	1.94 ± 0.23	0.14 ± 0.02	1.51 ± 0.29	0.78 ± 0.06	1.39 ± 0.99
T7	Cacao pod husk compost + legumes	1.88 ± 0.23	0.14 ± 0.02	1.19 ± 0.44	0.63 ± 0.17	0.59 ± 0.08
T8	Zai Na Tina compost + legumes	2.02 ± 0.14	0.14 ± 0.03	1.16 ± 0.41	0.62 ± 0.11	0.54 ± 0.08
T9	Fertiliser (N100P90K150)	1.94 ± 0.15	0.14 ± 0.03	1.54 ± 0.23	0.68 ± 0.11	2.05 ± 0.86
T10	Fertiliser (N100P90K150) + legumes	2.02 ± 0.16	0.16 ± 0.02	1.03 ± 0.13	0.55 ± 0.11	0.59 ± 0.09
T11	Fertiliser (N150P90K150)	1.78 ± 0.15	0.14 ± 0.04	1.34 ± 0.47	0.62 ± 0.12	0.95 ± 0.62
T12	Fertiliser (N150P90K150) + legumes	1.98 ± 0.25	0.12 ± 0.02	1.47 ± 0.35	0.69 ± 0.14	1.56 ± 1.01
	P value	*NS*	*NS*	*NS*	*NS*	*NS*

Values are means ± standard error. *NS* denotes not significant.

4.3.4 Effect of conventional (NPK) fertiliser treatments on cacao yields

Site 1

At Site 1, the Control (no fertiliser) treatment produced monthly average pod numbers of 2.8 and 7.0 pods tree^{-1} month^{-1} in Years 1 and 2 of the study, respectively (Table 4.8). In Year 1 there was moderately strong statistical evidence ($p=0.059$) of a significant difference between treatments. The pod numbers for the T4 (N100P90K150) treatment were insignificantly higher than most other treatments. The T4 treatment pod numbers were 189% higher than the Control treatment value. Based on the average number of trees per hectare at this site of 620 and using an average weight of dry beans of 37.9 g per pod, this increase in pod numbers would be equivalent to an increase in yield of 1,472 kg dry beans ha^{-1}, compared to a Control treatment value of 777 kg dry beans ha^{-1}.

There was a trend of yield increasing with increasing N fertiliser rates up to 100 kg N ha^{-1} and then declining at 150 kg N ha^{-1}, for treatments that also received the highest rates of P (90 kg P ha^{-1}) and K (150 kg K ha^{-1}). In other studies, high rates of N fertiliser have been shown to reduce cacao yield by promoting excessive vegetative growth and reducing flowering (Weinstein *et al*. 2024).

While there appeared to be an influence of N fertiliser rates on cacao pod numbers in Year 1, this was not evident in Year 2. In this trial, all fertiliser treatments were applied only in Year 1, therefore, there appeared to be no clear carry over effect of fertiliser application on pod numbers in Year 2. The ability of fertiliser applications to influence nutrient availability in the subsequent year will depend on the nutrient's mobility and retention in the soil. Also, fertilisier responses will also depend on the internal nutrient reserves stored within the trees, as cacao can immobilise and recycle nutrients from its biomass, influencing nutrient demand and uptake dynamics in subsequent seasons (Akane, 2017). Among the nutrients applied, N in the main plant available form nitrate is particularly prone to losses through leaching, especially in high rainfall such as was apparent at Site 1 (Sape farm) with an annual average rainfall of 2325 mm. Given that yield appeared to be influenced by N fertiliser in Year 1, then it is likely that not reapplying N fertiliser in Year 2 could have contributed to the lack of yield response in Year 2.

In a similar study in Colombia, Uribe et al. (2001) assessed the effects of conventional fertiliser treatments with varying rates of N, P and K, applied each year for five years, on yield of cacao grown as a monocrop. The fertiliser treatment with the highest rates of nutrients applied was 150 kg N, 40 kg P and 166 kg K ha^{-1}. This rate of fertiliser increased yield on average over the five years to 1,160 kg dry beans ha^{-1}, compared to the Control treatment value of 562 kg dry beans ha^{-1}. However, most of the increase in yield occurred for the 100 kg N ha^{-1} rate of N fertiliser, when also applied with the highest rates of P and K fertiliser. However, yields in the first year of the study were on average lower than in subsequent years, with the overall average yields being about 25 and 30% higher in years two and five, compared to year one. Therefore, with the fertiliser treatments only being applied in the first year in the current study, the potential additive benefit of repeated application on yield in subsequent years could not be assessed.

Moreover, it's important to note that the data presented only reflects pod number per tree, without accounting for bean weight, which is a key component of total yield and economic value. Fertiliser treatments can influence not just pod numbers, but also bean development, including size, number and weight (Goudsmit et al., 2023). Therefore, any fertiliser induced changes in bean quantity and weight were not captured in these results, and the full impact of fertiliser addition on overall cacao productivity may be underestimated in the current study. Future assessments should include bean-level metrics to provide a more comprehensive understanding of fertiliser effects.

Table 4.8 Effect of fertiliser treatments on cacao pod numbers at Site 1.

		Year 1 (Oct 2021 - Sep 2022) Mean monthly pods (pods tree^{-1} month^{-1})	**Year 2 (Oct 2022 - Sep 2023) Mean monthly pods (pods tree^{-1} month^{-1})**
T1	Control (no fertiliser)	2.8±1.1 b	7.0±2.2
T2	N0P90K150	2.6±0.6 b	4.0±0.9
T3	N50P90K150	4.2±0.8 b	8.0±2.6
T4	N100P90K150	8.1±0.9 a	9.8±1.0
T5	N150P90K150	4.1±1.4 b	5.7±2.2
T6	N150P0K150	5.9±1.0 ab	8.8±2.9
T7	N150P30K150	4.1±1.5 b	10.1±5.2
T8	N150P60K150	3.5±0.6 b	9.0±4.2
T9	N150P90K0	5.2±1.8 ab	9.5±2.4
T10	N150P90K50	3.1±0.8 b	7.7±2.0
T11	N150P90K100	3.9±0.6 b	3.7±1.5

P-value	*0.059*	*NS*

Different letters in the same column indicate significant differences according to Duncan’s test ($p < 0.05$). Values are means ± standard error. *NS* denotes not significant.

Site 2

At Site 2, the Control (no fertiliser) treatment produced an average of 3.0 and 4.1 pods tree^{-1} month^{-1} in Years 1 and 2 of the study, respectively (Table 4.9). The effect of fertiliser treatments on the number of pods produced per tree was not statistically significant in either year. At this site cacao is intercropped with coconut, which is the most common cacao system in the SI. Other studies investigating cacao yield responses to fertiliser addition in cacao intercropped/agroforestry systems are less consistent, and typically minimal, compared to cacao monocropping systems, like at Site 1. It has been observed that full sunlight-exposed cacao trees generally are more responsive to fertiliser addition because of greater photosynthetic activity (Uribe et al. 2001). The lack of a fertiliser yield response at Site 2 supports the conclusion from other studies that the benefits of fertiliser are less reliable in cacao intercropped systems.

Table 4.9 Effect of fertiliser treatments on cacao pod numbers at Site 2.

		Year 1 (Oct 2021 - Sep 2022) Mean monthly pods (pods tree^{-1} month^{-1})	**Year 2 (Oct 2022 - Sep 2023) Mean monthly pods (pods tree^{-1} month^{-1})**
T1	Control (no fertiliser)	3.0±0.4	4.1±0.9
T2	N0P90K150	3.0±0.5	2.8±0.2
T3	N50P90K150	4.1±0.5	5.5±1.6
T4	N100P90K150	3.9±0.7	4.9±2.2
T5	N150P90K150	4.3±0.9	4.9±2.8
T6	N150P0K150	4.3±0.9	5.9±1.7
T7	N150P30K150	3.1±0.2	2.8±0.6
T8	N150P60K150	3.2±0.5	4.2±1.7
T9	N150P90K0	4.1±0.6	4.9±0.6
T10	N150P90K50	3.5±0.6	3.5±1.1
T11	N150P90K100	2.9±0.5	2.3±0.5
	P-value	*NS*	*NS*

Values are means ± standard error. *NS* denotes not significant. ^

4.3.5 Effect of legume ground covers, composts and fertilisers on cacao yields (Combined trial)

At Site 3, the Control (no fertiliser) treatment produced an average of 6.1 and 5.4 pods tree^{-1} month^{-1} in Years 1 and 2 of the study, respectively (Table 4.10). There was a wide variation between average monthly cacao pod numbers as a function of treatment for both years. However, the effect of treatments on the number of pods produced per tree was not statistically significant in either year. This site also grows cacao as a monocrop, like Site 1, therefore it is expected to more likely show a yield response, compared to intercropped cacao (Uribe et al. 2001). The lack of a yield response from the compost treatments could be due to the general lower quantity of nutrient applied, and potentially lower availability, with a portion of nutrients being in organic forms. Furthermore, the intended nitrogen contribution from the legume cover crops was not realised, as *Pueraria* failed to establish and died early in the trial, leaving only peanuts to persist. This limits the likelihood of any meaningful quantity of biologically fixed N input. However, this does not explain the lack of evidence of a response from conventional fertiliser treatments at this trial site. But high tree variability would have been contributing factor.

Table 4.10 Effect of legume ground cover, compost and fertiliser treatments on cacao pod numbers at Site 3.

		Year 1 Mean monthly pods (pods tree^{-1} month^{-1})	**Year 2^** Mean monthly pods (pods tree^{-1} month^{-1})
T1	Control	6.1±1.8	5.4±1.7
T2	Legumes only	9.1±3.5	5.9±1.5
T3	Pig manure compost	4.8±1.7	2.8±0.9
T4	Cacao pod husk compost	6.2±2.1	3.7±1.4
T5	Zai Na Tina compost	6.6±0.9	3.9±0.7
T6	Pig manure compost + legumes	8.0±1.6	5.3±0.9
T7	Cacao pod husk compost + legumes	4.1±0.6	3.3±0.7
T8	Zai Na Tina compost + legumes	7.7±1.3	5.5±1.3
T9	Fertiliser (N100P90K150)	6.2±1.0	6.0±0.8
T10	Fertiliser (N100P90K150) + legumes	6.0±0.8	6.4±0.9
T11	Fertiliser (N150P90K150)	7.6±1.4	3.7±1.5
T12	Fertiliser (N150P90K150) + legumes	4.8±1.3	4.5±1.2

P-value	*NS*	*NS*

Values are means ± standard error. *NS* denotes not significant. ^Means are for the first 7 months of Year 2.

4.3.6 Comparison between sites

Site 1

At Site 1 (Table 4.11), the average monthly number of cacao pods harvested for all treatments over a 24-month assessment was 5.7 pods tree^{-1} month^{-1}, being 4.2 and 7.2 pods tree^{-1} month^{-1} for Years 1 and 2, respectively. The average tree density for this site is 610 trees ha^{-1}, based on an average tree spacing of 4.05 m. Using values obtain during a 1-month survey at this site, the average pod weight was 328 g pod^{-1} (range 127-598 g pod^{-1}). Assuming an average percentage dry bean weight of 11.6%, then the average experimental site estimated dry bean weight would be 1,574 kg ha^{-1} year^{-1}, being 1,159 and 1,989 kg ha^{-1} year^{-1} in Years 1 and 2, respectively. These estimated yields are high compared to the dry bean yields estimated for this location in the grower survey (Chapter 3) of 720 kg ha^{-1}. One explanation is that this experimental site was selected from part of the farm that was identified as being a well-managed and high performing part of the farm, hence, would be expected to yield better than the farm average. Also, although the high tree variability affected the ability to measure treatment effects for most treatments, the majority of trees in this site received fertiliser in this study in Year 1. Therefore, this could have resulted in an overall improvement in yields for the site compared to previous assessments by the grower.

Table 4.11 Comparison of tree densities, pod dry bean weights and average yields between trial sites.

	Site 1	**Site 2**	**Site 3**
Farm	Sape	Tarou	Sape
Farm system type	Monocropping	Intercropping	Monocropping
Duration of assessment (months)	24	24	19
Average tree spacing (m)	4.05	5.01	3.56
Average number of trees ha^{-1}	610	399	789
Average monthly pods tree^{-1}	5.7	3.9	5.8
Average annual pods tree^{-1}	68.1	47.0	69.5
Average pod weight (g)$^{\wedge}$	328	384	349
Estimated pod percentage dry bean weight (%)$^{+}$	11.6	10.4	11.1
Estimated average dry bean weight (kg ha^{-1})	1,574	752	2,133

$^{\wedge}$Based on a 1-month (March 2025) harvest survey at each research site. $^{+}$Based on a relationship derived from Bhavishya *et al.* 2024.

At Site 2 (Table 4.11), the average monthly number of cacao pods harvested for all treatments over a 24-month assessment was 3.9 pods tree^{-1} month^{-1}, being 3.5 and 4.3 pods tree^{-1} month^{-1} for Years 1 and 2, respectively. The average tree density for this site is 399 trees ha^{-1}, based on an average tree spacing of 5.01 m. Using values obtain during a 1-month survey at this site, the average pod weight was 384 g pod^{-1} (range 119-624 g pod^{-1}). Assuming an average percentage dry bean weight of 10.4%, then the average experimental site estimated dry bean weight would be 752 kg ha^{-1} year^{-1}, being 681 and 823 kg ha^{-1} year^{-1} in Years 1 and 2, respectively. The lower tree density and yield on this farm, compared to the Site 1 farm, can be attributed to the intercropping system where cacao is grown between coconut trees and surrounded by fruit trees as boundary crops. Studies show that excessive shade significantly reduces irradiance and impairs cacao growth, nutrient-use efficiency, and reproductive development (Arévalo-Gardini et al., 2021). At Site 3 (Table 4.11), the average monthly number of cacao pods harvested for all treatments on average over a 19-month assessment was 5.8 pods tree^{-1} month^{-1}, being 6.4 and 4.7 pods tree^{-1} month^{-1} for Years 1 and 2 (first 7 months), respectively. The average tree density for this site is 789 trees ha^{-1}, based on an average tree spacing of 3.56 m. Using values obtain during a 1-month survey at this site, the average pod weight was 349 g pod^{-1} (range 116-764 g pod^{-1}). Assuming an average percentage dry bean weight of 11.1%, then the average experimental site estimated dry bean weight would be 2,133 kg ha^{-1} year^{-1}, being 2,367 and 1,732 kg ha^{-1} year^{-1} in Years 1 and 2, respectively. This site is located on the same farm as Site 1, which also had high yields, which will be influenced by the cacao monocropping system and, the higher tree density. Although Site 3 had similar soil properties (Table 4.1 and 4.5) to Site 1, its higher yields are likely attributable to its greater planting density. With more trees per hectare, Site 3 would have the potential to have a higher total pod-bearing capacity, allowing it to achieve greater productivity.

4.3.7 Causes of high tree yield variability

At all trial sites, the high variation between pod numbers across individual trees influenced the statistical significance of differences between treatment. Two factors that are likely to have had an influence on individual tree responses are tree size and the incidence of pest and diseases. These factors are discussed in more detail in the following sections.

Tree size

At Site 1 there was a wide range in trunk circumference of individual trees, of approximately 32 to 82 cm (Figure 4.13). This variation will in part reflect differences in tree ages, due to ongoing replacement of trees as the result of old age or pest and disease incidence. The relationship between tree trunk circumference and cacao yield is illustrated by a scatter plot showing a moderate positive correlation ($R^2 = 0.437$). In general, there was a trend of higher pod numbers per tree with increasing tree circumference. The majority of trees with circumference < 50 cm produced average monthly pod numbers less than about 6 pods tree^{-1}. In comparison, the majority of trees with circumference > 55 cm produced average monthly pod numbers greater than about 6 pods tree^{-1}. These results highlight the benefits of maintaining the health of larger trees to help optimise yields, while also emphasising high tree variation and the need to use a standard tree size for research trials. An alternative design approach that can be inferred from these results is the use of a plot consisting of a number of trees to provide a single treatment replicate, rather than using individual trees as replicates.

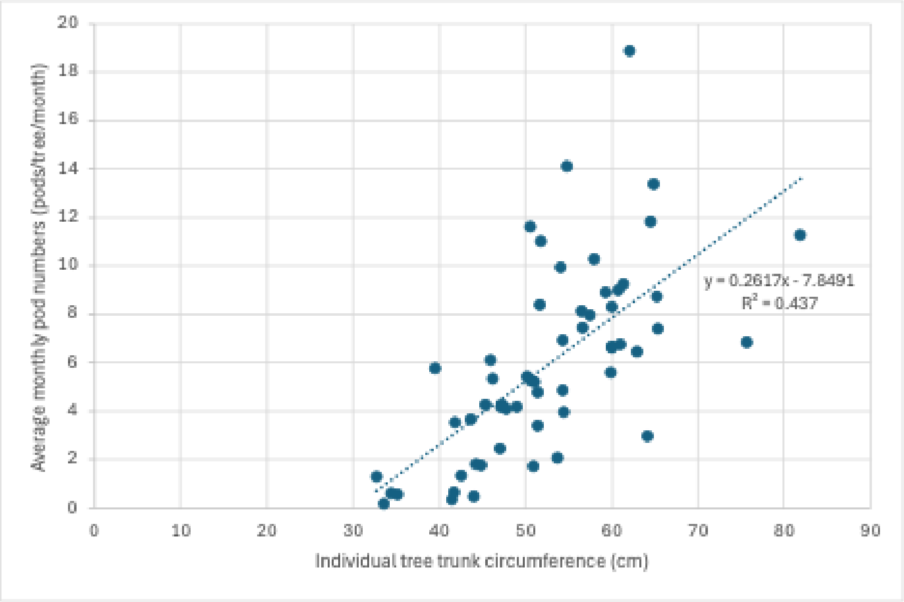


Figure 4.13 Relationship between individual tree trunk circumference and monthly pod numbers over a 24-month period following establishment of the field trial at Site 1 (Sape farm).

At Site 2, the trunk circumference of individual trees varied widely, ranging from approximately 28 to 74 cm (Figure 4.14). The relationship between tree trunk circumference and cacao yield at this site was weak ($R^2 = 0.164$). Overall, the majority of the trees had produced average monthly pod numbers less than about 6 pods tree^{-1}. However, of the trees that did achieve average monthly pod numbers greater than 6 pods tree^{-1}, almost all had trunk circumferences of > 55 cm. The poorer relationship between tree trunk circumference and pod numbers, compared to Site 2, could be due to the lower level of pod production, which is influenced by it being an intercropped cacao system.

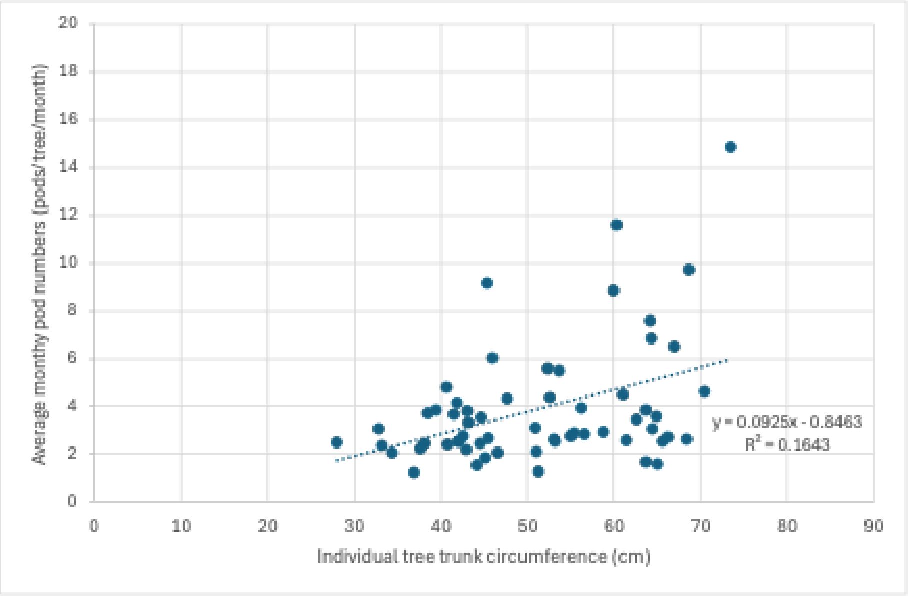


Figure 4.14 Relationship between individual tree trunk circumference and monthly pod numbers over a 24-month period following establishment of the field trial at Site 2 (Tarou farm).

At Site 3 trunk circumference of individual trees ranged from approximately 26 to 68 cm (Figure 4.15). A linear regression between tree trunk circumference and cacao yield showed a moderate positively relationship (R^2 = 0.358). At this site the majority of trees had trunk circumference < 55 cm. The higher proportion of trees with small tree trunk circumference, compared to the other two sites, could be partially due to this site having a higher tree density.

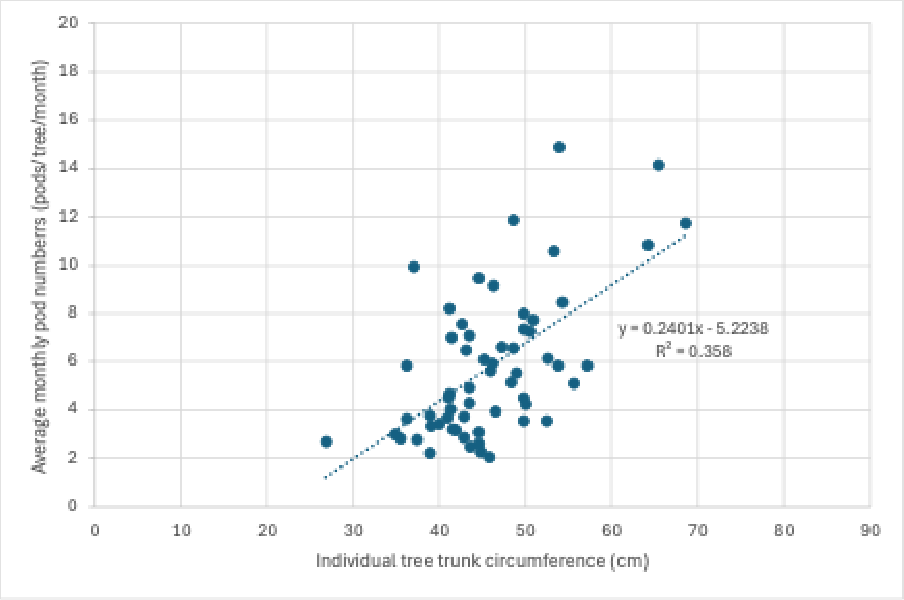


Figure 4.15 Relationship between individual tree trunk circumference and monthly pod numbers over a 19-month period following establishment of the field trial at Site 3 (Sape farm).

Because the of the apparent influence of tree trunk circumference on average monthly pod numbers, trunk circumference was used as a covariate in an ANOVA analysis to investigate the effect of treatments. The addition of trunk circumference as a covariate did not appreciably influence the statistical significance of the treatment effects on average monthly pod numbers, therefore, these results are not presented or discussed further.

Pests and diseases

Black pod disease was consistently observed across all three study sites, indicating its widespread presence in the trial area. Additionally, signs of bat activity were noted, particularly their feeding on cacao pods. This was evidenced by beans scattered on the ground and pods with visible holes while still attached to the trees.

Sites 1 and 3, which are located on the same farm, also showed signs of woodborer infestation, followed by termite activity. Termite damage was observed on several trees, some of which eventually died. These infestations were likely exacerbated by two flooding events that occurred during the trial period (Section 4.4.2). It is important to note that at the time of site selection, in general, the trial trees were healthy and showed no obvious visual signs of pest or disease stress.

4.3.8 Additional considerations with conventional fertiliser use

Organic farming status

Organic farming focuses on avoiding the use of manufactured conventional fertiliser. Some single origin chocolate from the SI is marketed as being organically grown, therefore, it is an important consideration for growers to be aware of when deciding on the use of inputs like fertiliser. Therefore, the use of improved recycling of tree resides, including pod husk, and the use of organic certified nutrient inputs will be important to help growers who want to maintain organic status. This is particularly important if fertiliser inputs do not show clear improvements in yield, as is the case with the cacao intercropped systems that are more common in the SI.

Cost of available fertiliser

In the current study there was some evidence of an improvement in pod numbers when N100P90K150 treatment was applied to cacao grown in a monocropping system. However, it is important to assess the cost of the fertiliser inputs to assess whether the economic returns are sufficient to cover the investment cost. Cocoa production in the SI faces numerous agronomic and economic challenges. This chapter evaluates the cost-effectiveness of fertiliser treatments, particularly the formulation, and explores the financial barriers and risks associated with its adoption.

Fertiliser prices vary with the form of fertiliser and weight purchased. In the SI growers are only able to purchase fertiliser in 5 kg bags. The cost per kilogram of nutrient is highest for urea (NZ\$19.10 kg^{-1} N), followed by TSP (NZ\$17.10 kg^{-1} P), and then MOP (NZ\$12.80 kg^{-1} K). The cost of applying 100 kg N, 90 kg P, and 150 kg K per hectare is therefore NZ\$5,369. To break even, farmers must achieve a yield increase of 1588 kg ha^{-1} at a cocoa price of NZ\$3.38 kg^{-1} (2020-25 average). This yield is higher than that achieved in this study and highlights that fertiliser cost will likely exceed the returns from fertiliser investment. In comparison, the cost of this fertiliser application rate in New Zealand, purchased in 20 kg bags, is approximately \$1,660 ha^{-1}. Therefore, growers in the SI pay over 3-fold more for bagged fertiliser, which makes it cost prohibitive.

Despite the potential for increased yields, fertiliser use also carries significant finance risks for growers. Natural disasters such as cyclones, floods, and droughts are common in the SI and can severely impact crop performance. These events not only reduce yields but also threaten the farmer’s ability to recover input costs, making fertiliser investments highly uncertain. Additionally, fluctuations in cocoa prices further complicate profitability projections.

Soil Cadmium

The application of phosphate fertilisers in cacao farming systems also requires careful consideration due to their potential role in increasing soil cadmium (Cd) levels, a growing concern for food safety and international trade. In Peru, a major producer of fine-flavoured cacao, recent studies have highlighted that both geogenic and anthropogenic sources contribute to elevated Cd concentrations in cacao-growing soils (Guarín et al., 2023). Notably, phosphate fertilisers derived from Cd-rich rock material have been identified as a significant contributor to soil Cd accumulation, especially when applied repeatedly over time. Due to the important issue for cacao growers in terms of market access and it’s the potential impacts of fertiliser management. This study compared the soil total Cd level of five soil samples from Control (no fertiliser) trees and five selected trees that had received the highest rate of P of 90 kg P ha^{-1} yr^{-1} and had the highest Olsen P levels at Site 1 and Site 2.

At Site 1, Control treatment had an average Olsen P of 6.0 mg P kg^{-1} and average Cd concentration of 0.17 mg Cd kg^{-1} (range 0.11-0.23). While the five P-fertiliser added treatments had an average Olsen P of 18.6 mg P kg^{-1}, they had the same average Cd concentration of 0.17

mg Cd kg^{-1} (range 0.10-0.24). At Site 2, Control treatment an average Olsen P of 4.0 mg P kg^{-1} and average Cd concentration of 0.08 mg Cd kg^{-1} (range 0.01-0.13). While the five P-fertiliser added sample had an average Olsen P of 24.1 mg P kg^{-1}, they are the same average Cd concentration of 0.07 mg Cd kg^{-1} (range 0.04-0.11). Overall, the Cd concentration was low at both sites and P fertiliser addition made no appreciable influence on increasing Cd concentration at either site. This is demonstrated by the observation that soil Olsen P level was raised to a level considered optimum, without changing the Cd status of the soil. While the Cd concentration of the original P fertiliser used in this study was not measured, cacao farmers are recommended to use P fertiliser with the lowest Cd available, especially if they plan to use repeated applications.

There was a difference between sites with the Cd levels at Site 1 being a little over double the levels at Site 2. Over average values at both sites, as well as the upper range (0.24 mg Cd kg^{-1}) are within the Cd range considered low for cacao growing (<0.25 mg Cd kg^{-1}). The Peru study found that cacao grown on soils with Cd concentrations below 0.25 mg kg^{-1} typically produced dry beans with Cd levels below 0.30 mg kg^{-1}, which is within acceptable limits for export to the European Union. Further research is needed to see if there are results for typical of soils in the main cacao growing regions of the SI.

4.4 Summary

Of the two conventional trial sites in this study, only at Site 1 was there evidence of a cacao yield response to conventional fertiliser addition. At this site, relatively high rates of N, P and K were required to show an improvement in the number of pods produced per tree. However, this site is on a monocropping cacao farm, and other studies support that fertiliser responses are less reliable on intercropped cacao farms, like Site 2, which are more common in the SI. In addition, conventional fertiliser treatments were only applied in the first year of experiment and there was no evidence of a carry-over effect on cacao pod numbers in the second year of the study at either trial sites. At Site 3, the effect of conventional fertiliser and compost treatments on the number of pods produced per tree were not statistically significant in either year. High tree variability would have also been a contributing factor at this site, affecting the statistical evidence available to support a significant effect from nutrient inputs. In another PhD study, Hougni (2023) evaluated whether fertiliser use could improve low cacao yields in Nigeria. On-farm trials also did not show a significant increase in yields from fertiliser use, which was attributed to large field variability. Hougni (2023) concluded that fertiliser application in existing cacao plantations does not consistently increase yields under smallholder management and, therefore, should not be the first approach for improvement efforts.

There was also no consistent influence of conventional fertiliser or compost treatments on soil and cacao leaf nutrient status at any of the trial sites. This is in part likely due to high variation between treatment replicates. For the soil test results, fertiliser placement and the use of a soil auger, rather than a soil corer, are likely to have contributed to some of this variation. For the leaf test results, the variability could have been influenced the variation in tree sizes. Tree size variation is also likely to have contributed some of differences in the number of pods produced between trees, influencing the ability to demonstrate treatment effects. High variability in yield between trees may also have been affected by their genetic potential. As most growers replace trees with seeds grown from seedlings, then the yield potential will differ between trees. The following chapter explores strategies that growers could use to improve the genetics of the trees on their farms.

While there was not a consistent effect of treatments on cacao yield in this study, what is clear is that the cost of conventional fertilisers in the SI is major constraint to their use by growers. In the SI, growers can only purchase fertiliser in 5 kg bags, which are over three times more expensive than for bagged (20 kg) fertiliser sold in New Zealand. In some cases, growers would need as much as a 300% increase in yield to achieve a break-even return on the cost of fertiliser inputs. This indicates that fertiliser use will be cost prohibitive for most cacao growers, unless fertiliser prices decrease markedly. Added to this is the financial risk of purchasing additional inputs like fertiliser and not having certainty of a yield response. In addition, because some growers sell their cacao beans for use in single origin chocolate marketed as being organically grown, this is another reason for growers to avoid the use of conventional fertilisers. Therefore, the use of improved recycling of tree resides, including pod husks, and the use of organic certified nutrient inputs will be important to help growers who want to maintain organic status. Overall, these findings support that, under the current conditions, conventional fertiliser use is not likely to contribute to the financial sustainability of smallholder cacao grower in the SI.

Soil Cd concentration was low at Sites 1 and 2 in this study, and P fertiliser addition made no appreciable influence on increasing Cd concentration at either site. Producing cacao on soil with low Cd is associated with lower levels of Cd in dry beans, which is an advantage for market access (Thomas et al., 2023). If the observations made in this study are typical of soils in the SI, then this could be an advantage for the SI cacao industry. To support this, further research is required to assess the soil Cd status of the main cacao growing areas of the SI.

Chapter 5 Cacao pruning and grafting practices survey

5.1 Introduction

Optimum cacao tree crop production is influenced by a range of management practices, including fertiliser use, pest and disease control measures, and pruning or other tree rejuvenation practices (CIFOR-ICRAF, 2022). The results of the initial grower survey (Chapter 3) highlighted that both low soil fertility and differences in pruning practices on cacao farms on Guadalcanal and Malaita Islands, as potential causes of the low and variable cacao yields. The results from the fertiliser trials (Chapter 4) supported that cacao yield responses to fertiliser use may be limited or negligible, especially for intercropped cacao farms, which are the main cacao system in the SI. In addition, the financial benefit from fertiliser use is unlikely to compensate for the investment cost of fertiliser inputs. Therefore, these findings support that growers should initially focus on pruning and other tree rejuvenation practices to improve cacao yields, rather fertiliser use.

The initial grower survey highlighted that there is potentially a yield advantage for farms that use intensive pruning and grafting practices. Grafting is when the new growth material (scion or bud chip) is cut from a desired tree and is physically joined to a compatible root stock (Mudge et al., 2009). Grafting targets boosting of cacao production through the selection of the best trees based on their traits such as fruit quality, disease resistance and high yield (Isele et al., 2020). The types of common grafting techniques used on cacao are top grafting and budding or bud grafting (Daouda et al., 2015). And top grafting is more effective for cacao seedlings at the juvenile nursery stage and budding for trees in the field.

There is currently limited information on the effect of rejuvenation practices, like intensive punning and grafting, on cacao yields in the SI. This chapter addresses this gap by presenting the results of a targeted survey of cacao growers on Guadalcanal and Malaita Islands. The survey aimed to assess the adoption of pruning and grafting practices, quantify their effects on farm yields, and identify the constraints and opportunities for wider implementation. By comparing farms that use standard pruning alone with those that have adopted more intensive rejuvenation practices, this study provides insights into the agronomic and economic benefits of cacao tree management strategies. The findings from this chapter contribute to the broader understanding of how improved tree management can enhance cacao productivity in the SI and inform policy and development initiatives aimed at revitalising the sector.

5.2 Methodology

Research for this chapter involved grower selection, grower survey questionnaires, recording of monthly cacao yield and data analysis. The design of this research was based on previous cacao growers' studies described in Chapter 3.

5.2.1 Grower selection

Data collected from the original growers' survey, described in Chapter 3, was used as the primary source to identify participants for this current survey. However, to include more growers that had used grafting practices, additional growers that had not been part of the initial survey were also included. Fourteen growers were selected that have farms located on either Guadalcanal or Malaita Islands (Figure 5.1) and use standard pruning practices. Standard pruning practices refer to regular routine pruning as part of general tree maintenance, and involves controlling the structure and shape of trees, sucker removal, and phyto-sanitation (SKIA, 2019).

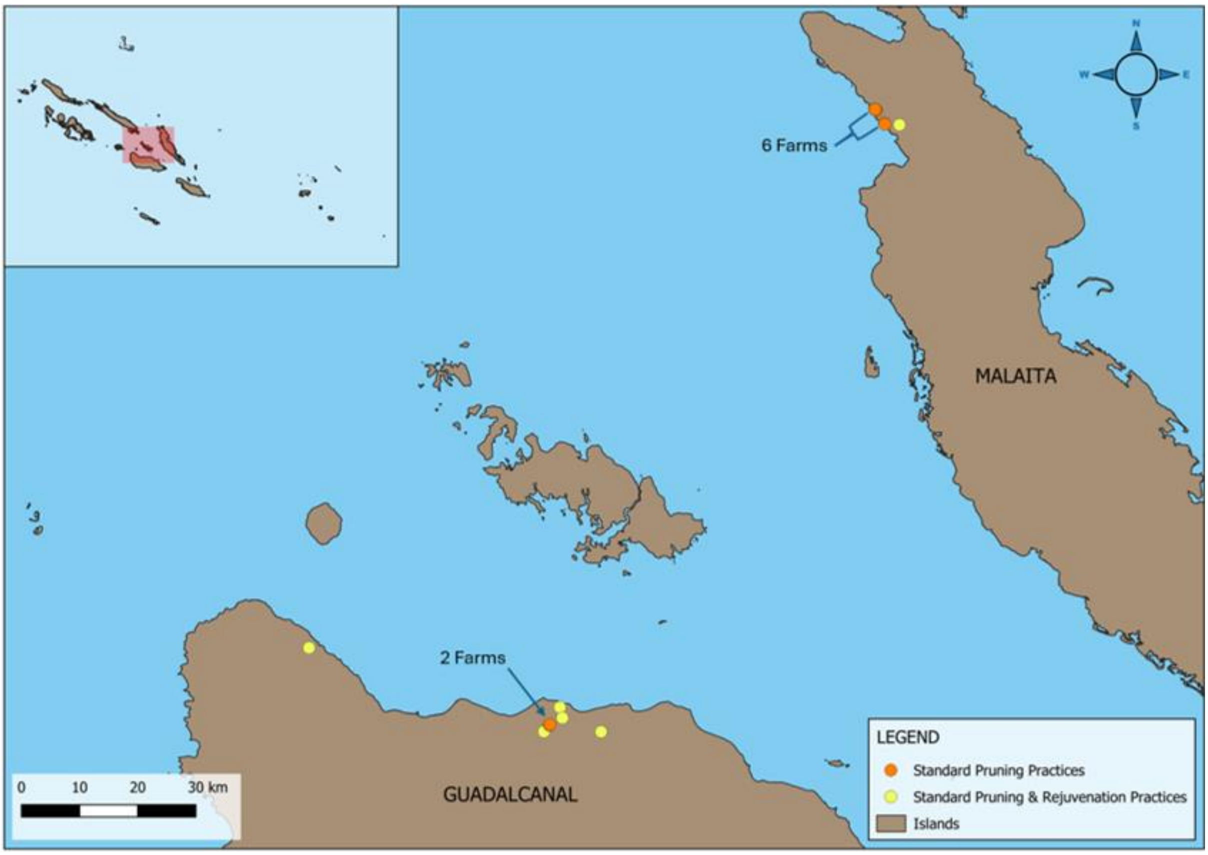


Figure 5.1 Location of farms selected for the survey on pruning cacao tree rejuvenation practices in the Solomon Islands (Imagery, 2023).

Eight of the farms in this survey have not used any rejuvenation practices, other than replanting trees as needed with seedlings (hereafter referred to as 'Control Farms'). The remaining six of the selected growers were identified because, in addition to standard pruning, they have also conducted more substantial tree rejuvenation practices on > 25% of their farms within the 15-year period prior to this survey (hereafter referred to as ‘Rejuvenation Farms’). These tree rejuvenation practices refer to either intensive pruning and grafting (Figure 5.2) or new planting of grafted clonal cacao tree seedlings (Figure 5.3). These practices are used to improve tree health and longevity, and improve cacao yields (Ocampo-Ariza et al., 2025). Pruning and grafting of trees in the field is typically undertaken between the months of July – August and January – March in the SI, to avoid the peak harvest seasons (April – June and September – December). Although the intention with this study was to have the same number of Rejuvenation Farm as Control Farms, this was not possible due to the limited number of known farms using rejuvenation practices to select from. This is because it is not common for farms to use rejuvenation practices, but also there is a lack of updated records or guidance from the Ministry of Agriculture and Livestock regarding the status and adaptation of rejuvenation practices by farms in the SI.

Figure 5.2 Simon Sefa (left) with a grower (right) pointing at pods of grown side-grafted cacao material still attached to the original tree trunk.

Figure 5.3 Cacao seedlings covered with plastics after top grafting.

5.2.2 Grower survey research mechanism

The grower survey questionnaire of pruning and grafting practices was conducted between May 2022 and April 2023 on 14 selected cacao plantation farms. The growers who participated were given information sheets and consent forms seeking official acceptance and engagement to participate in the survey. A research questionnaire (Appendix III) was prepared and included a harvest record sheet. Before the survey, research assistants conducted a pre-testing of the questionnaires using face-to-face interviews with two previous participating growers to allow for possible amendments to questions (Figure 5.4). The use of a face-to-face interview approach is expected to improve participation and response rates and help with clarifying questions. This is because interviews enable direct interaction, which enhances engagement, ensures more comprehensive responses, and allows for deeper exploration of topics, compared to other methods such as online surveys or emails (Hecker & Kalpokas, 2025). There are 63 distinct languages in SI, with numerous local dialects (DFAT, 2024), therefore, the survey needed to ensure that a number of different languages were used to suit the participants. This involved four field officers who, between them were able cover the following languages in the survey: English, Pidgin English, Doku, Dee, Gae, Baelelea and Toabaita. This survey was conducted under same ethical approval (#4000023988) granted through Massey University's Low Risk Notification process described in Chapter 3 (Section 3.2.1).

Figure 5.4 Simon Sefa (right) conducting a face-to-face interview with a cacao grower (left) in Malaita.

5.2.3 Farm cacao yields

The growers in the survey were provided with harvest record sheets to record monthly cacao yields. Yield data was collected over the 12-month period from May 2022 to April 2023. For the six farms in the tree rejuvenation group, yield data was collected on a whole farm basis, as it was not practical for the growers to collect yield data only on the areas of the farm where rejuvenation was practiced within the previous 15 years. Consequently, farm yields do not show the full influence on these practices on tree yields. Instead, they provide an indication of the yield benefits that could be gained for the entire farm, when tree rejuvenation practices are implemented on at least a quarter of the farm.

5.2.4 Data analysis

The data was analysed using a Microsoft Excel spread sheet to determine mean and standard error values.

5.3 Results and Discussion

5.3.1 Description of survey farms

Farm location, size, age, topography, system and nutrient inputs

The farms surveyed cover a combined area of 13 hectares, with an average size of 1.6 ha per farm (ranging from 0.4 to 3.0 ha). For comparison, the average size of the 60 farms included in the first grower survey, presented in Chapter 3, was 1.5 ha. The Control Farms reported an average cacao plantation age of 31 years (range of 22 to 36 years), with half of these farms growing cacao for more than 35 years.

The six Rejuvenation Farms in this survey included five farms from Guadalcanal Island and one from Malaita Island. These farms have an average cacao plantation age of approximately 30 years (range of 18 to 43 years), with a third of the farms growing cacao for more than 35 years. On one farm the rejuvenation practice involved planting new clonal seedlings on 33% of the farm area, while the remaining five farms used intensive pruning and grafting techniques on between 24 - 57% of the farm area with the previous 15 years. Together, these six farms spanned 30.3 ha, averaging 5.1 ha per farm (ranging from 1.5 to 14 ha) (Table 5.2). Therefore, these farms are on average larger than typical cacao farms in the SI. This suggests that there may be a tendency for larger farms to be more proactive in using rejuvenation practices and adopted semi-commercial operations. Growers with larger farms may also be more likely to receive support though development programmes provided by the government and its development partners.

The 14 farms in this survey are all located on flat lowland areas, such as coastal zones, plains, and riverbanks. All of these cacao farms are intercropped with coconut except for one farm, which is a cacao monocropping farm. In the first grower survey (Section 3.3.1) 95% of the 60 farms use intercropping of cacao under coconuts and only 5% use cacao monocropping. The advantage of the monoculture cacao farming systems is that it allows higher cacao tree planting densities and, therefore, higher yields per hectare. However, intercropping cacao with coconut is preferred by most growers because it makes efficient use of land by pairing tall coconut palms with shade-loving cacao trees. Economically, it offers growers year-round income from coconuts and higher seasonal earnings from cacao, which diversifies the income.

None of the growers in this survey use fertiliser and other nutrient inputs on their cacao plantation, and rely on nutrients from soil reserves, atmospheric inputs, and recycling of prunings, leaf litter and empty cacao pods.

Lead growers and agricultural support

Lead growers play an important role in improvements in the cacao industry over the long term, mainly through networking (Jansen & Maike, 2011, 2012; R. Vava, Pers. Comm. July 9, 2025). Lead growers are typically identified through a combination of peer recognition, demonstrated farming success, and active participation in training initiatives. Lead growers are often respected members of their communities who consistently apply best practices in cocoa production (such as pruning, pest management, and fermentation) and willingly share their knowledge with others. Development programmes or extension services may select lead growers based on criteria like productivity, leadership potential, communication skills and openness to innovation. In this study none of the Control farm growers are lead growers, whereas two-thirds of the Rejuvenation farm growers are considered to be lead growers (Table 5.3).

In this survey, two out of eight Control farm growers received support on training and tools for pruning and grafting between 2009 and 2021 (Table 5.2). In contrast, all of the Rejuvenation Farm growers received this type of agriculture support (Table 5.3).

5.3.2 Farm Yields

Control Farms

In the current survey, the average yield for the Control Farms was 498 kg dry beans ha^{-1} (ranging from 138 to 697 kg dry beans ha^{-1}), indicating high variability in productivity amongst these farms (Table 5.1). This average yield is higher than the average of 346 kg dry beans ha^{-1} for the 33 farms that used standard pruning in the first grower survey reported in Chapter 3. While the initial survey had a higher number of growers, it relied on grower reported yields, which may not have been for consistent periods and relied on growers' own recording methods, which may have varied. In comparison, the current survey compares all farm yields in the same 12-month period and uses the same protocol for yield recording. Therefore, this yield information is intended to improve comparisons between farms within a season, rather than provide an estimate of more typical yields over a number of seasons.

Table 5.1 Summary for Control Farms, defined as those using only standard pruning practices in the previous 15 years.

	Farm number							
Factors	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Island	Malaita	Malaita	Malaita	Malaita	Malaita	Malaita	Guadalcanal	Guadalcanal
Area	2 ha	3 ha	0.5 ha	0.4 ha	1.5 ha	1 ha	2 ha	2.5 ha
Farming system	Intercropping	Intercropping	Intercropping	Intercropping	Intercropping	Intercropping	Intercropping	Intercropping
Duration (years) growing cacao	22	24	36	36	36	32	24	36
Assistance with pruning/grafting	Tools/Training	Tools/Training	None	None	None	None	None	None
Cacao type	Trinitario & Amelonado	Trinitario & Amelonado	Trinitario & Amelonado	Amelonado	Trinitario & Amelonado	Trinitario & Amelonado	Trinitario & Amelonado	Foresterio & Amelonado
Yield (kg ha^{-1})	138	313	520	538	540	571	697	662

Rejuvenation Farms

The six Rejuvenation Farms in the survey had an average yield of 828 kg dry beans ha^{-1} yr^{-1}, which is 330 kg dry beans ha^{-1} yr^{-1} (66%) higher than the average yield for the Control Farms. In the first grower survey (Chapter 3) there were only three farms included that used intensive pruning and grafting rejuvenation practices, with an average yield of 720 kg dry beans ha^{-1} yr^{-1}. While this average is lower than the average from the current survey, this could be due to the same reasons as discussed in the previous section (i.e. the current survey compares all farm yields in the same 12-month period with same method for yield recording). In the first survey the average yield for the farms that used intensive pruning and grafting was 374 kg dry beans ha^{-1} yr^{-1} higher than for the farms that used only standard pruning, which is a similar difference to the current survey.

The Rejuvenation Farms also had high variability between farms, ranging from 482 - 1,216 kg dry beans ha^{-1} yr^{-1} (Table 5.2). However, these results show that some farms can achieve high yields without fertiliser inputs. For the Rejuvenation Farms some of this variation could be influenced by the proportion of farms that have undergone rejuvenation practices in the previous 15 years. The farm that had the lowest percentage area receiving intensive pruning and grafting practices of only 24%, also had the lowest yield of 482 kg dry beans ha^{-1} yr^{-1}. Whereas the two farms with the highest proportion of intensive pruning and grafting of 57 and 53%, had the two highest yields of 906 and 1216 kg dry beans ha^{-1} yr^{-1}, respectively.

Farm 13 had an above average yield (836 kg dry beans ha^{-1} yr^{-1}) even though the area of rejuvenation was the second lowest (28.6%), and this was the only farm with a mono-cropping system, which would give it a yield advantage. In Bolivia, Armengot et al. (2023) measured a 56% higher yield for an organic mono-cropped cacao compared to an organic agroforestry system where cacao was intercropped with bananas and other fruit and timber tree species.

There are a number of factors, in addition to the use of rejuvenation practices, that could explain the differences in average yields between the Control Farms and Rejuvenation Farms. For example, two thirds of the growers of Rejuvenation Farms are lead growers, whereas none of the Control farm growers are lead growers. Lead growers may be more likely to implement a range of improved practices on farms that influence yield, in addition to rejuvenation practice, such as better pest and disease management. Also, the Rejuvenation Farms are on average larger than the Control farms, which could provide advantages in terms of economies of scale.

A number of international studies have quantified the appreciable yield advantages can be achieved through improved tree genetics. For example, in India, Apshara (2017) observed that the dry bean yield of cloned trees was on average 22% (367 kg dry beans ha^{-1} yr^{-1}) higher than for trees grown from seeds. But the difference was up to 54% higher for the cloned trees of one cultivar. Also, the choice of clonal material can influence yield differences. Armengot et al. (2023) measured a 73% (500 kg dry beans ha^{-1}) higher yields on average for local cacao clones compared to international clones. Observations (R. Vava, Pers. Comm., July 9, 2025) made in SI, have anecdotally estimated that clonal trees are capable of achieving yields in excess of 1000 kg dry beans $tree^{-1}$ yr^{-1}, which is > 500 kg dry beans ha^{-1} greater than the average yields for the Control Farms in the current study. Therefore, is reasonable to surmise that the difference in the average yield between the two groups of farms in the current study, of 330 kg dry beans ha^{-1} yr^{-1}, could be attributed to improved genetic traits. On average the Rejuvenation Farms rejuvenated an average of 40% of their farms in the previous 15 years. If farms aimed to rejuvenate their entire farms over a 30-year period, then this would require 50% of their farms every 15 years, which is a similar rate to the farm with the highest yield in the current study. Expressed on an annual basis this is a rejuvenation rate of 3.3% of their farm each year.

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Table 5.*2* Summary for Rejuvenation Farms, defined as farms using standard pruning and rejuvenation practices in the previous 15 years.

	Farm number					
Factors	**9**	**10**	**11**	**12**	**13**	**14**
Island	Guadalcanal	Guadalcanal	Malaita	Guadalcanal	Guadalcanal	Guadalcanal
Area	1.5 ha	14 ha	5 ha	2.5 ha	3.5 ha	3.8 ha
Farming system	Intercropping	Intercropping	Intercropping	Intercropping	Monocropping	Intercropping
Duration (years) growing cacao	38	43	25	32	18	22
Lead grower	Yes	Yes	Yes	Yes	No	No
Assistance with pruning/grafting	Tools/Nursery	Tools/Nursery	Tools/Drier	Tools	Plant materials/Nursery	Tools/Plant materials
Rejuvenation type	New Plantings	*Inten. & Graft.	Inten. & Graft.	Inten. & Graft.	Inten. & Graft.	Inten. & Graft.
Grafting Method	Top seedling	Side grafting	Side grafting	Side grafting	Side grafting	Side grafting
Area rejuvenated (% of total area)	0.5 ha (33.3%)	8 ha (57.1%)	2 ha (40%)	0.6 ha (24.0%)	1 ha (28.6%)	2 ha (52.6%)
Year of rejuvenation	2010	2009	2014	2013	2021	2010
Yield (kg^{-1} ha^{-1})	589	906	702	482	836	1216

*Inten. & Graft. refers to Intensive pruning and Grafting

5.3.3 Potential economic benefits of rejuvenation practices

The study has provided an indication of the potential yield benefits of using rejuvenation practices. While further research with a larger number of farms is required to gain greater confidence in the size of the yield potential, the values obtained in this study provide a good starting point for making initial assessments of the economic benefits for growers and the cacao industry in the SI that is associated with rejuvenation practices. However, there are other stakeholders in the value chain in the SI, including those involved with fermenting, drying, and transporting and exporting the cacao, who also rely on the cacao industry for their incomes. Any assessment of the management techniques described in this study need to be considered in the context of the full value chain.

To assess the economic benefits of rejuvenation practices for the cacao industry, it is important to factor in realistic prices over the medium and longer-term, such as over the next 3-5 years or longer. This is because there is a longer time lag between when investment in improvements is made and when economic returns received for tree crops compared to field crops. This is a challenge given the considerable volatility in prices over the past decade, with the annual average export price per kilogram of dry cacao beans ranging from NZ$3.25 to $11.70 (hereafter all prices are in NZ dollars). Between 2015 and 2023, prices were relatively low and stable, ranging from $3.25 to $4.60. But in 2024, prices increased dramatically to an annual average of $11.70. The annual average price for 2025 is forecast to remain high at about $12.00. The extreme volatility in prices over the previous two years is mostly caused by climate events impacting production in Western Africa, so it is difficult to predict prices in the medium to long-term for investment planning. Given this uncertainty in prices, this analysis uses an average export price over the previous 5 years of $7.50, which includes a wide range of prices. If it is assumed that growers using rejuvenation practices on 50% of their farms every 15 years would result in average yield increase of 330 kg dry beans ha^{-1} yr^{-1}, this would be an additional 6.6 million kg of cacao from 20,000 ha. At an average annual export price of $7.50, this would be an increase in value for the cacao industry in the SI of $49.5 million, which would be an increase of approximately 7% in the total export earnings (2021-2023 average) for the SI.

The proportion of the export price that growers receive (i.e. ‘farm gate’ price) per kilogram of dry cacao beans varies with price. For example, in 2022 when the export price was $4.50 the farm gate price was only $1.50, which was 33.3% of the export price. In contrast, in 2025 with an export price of $12.00 the farm gate price was $7.50, which is 62.5% of the export price. This highlights that the proportion that growers receive of the export price increases as price increases. Presented another way, while the export price was 2.7-fold higher in 2025 than in 2022, but the farm gate price was 5-fold higher. The SI industry share of the export price post the farm gate was more consistent, increasing only 1.5-fold, from \$3.00 in 2022 to \$4.50 in 2025.

Using the proportion of export price that is the farm gate price in both 2022 and 2025, the relationship between export price and the percentage of this price that is the farm gate price is described by Equation 1.

Equation 1 $$y = 3.89x + 15.78$$

where x = the export price and y = the percentage of the export price that is the farm gate price. Using Equation 1 and the 5-year annual average dry bean export price \$7.50, then the expected farm gate percentage share would be 45% or a price of \$3.38. At this farm gate price and using the same assumption that rejuvenation practices have potential to increase farm cacao yields by 330 kg dry bean ha^{-1} yr^{-1}, then this would increase farm incomes by \$1,115 ha^{-1} yr^{-1}. However, if farm gate prices returned to the low levels seen prior to 2022 of \$1.50, then the increase in farm income would only be \$495 ha^{-1} yr^{-1}.

The 2022 farm gate price was more typical of the price growers received in the 8-year period from 2015 to 2022. Therefore, using the both the recent 5-year annual average price (i.e. medium-term price) and the pre-2023 8-year annual average price (i.e. 'long-term' price), then the use of rejuvenation practices is predicted to increase farm incomes by between \$9.9 million and \$22.3 million yr^{-1}. These estimates can be used as part of a cost benefit analysis to assess different options to assist growers to adopt cacao tree rejuvenation practices.

5.3.4 Constraints to growers using rejuvenation practices

While the economic benefit from improving cacao yields have greatly improved in recent years, there remains a range of constraints that limit cacao growers' ability to adopt cacao tree rejuvenation practices to improve yields. Growers face a complex interplay of agronomic, economic, institutional, and behavioural challenges that collectively hinder productivity and sustainability (Somarriba et al., 2021). Agronomically, aging tree stock and limited adoption of advanced techniques, such as grafting and coppicing reduce the effectiveness of rejuvenation efforts. Environmental stressors (including erratic rainfall patterns and persistent pest and disease pressures) further compromise yields and complicate farm management (Ocampo-Ariza et al., 2025).

Economically, growers are constrained by the volatility of cocoa market prices, which discourages long-term investment in farm improvement. Many growers lack the financial capacity to purchase recommended tools and materials, particularly when these are unavailable locally and require travel to distant suppliers such as those in Honiara (E. Dainao, Pers. Comm., August 21, 2022). The absence of subsidies within training programmes further deters the adoption of practices like grafting, as growers fear short-term income loss due to reduced production during the transition period (R. Waisu, Pers. Comm., July 8, 2025). Institutional limitations compound these challenges. Extension services are very limited, largely due to insufficient capacity building and financial support (R. Vava, Pers. Comm., July 9, 2025). The short duration of the cacao grafting programme (2009–2012) limited its impact, as it did not span a sufficient period for growers to observe long term results, refine techniques, and build confidence. Future programmes should align with cacao's biological timeline to support sustained adoption. Despite some growers receiving training in pruning, grafting, and record keeping, many did not apply these techniques on their own farms or share knowledge with others. This was attributed to the limited duration of training and lack of follow-up support, which undermined growers' ability to internalise and disseminate skills (G. Oliouou, Pers. Comm., July 8, 2025).

Resource gaps also play a significant role. Poor-quality tools and the unavailability of rejuvenation materials at nearby suppliers, restrict growers' ability to implement practices effectively. A case in point is the cacao breeding nursery plots at the St. Martin School, which was established to supply improved cloned cacao varieties for grafting. However, after the programme ended, coordination between the Ministry of Agriculture and Livestock and the school ceased, resulting in no further distribution of clonal cacao plant materials or monitoring of tree performance (R. Vava, Pers. Comm., July 9, 2025).

Behaviourally, growers in this survey expressed reluctance to adopt grafting due to perceived risks, including potential tree mortality and income disruption. Some preferred to wait and observe outcomes from peers before making decisions, but the short duration of the programme did not allow sufficient time for such peer validation. A few growers who attempted grafting, reported tree death following intensive pruning, which they attributed to differences in tree health and the lack of technical guidance from extension services (E. Dainao, Pers. Comm., August 21, 2022).

5.3.5 Strategies for increasing the adoption tree rejuvenation

This current survey has highlighted the potential yield gains and economic benefits that growers can gain from adopting rejuvenations practices. However, the challenges and constraints that growers experience, as discussed, limit the adoption of these practices. With the current higher price being paid for cacao, it is an opportune time to explore practical and sustainable ways that growers can be supported to help implement improvements to their management practices. While the importance of sustained, hands-on engagement and technical support is recognised as being important in driving successful cacao rehabilitation, the provision of affordable and accessible methods for growers to use clonal trees to replace aging, diseased and unproductive trees is also important. Clonal propagation ensures consistency in yield, disease resistance, and bean quality, making it a cornerstone of long-term productivity. Hence, to facilitate adoption of rejuvenation, the cost and benefits of three strategies are proposed. For each of the following three strategies the same average yield benefit of 330 kg dry beans ha^{-1} yr^{-1} was assumed. This value was obtained from the survey of growers and is based on assuming that growers will use rejuvenation practices on 50% of their farms every 15 years (Section 5.3.2). While it is likely that the actual yield benefit would vary between the strategies, there is not sufficient information to estimate these differences. Therefore, the following comparisons primarily demonstrate the differences in the implementation costs.

Strategy 1: Providing clonal seedlings

The provision of clonal seedlings represents a foundational strategy for enhancing cacao productivity and genetic uniformity across the SI. Clonal propagation, particularly through somatic embryogenesis, is gaining attention for its potential to produce uniform, disease-resistant, and high-yielding cacao plants. (Henao-Ramírez & Urrea-Trujillo, 2020). Public sector initiatives in countries like Ghana and Côte d'Ivoire are gradually promoting clonal propagation, signalling a shift toward more resilient and productive cacao systems in the region. According to Obeng-Bio et al. (2024), these hybrid seedlings are propagated in designated cacao seed gardens and distributed annually by the Seed Production Division (SPD), a subsidiary of the Ghana Cocoa Board. The sustainability of this system, they emphasize, hinges on the continuous identification and conservation of elite germplasm sources, which serve as potential parents in the national breeding programme led by the Cocoa Research Institute of Ghana (CRIG). Clonal propagation plays a central role in maintaining true-to-type identity within germplasm collections. As Efron et al. (2003) have shown, cacao trees raised from seed exhibit high heterozygosity and significant tree-to-tree variability, underscoring the importance of asexual propagation in breeding programmes. Obeng-Bio et al. (2024) further argues that from within hybrid populations, superior genotypes can be selected and cloned for both further breeding and commercial production.

In the SI, private sector initiatives have played a pivotal role in supplying cacao clonal seedlings. For example, RN Sons Farm operate the remaining main clonal seedling nursery in the SI. They have maintained five improved genetic lines of Trinitario hybrid cacao (BE82, BD68, BC148, BC32 and BB66, Figure 5), which have been replicated from trees at the Saint Martin School in Guadalcanal. These materials were originally imported from the Cocoa Coconut Institute of Papua New Guinea (CCI-PNG) in 2012 and included the high-performing varieties BE82 and BC32. Although formal trials were initially planned, several growers independently adopted the BE82 variety following the conclusion of earlier development programmes (R. Vava, Pers. Comm., March 18, 2024). RN Sons Farm are reported to have produced and distributed approximately 10,000 clonal seedlings between 2022 and 2024 to up to 20 – 50 farms, without subsidy support (R. Waisu, Pers. Comm., July 8, 2025). These seedlings were sold to up to approximately 50 farms in total at a price of about $5.00 per plant.

Figure 5.5 An example of imported genetic material (BC32 type) at RN Sons farm.

These insights underscore the dual importance of institutional infrastructure and genetic fidelity in delivering clonal seedlings. Although seed-based propagation remains prevalent in some regions, the strategic use of clonal materials (backed by breeding programs and grower participation) presents a promising pathway to boost cacao productivity, quality, and sustainability. Adoption of clonal materials is shaped by various factors. Improved clones often offer higher yields and disease resistance (Monteiro et al., 2009; Sodre & Gomes, 2019), but their intensive management and elevated input costs can be prohibitive for resource-limited smallholders (Daymond & Bekele, 2022). Socio-economic elements such as income, education, access to extension services, and group membership also influence adoption, as shown in Indonesia (Rasyidin et al., 2024). Locally adapted clones, selected through participatory approaches, tend to perform better under diverse field conditions, offering greater environmental adaptability and yield stability (Armengot et al., 2023). For example, Amelonado cacao has gained traction due to its resilience in low-input and agroforestry systems, broader genetic diversity, and lower agronomic demands (Bediako et al., 2024). While imported clones like BE82 and BC32 are still under field evaluation, integrating formal breeding efforts with informal propagation (supported by varietal trials and grower engagement) is essential for scaling adoption. Aligning clonal seedling provision with local capacity and ecological contexts can significantly enhance cacao systems (Armengot et al., 2023). Echoing findings from Nelson et al. (2011) in PNG, collaboration with the Ministry of Agriculture and Livestock and international partners is vital for supplying affordable, high-quality clonal material and technical support to growers.

The provision of clonal seedlings to growers is easy to adopt, as it requires no special tools or training, as is the case for grafting practices. However, the main constraints are the cost and adequate supply to meet grower's demand. Therefore, it is useful to assess how many clonal seedlings would need to be produced each year in order for growers to be about to replace all of their trees over a 30-year period. This would require each grower to replace 3.3% of their trees each year. For example, assuming there are about 20,000 ha of cacao with an average tree density of 800 trees ha^{-1}, if 3.3% is replaced with clonal seedlings every year this would be 528,000 seedlings needed each year. Assuming the cost of a seedling is \$5, this would be a total cost of \$2.64 million year^{-1} (\$132 ha^{-1} year^{-1}). This cost is equivalent to 5.3% and 11.7% of the estimated increase in 5-year medium-term export income and farm gate income, respectively, from rejuvenation adoption. This indicates that when the cacao price is more favourable, then the cost of clonal seedlings would be relatively low compared to the potential economic returns for both the SI cacao industry and for individual growers. However, when the longer-term 8-year pre-2023 low average annual farm gate price is used, then the cost of clonal seedlings could increase to as much of 26.5% of the potential increase in farm gate income.

There is a time lag between the planting of seedlings and an increase in income, as it can take up to 4 years for trees grown from seedlings to reach peak production levels. In addition to the cost of clonal seedlings, both the uncertainty of future prices and delay in return on investment are significant barriers to adoption for growers. Also, due to the current low demand for seedlings, the RN Sons Farms is the only main source of clonal seedlings in the SI, and they only produce about 5,000 seedlings per year. In order for all growers to replace 3.3% of their farms each year with clonal seedlings, they would need about a 100-fold increase in the production of clonal seedlings. To achieve this very large increase in the supply of seedlings, they would likely require significant subsidies of the seedling price to increase demand and also major investment in expanding the scale of the seedling propagation. There also needs to be consideration of lower-cost propagation methods such as mini-grafting or rooted cuttings, which could reduce production costs and make seedlings more affordable for growers. Additionally, establishing decentralised community-based nurseries could help improve access and reduce logistical challenges, while also creating local employment opportunities.

Strategy 2: Provide training and tools for on-farm grafting

An alternative to the new plantings with clonal seedlings is tree rejuvenation through more effective training and tools for on-farm grafting. Successful adoption of on-farm grafting of trees requires the implementation of a robust and sustainable support system that combines technical training, accessible propagation materials, provision of tools, and institutional coordination.

A previous cacao development programme (2009–2021) funded by Australian Agency for International Development (AusAID) in the SI introduced the concept of lead growers as peer educators and innovation champions (Jansen & Maike, 2011, 2012; R. Vava, Pers. Comm., July 9, 2025). This programme involved selecting groups of twelve cocoa growers from various regions based on their leadership potential, willingness to learn, and prior experience in cocoa farming, who were informally referred to as the “twelve disciples”. These lead growers underwent hands-on training in key areas including cocoa rejuvenation practices such as pruning and shade management, grafting, pest and disease control, post-harvest processing methods like fermentation and drying, as well as record keeping and basic business skills.

Following their training, each disciple was tasked with mentoring between 10 to 20 other growers in their local communities, effectively serving as grassroots extension agents by demonstrating improved farming practices and offering guidance. To ensure the success of this knowledge transfer, field officers conducted regular follow-ups and provided lead growers with essential tools and materials to support their outreach efforts. The lead grower role extended beyond demonstration plots to include logistical coordination, data collection for research trials, and mobilisation of grower groups for collective marketing and certification efforts (Vadnjal & Pelomo, 2014). In total it was estimated that approximately 1,350 growers received training and/or mentoring though this programme over the three-year period it operated.

Despite the strategic importance of the lead grower initiative, it became largely inactive due to the discontinuation of programme funding and the absence of a clear government policy on cacao rejuvenation. Interviews with stakeholders indicate that while lead growers received initial training in grafting and rejuvenation techniques, they lacked ongoing technical support and extension services to confidently disseminate these practices within their community farms or groups (R. Waisu, Pers. Comm., July 8, 2025). This gap underscores the need for a renewed investment in capacity building, not only for lead growers but also for extension officers who support them.

A structured training programme should be developed to equip growers and extension staff with practical grafting skills and clonal management techniques (Nelson et al., 2011). This includes: chupon and side grafting methods for rejuvenating old trees; on-farm selection protocols to identify elite mother trees based on pod load, bean quality, and disease resistance; and IPDM training to ensure the long-term viability of clonal trees (Konam et al., 2011; MALPRESS, 2011; Toramo et al., 2019). Training should be delivered through modular workshops, field demonstrations, and visual manuals tailored to local contexts. Extension officers must be trained not only in technical skills but also in participatory facilitation to foster farmer-led innovation and peer-to-peer learning (MAL/SIARTPRESS, 2025). A successful model from PNG that could inform training in the SI is the EU-STREIT Programme, which was implemented in the Greater Sepik Region (FAO, 2021). This initiative combined practical bud grafting training, establishment of cocoa nurseries, and modular workshops tailored to remote communities. It emphasised hands-on learning, visual manuals, and peer-to-peer knowledge sharing, with strong inclusion of youth and women. Lead growers were empowered to train others, fostering local innovation and uptake. The programme's integrated approach to clonal propagation, IPDM, and participatory facilitation makes it a strong candidate for adaptation in the SI.

Regular monitoring of clonal farms is essential to assess productivity, survival rates, and adoption levels. Participatory evaluation methods should be employed to capture grower experiences and adapt training content accordingly (Nelson et al., 2011). Mobile-based data collection tools can facilitate real-time feedback and inform policy decisions. Providing training and tools for clonal propagation is not merely a technical intervention but a strategic pathway to revitalising the cacao sector. By reactivating lead grower networks, decentralising access to propagation materials, and embedding participatory training models, the SI can foster a resilient, high-yielding, and grower-driven cacao system (ACIAR, 2025; CLIP, 2010). International experiences affirm that locally adapted, well-supported clonal programmes can transform smallholder livelihoods when implemented with continuity, collaboration, and contextual sensitivity. The Philippines' CPAR model successfully trained growers in chupon grafting while providing tools and cooperative support, leading to sustained adoption and income stability (DA-BAR, 2019).

Assuming that the 12 disciples' concept was developed again, an initial training day of 6 hours with 12 growers and a total of up to 10 hours of monthly follow up visits for individual contact time with each grower over a six-month period would be a total of 126 hours for a single cohort. Assuming each field officer could assist 6 groups of 12 growers over a 6-month period, then they would be able to train and support 72 growers every 6 months. Over a period of 5 years, a total of 34 dedicated field officers would be needed to train and support approximately 24,000 grower households (SINSO, 2019), which is 4,752 growers per year. However, if only half of the growers with the largest farms were trained by field officers, and each of these growers mentored at least one other grower with a smaller farm, then only 12,000 growers would need training by field officers. This would reduce the number of dedicated field officers needed to 17. Assuming it costs approximately \$50 day^{-1} for the cost of a field officer, including salary, field allowance, vehicle, and fuel costs, then the cost of each field officer would be approximately \$13,000 field officer^{-1} year^{-1}, which would be \$221,000 for 17 field officers per year. Another cost would be for the provision of tools needed by growers to do the intensive pruning and grafting, which is estimated to be approximately \$30 grower^{-1}. If tools are provided to 4,752 growers per year, this would be a cost of \$142,560. Therefore, the annual cost of the programme would be \$363,560 year^{-1}, which would be a total of \$1.82 million over the five-year period of the programme. The annual cost is equivalent to 0.7% and 1.6% of the estimated increase in the 5-year medium-term export income and farm gate income, respectively, from rejuvenation adoption. This indicates that when the cacao price is more favourable, then the cost of grafting training and tools would be relatively low compared to the potential economic returns for both the SI cacao industry and for individual growers. When the longer-term 8-year pre-2023 low average annual farm gate price is used, then the cost could increase to 3.7% of the potential increase in farm gate income.

Strategy 3: Integrated approach

Training for grafting and pruning is not only a lower cost than the clonal seedlings on an annual basis, but this cost would only be for a period of five years. If growers continually replaced 3.3% of their trees annually with clonal seedlings, the cost is higher per year and this cost would be ongoing every year. However, the main disadvantage of the training and tools approach, is that it relies on growers actively participating in training and being prepared to carry out grafting on their farms. Also, if growers have mostly been using seedlings grown from seeds collected from their farms, then the genetic material available to them may be less productive than using clonal seedling from established or new varieties.

The optimal overall policy may be an integrated approach that combines the advantages of Strategies 1 and 2. For example, providing growers with clonal seedlings to replace perhaps 10% of their farm over 10 years. These trees could be labelled and then used for grafting other trees in the future. This would involve less on-going costs and would help growers improve their tree genetics over time. For example, assuming there are about 20,000 ha of cacao with an average tree density of 800 trees ha^{-1}, if 1% is replaced with clonal seedlings every year this would be 160,000 seedlings needed each year (Table 5.4). Assuming the cost of a seedling is \$5, this would be a total cost of \$800,000 year^{-1} (\$40 ha^{-1} year^{-1}). In addition, the annual cost of the grafting training and tools programme would be \$363,560 year^{-1} for 5 years. Therefore, for the first 5 years of the combined approach programme would be \$1.16 million year^{-1}, which would then reduce to \$800,000 year^{-1} for the subsequent 5 years. The annual cost for the first 5 years is equivalent to 2.3% and 5.2% of the estimated increase in the 5-year medium-term export income and farm gate income, respectively, from rejuvenation adoption. This indicates that when the cacao price is more favourable, then the cost of clonal seedlings would be relatively low compared to the potential economic returns for both the SI cacao industry and for individual growers. However, when the longer-term 8-year pre-2023 low average annual farm gate price is used, then the cost could increase to as much of 11.7% of the potential increase in farm gate income. However, considering that the highest cost of this programme would be during the first 5 years, then the higher medium-term (2020-25) cacao price is more likely to represent returns over this period, compared to the longer-term 8-year pre-2023 low average.

Table 5.3 Summary of tree rejuvenation strategies.

Metric	**Strategy 1:** *Clonal seedlings*	**Strategy 2:** *Grafting training/tools*	**Strategy 3:** *Integrated approach*
Annual cost (NZ$)	$2.64 million per year	$363,560	$1.16 million (first 5 years), $800,000 (subsequent 5 years
Period needed	Ongoing annually (3.3% farm area per year)	5 years	10 years of clonal seedlings (1% farm area per year); 5 years of grafting training/pruning
Percentage of predicted increase in export income*	5.3%	0.7%	2.3%
Percentage of predicted increase in farm gate income*	11.7%	1.6%	5.2%

*Assuming average increase in cacao yield of 330 kg dry beans ha^{-1} $year^{-1}$ for each strategy and using the average annual cacao price for the period 2020-25.

The combined approach presents a compelling and pragmatic strategy for cacao tree rejuvenation, balancing immediate impact with long-term sustainability. By initially supplying clonal seedlings to replace 10% of each farm, growers gain access to high-performing genetic stock that can serve as future scion sources. This gradual replacement keeps upfront costs manageable while still improving productivity. Once these elite trees are established, transitioning to on-farm grafting through targeted training and tool provision empowers growers to propagate improved genetics across their remaining trees. This phased model reduces reliance on external seedling supply, builds local capacity, and spreads investment over time. It also aligns with grower learning curves, allowing them to see the benefits of clonal trees before adopting grafting techniques. Overall, this combined strategy leverages the strengths of both approaches (genetic improvement and grower empowerment) while minimising financial and logistical burdens. This is supported by Jagoret et al. (2021) who advocated for context-specific, phased rehabilitation strategies that integrate both renovation and grower-led rejuvenation techniques, and emphasized the importance of grower empowerment, cost-effective interventions, and long-term sustainability in cacao agroforestry systems.

5.4 Summary

This chapter has examined the impact of cacao tree rejuvenation practices, primarily intensive pruning and grafting, on farm productivity in the SI. While further research with a larger number of farms is required to gain greater confidence in the size of the yield potential, the values obtained in this study support that average yield improvements of 66% are possible. This yield improvement was observed in the absence of fertiliser inputs, highlighting the potential of rejuvenation practices to sustainably increase productivity in low-input farming systems.

The analysis revealed that the extent of rejuvenation implemented on a farm was positively associated with yield outcomes. Farms that rejuvenated a greater proportion of their area, recorded the highest yields, suggesting that the scale of adoption plays a critical role in determining the benefits. Additionally, the presence of lead growers and the size of the farm were found to be important factors influencing adoption. Larger farms and those managed by lead growers were more likely to implement rejuvenation practices, receive training and support, and achieve higher productivity. This indicates that targeted interventions aimed at these groups could serve as effective entry points for scaling up adoption.

Despite the clear agronomic and economic benefits, adoption of rejuvenation practices remains limited. The study identified a range of constraints, including limited access to quality clonal planting materials, inadequate training and extension services, market price volatility, and behavioural hesitancy among growers. Institutional challenges, such as the discontinuation of support programmes and the lack of long-term policy frameworks, further hinder the widespread uptake of these practices. These findings underscore the need for a more coordinated and sustained approach to cacao sector development in the SI.

To address these challenges, the chapter evaluated three strategies to support growers to implement rejuvenation practices: provision of clonal seedlings, training and tools for on-farm grafting, and an integrated approach that combines the first two strategies. The integrated strategy emerged as the most promising, offering a balance between genetic improvement and grower empowerment while maintaining cost-effectiveness. By initially supplying clonal seedlings to improve genetic stock and subsequently training growers in grafting techniques, this approach enables gradual but scalable rejuvenation of cacao farms. The economic analysis suggests that the costs of implementing such a strategy are modest relative to the potential gains in farm income and national export earnings, particularly under favourable market conditions.

In conclusion, this chapter provides evidence that cacao tree rejuvenation practices can play a important role in improving yields and livelihoods for smallholder growers in the SI. However, realising this potential will require a national strategy that integrates technical, institutional, and economic support mechanisms. Future research should focus on long-term monitoring of rejuvenated farms, evaluation of varietal performance, and the development of participatory models that empower growers to lead the transformation of the cacao sector.

Chapter 6: General summary and recommendations for future research

6.1 Introduction

The SI is the second largest producer of cacao in the South Pacific, exporting about 5,000 tonnes of dry cacao beans in 2024. Cacao is also the second largest agricultural export earner for the SI, and its export value increased substantially to NZ$55 million in 2024, mostly due to a sharp rise in the global price for cacao (Siliota, 2024). While cacao is an important income for the country, smallholder growers have received low financial returns for many years from growing cacao. This has been due to both low farmgate prices, prior to 2024, and the on-going challenge of low yields. Common causes of low yields include low soil fertility, old age trees, pest and diseases, climate related natural disasters and tree propagation practices (Asante et al., 2021; CLIP, 2010; Linton, 1984).

The cacao tree improvement programmes and projects (2009-2019) implemented in the SI had limited success in improving national average yields (MAL, 2019; PHAMA, 2016). The aim of this study was to provide new knowledge to support cacao growers in the SI to improve cacao yields. This involved interviewing growers and monitoring soil and tree nutrient status to gain insights into factors influencing yields. This information was then used to guide the design of subsequent field trials and surveys to assesses the effectiveness of nutrient and tree management practices on improving yields.

The specific objectives were:

1. To provide information on current grower practices, and on soil and plant nutrient status of cacao farms (Chapter 3).
2. To identify local sources of organic wastes that could be used as composts for use on cacao farms (Chapter 4).
3. To quantify the effect of improving the soil fertility of farms, using either conventional fertilises or locally sourced composts, on improving cacao yields (Chapter 4).
4. To identify the potential effect of tree improvement practices on cacao yields (Chapter 5).
5. To evaluate the cost effectiveness of different strategies to support growers to implement tree improvement practices (Chapter 5).

6.2 Key findings

The first grower survey in this study (Chapter 3) showed that cacao yields were low for most farms and identified differences in pruning practices as potential causes of yield variation. Growers who adopted intensive pruning achieved average higher yields than those using only standard pruning or who did not use any pruning practices. Growers who used both intensive pruning and selected grafting practices appeared to have additional yield benefits. All the growers that used intensive pruning alone or with selected grafting practices had previously received training and tools from support programmes. This demonstrates the importance of support programmes to assist farmers to implement improved practices.

The soil test results from the survey farms indicated that both plant available P and K were low on most of the farms sampled. Whereas the leaf test results indicated below optimum leaf N and K levels for most of the farms sampled. Overall, the majority of the farms sampled had low soil and leaf nutrient status. Therefore, there is a need to identify cost effective methods to replace nutrient losses that occur over time.

Results from the fertiliser and compost response field trials (Chapter 4) showed limited and inconsistent results. Only at one of three sites, was there evidence of a cacao yield response to conventional fertiliser addition. High tree variability was one of the factors likely influencing the ability to observe significant effect yields from nutrient inputs. There was also no consistent influence of conventional fertiliser or compost treatments on soil and cacao leaf nutrient status at any of the trial sites. High variability in yield between trees may also have been affected by their genetic potential, caused by the common use of seeds to grow seedlings.

This study also highlighted that the cost of conventional fertilisers in the SI is a major constraint to their use by growers. In the SI, the cost of bagged fertiliser is more than three times that in New Zealand. This would require unrealistic yield responses to achieve a return on the fertiliser investment. In addition, because some growers sell their cacao beans for use in single origin chocolate marketed as being organically grown, this is another reason for growers to be cautious about the use of conventional fertilisers. Therefore, the use of improved recycling of tree resides, including pod husks, and the use of organic certified nutrient inputs will be important to help growers who want to maintain organic status. Therefore, there is little evidence that conventional fertiliser use would help smallholder growers be more financial sustainable, especially for those with intercropping farm systems. Soil Cd concentrations were low at both field trial sites tested, which is promising as it is associated with lower levels of Cd in dry cacao beans, an advantage for market access (Thomas et al., 2023). If the observations made in this study are typical of soils in the SI, then this could be beneficial for the SI cacao industry.

The second grower survey in this study (Chapter 5) examined the potential influence of cacao tree rejuvenation practices, primarily intensive pruning and grafting, on farm productivity in the SI. While further research is needed to provide greater confidence in the size of the yield potential, the analysis revealed that the extent of rejuvenation implemented on a farm was positively associated with yield outcomes. Larger farms and those managed by lead growers were more likely to implement rejuvenation practices, receive training and support, and achieve higher productivity. This indicates that targeted interventions aimed at these groups could serve as effective entry points for scaling up adoption.

Despite the potential agronomic and economic benefits of rejuvenation practices, adoption remains limited. The study highlighted the need for a more coordinated and sustained approach to cacao sector development in the SI. To address these challenges, three strategies to support growers to implement rejuvenation practices were assessed. These included providing clonal seedlings, training and tools for on-farm grafting, or an integrated approach that combines the first two strategies. The integrated strategy showed promise, offering a balance between genetic improvement and grower empowerment, while maintaining cost-effectiveness. The economic analysis suggests that the costs of implementing such a strategy are modest relative to the potential gains in farm income and national export earnings, particularly under favourable market conditions. However, realising this potential will require a national strategy that integrates technical, institutional, and economic support mechanisms.

6.2.1 Recommendation for future research

Further research is needed to build on the findings of this study to support smallholder cacao growers in the SI. This is needed to help identify practical and cost-effective ways to improve cacao yields and take advantage of current favourable prices. In particular, further evidence of the effect of tree rejuvenation practices on yield outcomes is needed over a larger number of farms to provide greater confidence in the benefits. In addition, a pilot study is needed to evaluate the effect of using an integrated approach to tree rejuvenation, combing providing clonal seedlings with training and tools for on-farm grafting, on a range of farms to provide support for the wider implementation of this type of improvement programme. Further research is also required to assess the soil Cd status of the main cacao growing areas of the SI and compare with cacao bean Cd levels. This will help to identify if the SI is a producer of low Cd cacao, which may help with market access in the future.

References

ACIAR. (2025). Aligning genetic resources, production and post-harvest systems to market opportunities for Pacific island and Australian cocoa. Retrieved 18/08/2025 from https://www.aciar.gov.au/project/hort-2014-078

Adams, C. (2023). Why is alluvium important to agriculture? Retrieved 28/03/2025 from https://www.agriculturelore.com/why-is-alluvium-important-to-agriculture/

Adejobi, K., Akanbi, O., Ugioro, O., Adeosun, S., Mohammed, I., Nduka, B., & Adeniyi, D. (2014). Comparative effects of NPK fertilizer, cowpea pod husk and some tree crops wastes on soil, leaf chemical properties and growth performance of cocoa (Theobroma cacao L.). *African Journal of Plant Science, 8*, 103-107.

Afoakwa, E. O. (2014). *Cocoa Production and Processing Technology*. Boca Ration, London & New York: Taylor & Francis Group, LLC.

Agbeniyi, S. O., Oluyole, K. A., & Ogunlade, M. O. (2011). Impact of Cocoa Pod Husk Fertilizer on Cocoa Production in Nigeria. *World Journal of Agricultural Sciences, 7*(2), 113-116.

Ahenkorah, Y., Akrofi, G., & Adri, A. (1974). The end of the first cocoa shade and manurial experiment at the Cocoa Research Institute of Ghana. *Journal of Horticultural Science, 49*, 43-51.

Ahenkorah, Y., & Akrofi, G. S. (1968). Amazon cacao (Theobroma cacao L.) shade and manurial experiment (K2-01) at the Cocoa Research Institute of Ghana. I. First first years. *Agronomy journal, 60*, 591-594.

Ahuja, I., Dauksas, E., Remme, J. F., Richardsen, R., & Loes, A. (2020). Fish and fish waste-based fertilizers in organic farming - with status in Norway: A review. *Elsevier, 115*, 95-112.

Aikpokpodion, P. E. (2010). Nutrients Dynamics in Cocoa Soils, Leaf and Beans in Ondo State, Nigeria. *Journal of Agricultural Sciences, 1*(1), 1-9. 10.1080/09766898.2010.11884647

Akanbi, O., Famaye, A. O., Olaniyi, O. O., Ipinmoroti, R. R., Iloyanomo, C. I., & Nduka, B. A. (2014). Comparative Effects of Cocoa Pod Husk and Oil Palm Bunch Ash on Nutrient Uptake, Growth and Dry Matter Yield of Cocoa (Theobroma cacao) in Ibadan, Southwest Nigeria. *Agricultural Sciences, 5*, 1046-1052.

Akane, B. (2017). Cacao Fertilization and Nutrient Requirements. Retrieved 05/06/2025 from https://wikifarmer.com/library/en/article/cacao-fertilization-nutrient-requirements

Akhtar, M., & Alam, S. M. (2021). Effect of incubation period on phosphate sorption from two P sources. *J Biol Sci, 1*(124-125)

Akrofi, A. Y., Amoako-Atta, I., Assuah, M., & Asare, E. K. (2015). Black pod disease on cacao (Theobroma cacao, L) in Ghana: spread of Phytophthora megakarya and role of economic plants in the disease epidemiology. *Crop Protection, 72*, 66-75. 10.1016/j.croprp.2015.01.015

Albert, S., Kvennefors, C., Jacob, K., Kera, J., & Grinham, A. (2017). Environmental change in a modified catchment downstream of a gold mine, Solomon Islands. *Environmental Pollution, 231*, 942-953.

AMARTA. (2010). *Annual Report of Project Activities and Achievements 2010 (October 2009 - December 2010)*. Jakarta, Indonesia. Retrieved from https://pdf.usaid.gov/pdf_docs/PDACX077.pdf

Ampofo, S. T. (1986). Spacing/Cultivar/Pruning Experiment. In *Report for period 1982/3-1984/5*. Ghana: Cocoa Research Institute.

Amponsah-Doku, B., Daymond, A., Robinson, S., Atuah, L., & Sizmur, T. (2022). mproving soil health and closing the yield gap of cocoa production in Ghana – A review. *Scientific African, 15* https://www.sciencedirect.com/science/article/pii/S2468227621003768?via%3Dihub

Anyimah-Ackah, E., Ofosu, I. W., Lutterodt, H. E., & Darko, G. (2019). Exposures and risks of arsenic, cadmium, lead, and mercury in cocoa beans and cocoa-based foods: A systematic review. *Food Quality and Safety, 3*(1), 1-8. https://doi.org/10.1093/fqsafe/fyy025

Appiah, M., Ofori-Frimpong, K., & Afrifa, A. (2000). Evaluation of fertilizer application on some peasant cocoa farms in Ghana. *Ghana Journal of Agricultural Science, 33*(2), 183-190.

Applied-Agricultural-Resources. (2014). Cocoa: Fertilizer Requirements "2005-2014". Retrieved 25/04/2020 from www.aarsb.com.my/cocoa-fertilizer-requirements

Apshara, S. E. (2017). Comparative study on clonal and seedling progenies of selected cocoa (Theobroma cacao L.) genotypes. *Indian Journal of Horticulture, 74*(2)

Arévalo-Gardini, E., Farfán, A., Barraza, F., Arévalo-Hernández, C. O., Zúñiga-Cernades, L. B., Alegre, J., & Baligar, V. C. (2021). Growth, physiological, nutrient-uptake-efficiency and shade-tolerance responses of cacao genotypes under different shades. *Agronomy for Sustainable Development, 11*(8), 1536. https://doi.org/10.3390/agronomy11081536

Armengot, L., Picucci, M., Hansen, J., K., & Schneider, M. (2023). Locally-selected cacao clones for improved yield: a case study in different production systems in a long-term trial. *Frontiers in Sustainable Food Systems, 7*

Arthur, A., Afrifa, A. A., & Dogbatse, J. A. (2017, 13-17 November). *Assessment of soil fertility status of cocoa farms around the Ankasa National Park in the Jomoro District of the Western Region of Ghana.* Paper presented at the 2017 International Symposium on Cocoa Research (ISCR), Lima, Peru.

Asante, P. A., Rozendaal, D. M. A., Rahn, E., Zuidema, P. A., Quaye, A. K., Asare, R., . . . Anten, N. P. R. (2021). Unravelling drivers of high variability of on-farm cocoa yields across enviornmental gradients in Ghana. *Agricultural Systems, 193*

Asare, R., & David, S. (Eds.). (2011). *Good agricultural practices for sustainable cocoa production: a guide for farmer training. Manual no. 1 Planting, replanting and tree diversification in cocoa systems*: Forest & Landscape Denmark.

Asomaning, E. J. A., Kwaka, R. S., & Hutcheon, W. V. (1971). Physiological studies on an Amazon shade and fertiliser trial at the Cocoa Research Institute of Ghana. *Ghana J Agric. Sci, 4*, 47-64.

Baah, F., & Anchirinah, V. (2011). A review of cocoa research institute of Ghana extension activities and the management of cocoa pests and diseases in Ghana. *Americian*

Journal of Scocial and Management Sciences, 2, 196-201. 10.1111/j.1746-1049.2008.00065.x

Babalola, F., Ayinde, O. E., Chirwa, P. W., & Thiam, D. R. (2017). Risks and coping strategies of production and marketing of cocoa in Ondo State, Nigeria. *Agroforestry Systems, 91*(2), 211-220.

Baharuddin., Tang, A., Christine, A., Fitriyah, A. T., & Utami, R. R. (2022). *Farmer income analysis: Cocoa farming with side grafting technique (Case study in Mappesangka village, South Sulawesi, Indonesia)*. Paper presented at the 9th International Conference on Sustainable Agriculture and Environment Earth and Environmental Science. https://iopscience-iop-org.ezproxy.massey.ac.nz/article/10.1088/1755-1315/1114/1/012005/pdf

Bahaudin, M. J., Wazir, S. K. S., & Omar, S. (1986). Influence of timing and frequency of pruning on yield of hybrid of cocoa. *Cocoa & Coconut: Progress & Outlook*

Balasimha, D. (2007). Efficacy of pruning in enhancing bean yield of cocoa. *J. Plant. Crop, 35*, 201-202.

Baligar, V. C., Elson, M. K., Almeida, A.-A. F., de Araujo, Q. R., Ahnert, D., & He, Z. L. (2021). Carbon dioxide concentrations and light levels on growth and mineral nutrition of juvenile cacao genotypes. *American Journal of Plant Sciences, 12*, 818-839. https://doi.org/10.4236/ajps.2021.125056

Baligar, V. C., & Fageria, N. K. (2007). Agronomy and Physiology of Tropical Cover Crops. *Journal of Plant Nutrition, 30*(8), 1287-1339. 10.1080/01904160701554997

Beer, J., Muschler, R., Kass, D., & Somarriba, E. (1998). Shade management in coffee and cacao plantations. *Agroforestry Systems, 38*, 139-164.

Bilderback, T., Bir, R. E., & Ranney, T. G. (2014). Grafting and Budding Nursery Crop Plants. Retrieved 08/03/2023 2023 from https://content.ces.ncsu.edu/grafting-and-budding-nursery-crop-plants

Binam, J. N., Gockowski, J., & Nkamleu, G. B. (2015). Technical efficiency and productivity potential of cocoa farmers in West African countries. *Developing Economies, 46*(3), 242–263. https://scispace.com/papers/technical-efficiency-and-productivity-potential-of-cocoa-2iq4mgh7bm

Blakemore, L. C., Searle, P. L., & Daly, B. K. (1987). *Methods for chemical analysis of soils* ([Rev.ed] ed.). Lower Hutt, New Zealand: NZ Soil Bureau, Dept. of Scientific and Industrial Research.

Borges, A. L. (2022). Nutrient dynamic in cocoa leaves under different nitrogen sources: a reference tool for foliar analysis. *Brazilian Society of Fruit Crops*, 1-9.

Boyer, J. (1973). Cycles de la matière organique et des éléments minéraux dans une cacaoyère camerounaise. *Café Cacao Thé, 18*, 3-30.

Bryson, G. M., Mills, H. A., Sasseville, D. N., Jones, J. B., Jr., & Barker, A. V. (Eds.). (2014). *Plant Analysis Handbook III: A guide to sampling, preparation, analysis, interpretation and use of results of agronomic and horticultural crop plant tissue* (3rd ed.): Micro-Macro Publishing, Inc.

CACAO. (2024). Growing Cocoa. Retrieved from https://www.cacao.org.au/growing-cocoa/#:~:text=Pacific%20countries%20that%20grow%20cocoa%20are%20PNG%2C%20Solomon,Fiji%20%E2%80%93%20countries%20where%20Australia%20funds%20development%20projects.

CBSI. (2020). *Quarterly review 2020*. Honiara, Solomon Islands: Central Bank of Solomon Islands. Retrieved from http://www.cbsi.com.sb/wp-content/uploads/2021/03/QR-DEC2020-Final-.pdf

Charter, C. (1953). *Cocoa soils. Good and bad.* (WACRI Report). Tafo, Ghana.

Christophe, K., Kouadio, B., Jean-Luc, K., Lucien, D., Jane, K., Jean-Claude, N., & Daouda, K. K. (2018). Comparisonn of Grafting Techniques and their Effects on some Growth Parameters of Ten Elite Cocoa Clones (Theobroma cacao L.). *Academic Journals, 13*(41), 2249-2255.

CIFOR-ICRAF. (2022). Management of trees in agroforestry systems. In *AGROFORESTRY: A PRIMER* (Vol. 7, pp. 10). Online: CIFOR-ICRAF.

CLIP. (2010). *Solomon Islands Cocoa Book*. Honiara, Solomon Islands: Australian Government.

Cocoa-Life. (2024). Cocoa growing. Retrieved 07/03/2025 2025 from https://www.cocoalife.org/in-the-cocoa-origins/

Cooke, G. W. (1982). *Fertilizing for Maximum Yield*. Granada, London.

CSIRO, SPREP, & SIMS. (2018). *A preliminary case study assessment of climate change impacts and risks for cocoa farming in Guadalcanal Plain, Solomon Islands*. Commonwealth Scientific and Industrial Research Organisation, Secretariat of the Pacific Regional Environment Programme, and Solomon Islands Meteorological Service. Retrieved from www.pacificclimatechangescience.org

DA-BAR. (2019). *Farmers grow recommended cacao varieties through CPAR.* . Retrieved from https://agriculture.com.ph/2019/11/29/farmers-grow-recommended-cacao-varieties-through-cpar/

Dani, D., & Rokhmah, D. N. (2022). A review of the role of pollination on the yield of cocoa plant. *Kultivasi, 21*(3), 249-255.

Daouda, K. K., Jean-Claude, N., J ane, K., Lucien, D., J ean-Luc, K., Kouadio, B., & Christophe, K. (2015). Comparison of Grafting Techniques and their Effects on some Growth Parameters of Ten Elite Cocoa Clones (Theobroma cacao L.). *African Journal of Agricultural Research, 13*(41), 2249-2255.

Dar, W. D., & Asio, V. B. (2016). Soil degradation and its impact on food security and environmental sustainability. *Journal of Developments in Sustainable Agriculture, 11*(1), 1-15. https://www.jstage.jst.go.jp/article/jdsa/11/1/11_1/_article

David, S. (2005). *Learning about sustainable cocoa production: a guide for participatory farmer training. 1. Integrated crop and management.* Yaounde, Cameroon: Sustainable Tree Crops Program (STCP), Institute of Tropical Agriculture.

Daymond, A., & Bekele, F. (2022). Cacao. In A. Daymond & F. Bekele (Eds.), *Cacao* (pp. 15-42): Springer. https://doi.org/10.1007/978-3-030-74926-2_2

de Almeida, A. F., & Valle, R. R. (2007). Ecophysiology of the cacao tree. *Brazilian Journal of Plant Physiology, 19*(4), 425–448.

DFAT. (2024). Solomon Islands country brief. Retrieved 24/05/2024 2024 from https://www.dfat.gov.au/geo/solomon-islands/solomon-islands-country-brief#:~:text=The%20population%20of%20Solomon%20Islands,country%2C%20with%20numerous%20local%20dialects.

Dillon, N. L., Zhang, D., Nauheimer, L., Toramo, E., Nagalevu, P., Melteras, M., . . . Diczbalis, Y. (2023). Understanding the cocoa genetic resources in the Pacific to assist producers to supply the growing craft market. *New Zealand Journal of Crop and Horticultural Science, 52*(4), 306-320.

Dinesh, R., Chaudhuri, S. G., Ganeshamurthy, A. N., & Dey, C. (2010). Changes in soil microbial indices and crop productivity under integrated nutrient management in a tropical vegetable cropping system. *Scientia Horticulturae, 124*(2), 218-224. https://www.sciencedirect.com/science/article/pii/S0304423810000270?via%3Dihub

Djokoto, J. G. (2016). Adoption of organic agriculture: Evidence from cocoa farming in Ghana. *Cogent Food & Agriculture, 2*(1)

Doe, E. K., Attua, E. M., Dogbatse, J. A., & Fosu-Mensah, B. Y. (2022). Assessing the condition and capability of soils in cocoa districts of Ghana using geovisualization. *Soil Security, 7*, 1-12.

Duffy, E. A. J. (1963). *A Monograph of the Immature States of Australia Timber Beetles (Cerambycidae)*. London: British Museum (Natural History).

Efron, Y., Eskes, A. B., & Soria, R. (2003). *Cocoa breeding: Constraints and strategies.* . Paper presented at the Proceedings of the International Workshop on Cocoa Breeding for Improved Production Systems, Accra, Ghana.

ESRI-World-Imagery (Cartographer). (2023). Map of field trial experimental sites on Guadalcanal Island

Fairtrade. (2024). About cocoa. Retrieved 05/08/2025 from https://www.fairtrade.org.uk/farmers-and-workers/cocoa/about-cocoa/#:~:text=The%20average%20age%20of%20a,farmers%20growing%20cocoa%20(pdf

Falque, M., Vincent, A., Vaissiere, B. E., & Eskes, A. B. (1995). Effect of pollination intensity on fruit and seed set in cacao. *Plant Reproduction, 8*(6), 354-360. https://link.springer.com/article/10.1007/BF00243203

FAO. (2020). Taking care of the plantation. Retrieved 12/06/2020 from http://www.fao.org/3/ad220e/AD220E04.htm

FAO. (2021). *Sustainable cocoa value chain development in the Greater Sepik Region: Support to rural entrepreneurship, investment and trade in Papua New Guinea (EU-STREIT PNG)*. https://openknowledge.fao.org/server/api/core/bitstreams/85715d25-001b-4518-9e06-5ad9a38f1b7f/content

Fongers, E., & Visser, M. (2015). *Rehabilitation & Renovation of crop trees in cocoa, coffee, palm oil* (Report). Netherlands: The Sustainable Trade Initiative. Retrieved from https://www.idhsustainabletrade.com/uploaded/2017/03/RIAS-RR-Report.pdf

Fontes, A., Gama-Rodrigues, A., Gama-Rodrigues, E., Sales, M., Costa, M., & Machado, R. (2014). Nutrient stocks in litterfall and litter in cocoa agroforests in Brazil. *Plant and Soil, 383*, 313-335.

Foth, H. D. (Ed.) (1990). *Fundamentals of soil science* (8th ed ed.). New York: Wiley, c1990.

Franzen, M., & Mulder, M. B. (2007). Ecological, economic and sosical perspectivs on cocoa production worldwide. *Biodiversity Conservation, 16*, 3835-3849.

Frazer, I. L. (1973). *To'ambaita Report: A Study of Socio-Economic Change in North-Western Malaita*. Wellington, New Zealand: Department of Geography, Victoria University.

Friend, D., & Macfarlane, R. (1974). *Megaceresium horni* (Heller), a New Longicorn Stem Borer of Cocoa in the British Solomon Islands. *International Journal of Pest Management, 20*(2), 203-207. 10.1080/09670877409413634

Fungenzi, T., Sakrabani, R., Burgess, P. J., Lambert, S., & McMahon, P. (2021). Medium-term effect of fertilizer, compost, and dolomite on cocoa soil and productivity in Sulawesi, Indonesia. *Experimental Agriculture, 57*(3), 185-202.

Gallup, J. L., & Sachs, J. D. (2000). Agriculture, climate, and technology: why are the tropics falling behind? *American Journal of Agricultural Economics, 82*, 731-737.

Garden-Island-Chocolate. (n.d.). Growing – Garden Island Chocolate. Retrieved from https://gardenislandchocolate.com/growing-processing/

Garnsworthy, A. (2010). The Different Varieties of Cocoa Beans: Criollo, Trinitario & Forastero. Retrieved 14/04/2025 from https://www.chocolate.co.uk/blogs/news/the-different-varieties-of-cocoa-beans-criollo-trinitario-and-forastero

Geisseler, D., Horwath, W. R., & Moffitt, D. C. (2021). Nitrogen mineralization from organic fertilizers and composts: Literature survey and model fitting. *Journal of Environmental Quality, 50*(1), 1-14. https://doi.org/10.1002/jeq2.20295

Gimenez, I., Fantin, M., Santos, P., Paulo, S., & Grande, C. (2025). Cocoa enters new pricing era amid global supply-demand gap. Retrieved 21/04/2025 from https://valorinternational.globo.com/agribusiness/news/2025/04/17/cocoa-enters-new-pricing-era-amid-global-supply-demand-gap.ghtml

Gómez, F. S. (2024). *Pollination Networks of Cacao Agroforestry Systems in Colombia*. University of Toronto. https://utsc.library.utoronto.ca/sites/default/public/26%20-%20Felipe%20Sarmiento%20Gomez%20-%20Pollination-Laidlaw.pdf

Gordon, J. (2011). Too hot for chocolate? Retrieved 02/08/2015 from http://dapa.ciat.cgiar.org/too-hot-forchocolate/

Goudsmit, E., Rozendaal, D. M. A., Tosto, A., & Slingerland, M. (2023). Effects of fertilizer application on cacao pod development, pod nutrient content and yield. *Scientia Horticulturae, 313*(111869) https://doi.org/10.1016/j.scienta.2023.111869

Govindaraj, K., & Jancirani, P. (2017). Effect of pruning on Cacao (Theobroma Cacao L) on morphological, flowering and yield and quality of Cocoa beans. *Int. J. Agric. Sci. Res., 7*, 113-118.

Gray, J. M., & Murphy, B. W. (1999). *Parent Material and Soils: A guide to the Influence of Parent Material on Soil Distribution in Eastern Australia*. Australia: NSW Department of Land and Water Conservation.

Groeneveld, J. H., Tscharntke, T., Moser, G., & Clough, Y. (2010). Experimental evidence for stronger cacao yield limitation by pollination than by plant resources. *Perspectives in Plant Ecology, Evolution and Systematics, 12*(3), 183–191.

Guarín, D., Hamamura, R. N., Cortez, B. J., Benavides, J., Spargo, J., Guiltinan, M., . . . Drohan, P. J. (2023). Cadmium contamination in cacao farms of Piura, North Peru: A comprehensive assessment of geogenic and anthropogenic sources and implications for future production. *Environmental Challenges, 13*, 1-14. https://pure.psu.edu/en/publications/cadmium-contamination-in-cacao-farms-of-piura-north-peru-a-compre

Guinto, D. F., & Catto, W. (2016). *Analysis of the relationship between total nitrogen and available nitrogen in non-pastoral topsoils of New Zealand from a large soil test database*. Paper presented at the FLRC Conference, Massey University. https://www.massey.ac.nz/~flrc//workshops/16/Manuscripts/Paper_Guinto_2016.pdf

Hamilton, W. M., & Grange, L. I. (1938). *The Soils and Agriculture of Western Samoa (Bulletin No. 61)*. Wellington, New Zealand: Department of Scientific and Industrial Research.

Hansell, J. R. F., & Wall, J. R. D. (1976). *Land resources of the Solomon Islands. Volume 1- introduction and recommendations*.

Hartemink, A. E. (2005). In *Advances in Agronomy* (Vol. 86, pp. 227-253): Academic Press. https://doi.org/10.1016/S0065-2113(05)86005-5

Hecker, J., & Kalpokas, N. (2025). Face-to_Face Interviews. Retrieved 10/06/2025 from https://atlasti.com/guides/interview-analysis-guide/face-to-face-interview-research

Henao-Ramírez, A. M., & Urrea-Trujillo, A. I. (2020). Somatic embryogenesis for clonal propagation and associated molecular studies in cacao (Theobroma cacao L.). In *Agricultural, Forestry and Bioindustry Biotechnology and Biodiscovery* (pp. 63-102): Springer. https://doi.org/10.1007/978-3-030-51358-0_5

Hill-Laboratories. (2025). Soil nitrogen tests: Services offered. Retrieved from https://www.hill-labs.co.nz/media/3zcji4lr/14666v9_services-offered-soil-nitrogen-tests.pdf

Hoffmann, M. P., Cock, J., Samson, M., Janetski, N., Janetski, K., Rotter, R. P., . . . Oberthur, T. (2020). Fertilizer management in smallholder cocoa farms of Indonesia under variable climate and market prices. *Agricultural Systems, 178*

Houanihau, J. (2025). Cocoa working group held its first meeting. *The Island Sun*. Retrieved from https://theislandsun.com.sb/cocoa-working-group-held-its-first-meeting/

Hougni, D.-G. J. M. (2023). *Integrated soil fertility management: A path to sustainable intensification of cocoa production in West Africa?* (PhD), Wageningen University,

Hougni, D.-G. J. M., Schut, A. G. T., Woittiez, L. Z., Vanlauwe, B., & Giller, K. E. (2021). How nutrient rich are decaying cocoa pod husks? The kinetics of nutrient leaching. *Plant Soil, 463*, 155-170.

ICRAF. (2014). *Annual report Vision for Change Project: Building sustainable cocoa communities in Cote d'Ivoire*. Cote d'Ivoire: World Agroforestry Centre.

IFC. (2016). *SolTuna - tuna processing, Solomon Islands*. Washington, USA: World Bank Group. Retrieved from https://www.ifc.org/wps/wcm/connect/3432dc32-806a-4830-81c4-e231eaeeba8c/soltuna_updated_May2017.pdf?MOD=AJPERES&CVID=lMod8jG

Iroga, R. (2024). (KPSI) launches new locally produced drinking chocolate. Retrieved from https://sbm.sb/kpsi-launches-new-locally-produced-drinking-chocolate/

Isaac, M. E., Timmer, V. R., & Quashie-Sam, S. J. (2007). Shade tree effects in an 8-year-old cocoa agroforestry system: Biomass and nutrient diagnosis of Theobroma cacao by vector analysis. *Nutrient Cycling in Agroecosystems, 78*, 155-165. https://doi.org/10.1007/s10705-006-9081-3

Isele, E., Breen, M., & Galanti, R. (2020). Grafting Cacao. *Cooperative Externsion Publications*

Jagoret, P., Somarriba, E., Peguero, F., Cerda, R., Orozco-Aguilar, L., López-Sampson, A., . . . Sinclair, F. L. (2021). Rehabilitation and renovation of cocoa (Theobroma cacao L.) agroforestry systems: A review. . *Agronomy for Sustainable Development, 41*(64) https://link.springer.com/article/10.1007/s13593-021-00717-9

Jansen, T., & Maike, P. (2012). *Cocoa Livelihoods Improvement Project (CLIP) 2011–2012 Monitoring/Impact Assessment Annual Report*.

Kaba, J. S., Asare, A. Y., Andoh, H., Kwashie, G. K. S., & Abunyewa, A. A. (2022). Toward Sustainable Cocoa (Theobroma Cacao L) Production: The Role of Potassium Fertilizer in Cocoa Seedlings Drought Recovery and Survival. *International Journal of Fruit Science, 22*(1), 618-627.

Kale, M. (2023) *Cocoa pruning and managment practices/Interviewer: S. I. Sefa*. PhD research Unpublish, Honiara, Gudalcanal.

Karun, A. K., & Hubballi, V. N. (2019). *Cocoa Notebook (Technical bulletin No. 144)*. Karnataka: ICAR - Central Plantation Crops Research Institute - CPCRI.

Klein, A. M., Cunningham, S. A., Bos, M., & Steffan-Dewenter, I. (2008). dvances in pollination ecology from tropical plantation crops. *Ecology, 89*(4), 935–943. https://www.jstor.org/stable/27651632

Konam, J., Namaliu, Y., Daniel, R., & Guest, D. I. (Eds.). (2011). *Integrated pest and disease management for sustainable cocoa production: a training manual for farmers and extension workers* (2nd ed.). Sydney, Australia: ACIAR. https://www.aciar.gov.au/publication/books-and-manuals/integrated-pest-and-disease-management-sustainable-cocoa-production-training-manual

Kongor, J. E., Boeckx, P., Vermeir, P., Walle, D. V. D., Baert, G., Afoakwa, E. O., & Dewettinck, K. (2019). Assessment of soil fertility and quality for improved cocoa production in six cocoa growing regions in Ghana. *Agroforestry Systems, 93*, 1455-1467.

Kongor, J. E., Steur, H. D., Walle, D. V. D., Gellynck, X., Afoakwa, E. O., Boeckx, P., & Dewettinck, K. (2018). Constraints for future of cocoa production in Ghana. *Agroforestry Systems, 92*, 1373-1385.

Lal, R. (2021). *Development of sustainable nutrient management strategies for taro growers on Taveuni Island, Fiji.* (Doctoral dissertation), MASSEY UNIVERSITY, New Zealand.

Lander, T. A., Atta-Boateng, A., Toledo-Hernandez, M., Wood, A., Malhi, Y., Sole, M., . . . Wanger, T. C. (2025). Global chocolate supply is limited by low pollination and high temperatures. *Communications Earth & Environment, 6*(97)

Laven, A., & Hamilton, D. (2016). *Cocoa and Coconut in the Solomon Islands: A Family Affair* (Technical Report). Adelaide, Australia: Department of Foreign Affairs and Trade.

Lee, K. E. (1969). Some soils of the British Solomon Islands Protectorate. *Phil. Trans. Roy. Soc. B, 255*, 211-257.

Leiva-Rojas, E. I., Gutierrez-Brito, E. E., Pardo-Macea, C. J., & Ramirez-Pisco, R. (2019). Comportamiento vegetativo y reproductivo del Cacao (Theobroma Cacao L.) por efecto de la poda. *Rev. Fitotec. Mex., 42*, 137 - 146.

Lever, R. W. A. J. (1968). A checklist of economic insects and mites of crops in the British Solomon Islands. *Technical Document of the Plant Protection Committee, 65*

Lim, K. C., & Rahman, Z. A. (2011). The effects of oil palm empty fruit bunches on oil palm nutrition and yield, and soil chemical properties. *Journal of Oil Palm Research, 14*(2), 1-15.

Ling, A. H., Harding, P. E., & Ranganathan, V. (1990). Phosphorus requirements and management of tea, coffee and cacao. *Phosphorus requirements for sustainable agriculture in Asia and Oceania*, 383-398.

Linton, P. R. (1984). *A guide to growing cocoa in Solomon Islands* (Research Bulletin). Solomon Islands: Dodo Creek Research Station.

Lirag, M. T. B. (2021). Cost and Return Analysis of Small-scale Cacao (Theobroma cacao) Production in Camarines Sur, Philippines. *Journal of Agriculture and Ecology Research International* 1-9.

Lockard, R. G., & Asomaning, J. A. (1964). Mineral Nutrition of Cacao (Theobroma cacao L.) I. Deficiency symptoms and nutrient levels in plants grown in sand culture. *International Journal of Plant Nutrition, Plant Chemistry, Soil Microbiology and Soil-borne Plant Diseases, XXI*(2)

López-Mosquera, M. E., Fernández-Lema, E., Villares, R., Corral, R., Alonso, B., & Blanco, C. (2011). Composting fish waste and seaweed to produce a fertilizer for use in organic agriculture. *Procedia Environmental Sciences, 9*, 113-117.

MAL. (2011). *Ministry of Agriculture and Livestock Corporate Plan 2011-2014*. Honiara, Solomon Islands: Solomon Islands Government. Retrieved from https://solomonislands-data.sprep.org/dataset/ministry-agriculture-and-livestock-annual-reports-and-corporate-plans/resource/f8f2056f-f73c

MAL. (2012). *Solomon Islands Cocoa Industry Policy and Strategies 2012-2020*. Honiara, Solomon Islands: Ministry of Agriculture and Livestock, Solomon Islands Government.

MAL (2019). [Solomon Islands National Cocoa Development Programme].

MAL/SIARTPRESS. (2025). SIART Strengthens Cocoa Farming Skills in Guadalcanal through Training of Trainers Program. Retrieved 18/08/2025 from https://solomons.gov.sb/siart-strengthens-cocoa-farming-skills-in-guadalcanal-through-training-of-trainers-program/

MALPRESS. (2021). MAL trains Chale and Uzamba farmers on cocoa grafting for better production. Retrieved 18/08/2025 from https://solomons.gov.sb/mal-trains-chale-and-uzamba-farmers-on-cocoa-grafting-for-better-production/

MALPRESS. (2024). MAL MINISTER SET TO LAUNCH COCOA SECTOR INTERVENTION STRATEGY: A strategic framework aims to strengthen and enhance the country's cocoa industry amidst current challenges and opportunities. Retrieved from https://solomons.gov.sb/mal-minister-set-to-launch-cocoa-sector-intervention-strategy/

Mamu, M. (2024). Hike in cocoa price delights local farmers. *Solomon Star*. Retrieved from https://www.solomonstarnews.com/hike-in-cocoa-price-delights-local-farmers/

ManaakiWhenua–LandcareResearch. (2019). New Zealand Soils Portal. Retrieved from https://soils.landcareresearch.co.nz/

Mannan, A. (2025). Mastering EC in Hydroponics: Optimal Levels for Each Plant Type Explained. Retrieved 05/06/2025 from https://hydroponicshow.com/ec-for-hydroponics-by-plant-type/

Manso, E. F., Arthur, A., Eduah, J. O., Dogbatse, J. A., Afful, E. A., Yeboah, S., & Padi, F. K. (2025). Comparison of leaf mineral content and soil nutrient status and their combined effect as predictors of cocoa (*Theobroma cacao* L.) bean yield. *West Africa Journal of Applied Ecology, 33*(1), 51-65.

Martin, J. (2000). *Recent developments in Solomon Islands economy*. Paper presented at the Solomon Islands Update: Economics and Governance 16-17th March 2000, Honiara, Solomon Islands.

McAlister, E. (2017). The Secret Life of Flies. Retrieved from https://www.sciencefriday.com/articles/meet-the-flies-that-pollinate-cocoa-trees/

McLaren, R. G. (1996). *Soil Science: sustainable production and environmental protection* (New ed.). Auckland: Oxford Press.

McQuillan, K. (2016). Papua New Guinea cocoa production rising but borer disease a constant threat. Retrieved 05/03/2025 from Available at www.businessadvantagepng.com/papua-new-guinea-cocoa-production-rising-but-borer-disease-a-constant-threat/

Mendoza-Meneses, C. J., Feregrino-Perez, A. A., Guevara-Gonzalez, R. G., & Garcia-Trego, J. F. (2023). Implementation of pre-harvest techniques in emerging agroforestry systems to increase the yield of cocoa tree (Theobroma cacao L.). *Heliyon, 9*(3), 1-8.

MERIDIANCACAO. (2025). Cocoa Beans Varietals. Retrieved 11/04/2025 from https://meridiancacao.com/blogs/news/cocoa-bean-varietals

Minimol, J. S., Shija, T. K., Suma, B., Chithira, P. G., & Shilpa, K. S. (2019). Seasonal variation in yield and yield contributing characters of selected cocoa clones. *Journal of Plantation Crops, 47*(3), 173-179. 10.25081/jpc.2019v47.i3.6053

Miranda, D. (2025). The Impact of High Cocoa Prices on The Chocolate Industry. Retrieved 21/04/2025 from https://www.coffeetradingacademy.com/post/the-impact-of-high-cocoa-prices-on-the-chocolate-industry

Miyaji, K., da Silva, W. S., & Alvim, P. T. (1997). Productivity of leaves of a tropical tree, Theobroma cacao, grown under shading, in relation to leaf age and light conditions within the canopy. *New Phytologist, 137*(3), 463-472. https://www.jstor.org/stable/2559029

MMERE. (2025). *The Geology of North and Central Malaita*. Water & Mineral Resources Ministry of Mines, Energy & Rural Electrification. Honiara, Solomon Islands.

Monteiro, W. R., Lopes, U. V., & Clement, D. (2009). Genetic Improvement in Cocoa. In S. M. Jain & P. M. Priyadarshan (Eds.), *Breeding Plantation Tree Crops: Tropical Species* (pp. 589-626). New York, USA: Springer Science+Business Media.

Mowbray, S. (2025). Aiding natural pollination can boost cacao yields & climate resilience. Retrieved from https://news.mongabay.com/2025/02/aiding-natural-pollination-can-boost-cacao-yields-climate-resilience/

Moyin-Jesu, E. I. (2007). Use of plant residues for improving soil fertility, pod nutrients, root growth and pod weight of okra (*Abelmoschus esculentum* L). *Bioresource Technology, 98*, 2057-2064.

MR.-POPPLE'S-CHOCOLATE. (2024). Unveilling the Cacao Trio: Criollo, Forastero and Trinitario Varieties explained. Retrieved 11/04/2025 from https://mrpoppleschocolate.co.uk/unveiling-the-cacao-trio-criollo-forastero-and-trinitario-varieties-explained/

Mudge, K., Janick, J., Scofield, S., & Goldscmidt, E. E. (2009). A History of Grafting. *Horticultural Reviews, 35*, 437-493.

Mulia, S., McMahon, P. J., Purwantara, A., Purung, H. B., Djufry, F., Lambert, S., . . . Guest, D. I. (2017). Effect of organic and inorganic amendments on productivity of cocoa on a marginal soil in Sulawesi, Indonesia. *Experimental Agriculture, 55*(1), 1-20.

Munsell, A. H. (1905). *Munsell Soil Color Charts*: Munsell Color Company.

Murphy, J., & Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta, 27*, 31–36. https://www.sciencedirect.com/science/article/abs/pii/S0003267000884445?via%3Dihub

Murray, D. (1975) Shade and nutrition. In. *Cocoa*. London: Longman.

Museum, T. B. (2025). Melanesia, an introduction. Retrieved 05/08/2025 from https://smarthistory.org/melanesia-an-introduction/

Mussatto, S. I. (2014). Brewer's spent grain: A valuable feedstock for industrial applications. *Journal of the Science of Food and Agriculture, 94*(7), 1264-1275.

Nair, K. P. P. (2010). *The Agronomy and Economy of Important Tree Crops of the Developing World*.

Nathaniel, M. (2025). Role of phosphorus in plants, symptoms and importance. MarNat StudySpace. Retrieved from https://mnathall.com/role-of-phosphorus-in-plants-symptoms-and-importance/

NCSU. (2015). Seed viability test. Retrieved from https://richmond.ces.ncsu.edu/wp-content/uploads/2015/01/SeedViabilityTest.pdf 1

Ndubuaku, U. M., & Kassim, A. (2003). USE OF ORGANIC AND INORGANIC FERTILIZERS TO IMPROVE THE RATE OF COCOA SEEDLING ESTABLISHMENT IN THE FIELD IN NIGERIA. *Forests, Trees and Livelihoods, 13*, 101-106.

Nelson, P. N., Webb, M. J., Berthelsen, S., Curry, G., Yinil, D., & Fidelis, C. (2011). *Nutritional status of cocoa in Papua New Guinea*. Canbera, Australia: Australian Centre for International Agricultural Research (ACIAR).

Newhook, F. J., & Jackson, G. V. H. (1977). *Phytophthora Palmivora* in cocoa plantation soils in the Solomon Islands. *Tansactions of the British Mycological Society, 69*(1), 31-38.

Nurfy, A., & Junianto, J. (2021). The effects of green waste compost on soil N, P, K, and organic matter fractions in forestry soils. *RSC Advances, 11*(49), 31983–31991.

Obeng-Bio, E., Bediako, K. A., Dadzie, A. M., Ofori, A., Anokye, E., Arthur, A., & Padi, F. K. (2024). Exploitation of ortet - ramet relationship for the development of superior cocoa (*Theobroma cacao* L.) clones. *SPRINGER NATURE Link, 220*(83)

Obeng Adomaa, F., Vellema, S., Slingaerland, M., & Asare, R. (2022). The adoption problesm is a matter of fit: tracing the travel of pruning practices from research to farm in Ghana's Cocoa sector. *Agric. Hum. Values.*

Ocampo-Ariza, C., Müller, S., Yovera, F., Thomas, E., Vansynghel, J., Maas, B., . . . Tscharntke, T. (2025). Cacao grafting increases crop yield without compromising biodiversity. *Journal of Applied Ecology* https://doi.org/10.1111/1365-2664.14851[1](https://phys.org/news/2025-01-grafting-cacao-production-sacrificing-biodiversity.pdf)

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate (USDA Circular No. 939)*: United States Department of Agriculture.

Osama, M. (2025). Study Highlights Hidden Crisis in Cocoa Farming: How Pollination Affects Chocolate Production. Retrieved 23/04/2025 from https://www.azocleantech.com/news.aspx?newsID=35543

Osman, K. T. (2018). Acid Soils and Acid Sulfate Soils. In Management of Soil Problems (pp. 299-332). Australia: Springer Nature. Retrieved from https://link.springer.com/chapter/10.1007/978-3-319-75527-4_11

Paguntalan, D. P., Aggangan, N. S., & Buot Jr., I. E. (2023). The Effect of AMF-Cacao Association on Varying Physiochemical, Nutrient, and Biological Soil Parameters in an Agroforest System. *Philipp Agric Scientist, 106*(4), 400-413.

Paguntalan, D. P., Buot Jr., I. E., & Aggangan, N. S. (2020). Cacao - Arbuscular Mycorrhizal Fungi Association: A Review on Its Increased Potential in Improving the Ecology of Cacao Plantations in the Philippines. *Philippine Journal of Science, 149*(3-a), 903-914.

PHAMA. (2016). *Cocoa and Coconut in the Solomon Islands: A Family Affair*. Australia: Department of Foreign Affairs and Trade. Retrieved from https://phamaplus.com.au/wp-content/uploads/2016/12/PHAMA-TR096-Solomon-Islands-Cocoa-Coconut-161213.pdf

PHAYANAK. (2020). What are the different varieties of cacao? Retrieved 9/05/2020 from https://chocolatephayanak.com/unkategorisiert/what-are-the-different-varieties-of-cacao/

Phillips, J. D. (1992). The source of alluvium in large rivers of the lower coastal plain of North Carolina. *CATENA, 19*(1), 59-75.

Pirhadi, M., Enayatizamir, N., Motamedi, H., & Sorkheh, K. (2018). Impact of soil salinity on diversity and community of sugarcane endphytic plant growth promoting bacteria (Saccharumofficinaruml.var CP48). *Appl Ecol Environ Res, 16*(1), 725-739.

Quaresma, M. A. L., de Souza, H. A., de Oliveira, M. T., & Silva, M. L. (2017). Establishment and performance of legume ground covers under tropical conditions. *Journal of Tropical Agriculture, 58*(2), 123-130.

Quaye, A. K., Doe, E. K., Amon-Armah, F., Arthur, A., Dogbatse, J. A., & Konlan, S. (2021). Predictors of integrated soil fertility management practice among cocoa farmers in Ghana *Journal of Agriculture and Food Research, 5*, 1-8. https://ugspace.ug.edu.gh/server/api/core/bitstreams/8fcd9e6d-d912-405e-a201-53957dd6d224/content

Rahim, I., Jumardin, J., Suherman, S., & Nasruddin, A. (2019). *Biodegradation of Cocoa Pod Husk Waste used Rot Fungi Consortium at Various Storage Times*. Paper presented at the 1st International Conference on Science and Tecnology, ICOST 2019, 2-3 May, Makassae, Indonesia.

Raju, R. N. (2024). A review of the impact of climate change on cocoa production in the pacific islands. *Asia-Pacific Sustainable Development Journal, 31*(1), 77-93.

Rasyidin, M., Arsyad, M., & Rosmana, A. (2024). Factors Influencing Cocoa Farmers' Decision-Making in Choosing Marketing

Channels. *J. Glob. Innov. Agric. Sci., 12*, 1-9.

Rayment, G. E., & Lyons, D. J. (2011a). *Soil Chemical Methods*. Australia: CSIRO.

Rayment, G. E., & Lyons, D. J. (2011b). *Soil chemical methods – Australasia (Method 10D1: Sulfur)*: CSIRO Publishing. https://doi.org/10.1071/9780643101364

Rikolto. (2023). A new generation of cocoa producers in Central America. Retrieved 05/08/2025 from https://www.rikolto.org/projects/new-generation-cocoa-producers-in-central-america

Rowell, D. L. (1994). *Soil Science: Methods and Applications*. University of Reading: Taylor & Francis Group.

RSPO. (2011). Principles and Criteria for Sustainable Palm Oil Production. Retrieved from https://rspo.org/rspo-pc-specific-by-principle/

Samoa-Cocoa-Industry-Development-Initiative. (2019). Koko Bulletin – Issue 5, May 2019: Koko Samoa Industry Strategy 2019 and Beyond. Retrieved from https://agrichain-centre.com/wp-content/uploads/2019/05/koko_bulletin_issue_5_May_2019_web.pdf

Sari, R. R., Rozendaal, D. M. A., Saputra, D. D., Hairiah, K., Roshetko, J. M., & van Noordwijk, M. (2022). Balancing litterfall and decomposition in cacao agroforestry systems. *Plant and Soil, 473*, 251–271. https://doi.org/10.1007/s11104-021-05279-z

Schumacher, B. (2002). Methods for the Determination of Total Organic Carbon (TOC) in Soils and Sediments. *Research Gate*, 1-26.

Sefa, S. I. (2012). *A review of the nature of beef cattle industry in the Solomon Islands with emphasis on Soil Fertility factors influencing pasture production on selected farms*. Palmerston North, New Zealand: Massey University.

Sela, G. (2020). Timing and frequency of fertilizer application. Retrieved 12/06/2020 from https://www.smart-fertilizer.com/articles/timing-fertilizer-application/

Shahbandeh, M. (2025). Monthly cocoa price worldwide from January 2016 to August 2024 (in U.S. dollars per metric ton). Retrieved 221/02/2025, from Statista https://www.statista.com/statistics/498496/global-cocoa-price/

Shamshuddin, J., Anda, M., Fauziah, C. I., & Omar, S. R. S. (2011). Growth of cocoa planted on highly weathered soil as affected by application of basalt and/or compost. *Communications in Soil Science and Plant Analysis, 42*, 2751-2766.

Sharifuddin, H., & Zaharah, A. (1991). *Utilization of organic wastes and natural systems in Malaysian agriculture.* Paper presented at the First International Conference on Kyusel Nature Farming, Washington.

Sharma, L. K., Zaeen, A. A., Bali, S. K., & James, D. D. (2017). Improving Nitrogen and Phosphorus Efficiency for Optimal PLant Growth and Yield. In O. Celik (Ed.), *New Visions in Plant Science*.

SIART-PMU. (2024). *SITE-SPECIFIC ENVIRONMENTAL AND SOCIAL MANAGEMENT PLAN For the Construction of the Ministry of Agriculture and Livestock Office in Auki, Malaita Province*. Honiara: Ministry of Agriculture and Livestock, Solomon Islands Government. Retrieved from https://solomons.gov.sb/wp-content/uploads/2024/03/ESMP-Malaita-Auki-MAL-Office-Finalconsolidated.pdf

SIFLORA. (2025). Flora of Solomon Islands Retrieved 17/03/2025 http://siflora.nmns.edu.tw/specimen/SITW04736-TNM-001/

SIG. (2020). Key success of NFD and SOLTUNA is in their integration. Retrieved 30/03/2023 2023 from https://solomons.gov.sb/key-success-of-nfd-and-soltuna-is-in-their-integration/

SIG. (2023). Trade and export data. Retrieved from https://solomons.gov.sb

SIG. (2024). Minister Wasi pushes to revive cocoa industry. Retrieved from https://solomons.gov.sb/minister-wasi-pushes-to-revive-cocoa-industry/

Siliota, P. (2024). *Solomon Islands Cocoa Production and Exports (Volume & Value) 1960 - 2023*. Honiara, Solomon Islands: CEMA.

SIMS, SPREP, & CSIRO. (2018). *A preliminary case study assessment of climate change impacts and risks for cocoa farming in Guadalcanal Plain, Solomon Islands*. Melbourne, Australia: CSIRO.

SINSO. (2017). *Solomon Islands Demographic and Health Survey 2015*. Honiara, Solomon Islands: Solomon Islands National Statistics Office.

SINSO. (2019). *Report on National Agricultural Survey 2017*. Honiara, Solomon Islands: Solomon Islands National Statistics Office, Ministry of Finance and Treasury and Ministry of Agriculture and Livestock, in Collaboration with the Food and Agriculture Organization of the United Nations and the World Bank.

SKIA. (2019). Toolbox for koko Samoa Coaches: Good Cocoa Practice. In. Samoa.

Snoeck, D., Koko, L., Joffre, J., Bastide, P., & Jagoret, P. (2016). Cacao Nutrition and Fertilization. In E. Lichtfouse (Ed.), Sustainable Agriculture Reviews (Vol. 19, pp. 155-202). Switzerland: Springer International 10.1007/978-3-319-26777-7_4

Snoek, D., Koko, L., Joffre, J., Bastide, P., & Jagoret, P. (2016). Cacao Nutrition and Fertilization. In J. Joffre (Ed.), Sustaibale Agriculture Reviews (Vol. 19, pp. 155-202). Switzerland: Springer International Publishing Switzerland Retrieved from https://www.academia.edu/83500975/Cacao_Nutrition_and_Fertilization

Sodre, G. A., & Gomes, A. R. S. (2019). Cocoa propagation, technologies for production of seedlings. *Revista Brasileira de Fruticultura, 41*(2)

SolBrew. (2023). Our Brewery. Retrieved 31/03/2023 2023 from https://solbrew.com.sb/?fbclid=IwAR3_qnaFrs4aypML5eR4Zf7UhLbnYvGGR_TJr9WB40FVbixLA6iukcjWvh8

Somarriba, E., Peguero, F., Cerda, R., Orozco-Aguilar, L., López-Sampson, A., Leandro-Muñoz, M. E., . . . Sinclair, F. L. (2021). Rehabilitation and renovation of cocoa (Theobroma cacao L.) agroforestry systems. A review. *SPRINGER NATURE Link, 41*(64)

SPC. (2011). *Rapid Assessment of cocoa pre-harvest yield losses to Black Pod*. Secretariat of the Pacific Community (SPC).

Stapley, J. H. (1972). Principal Pests of Crops in the Solomon Islands. *PANS Pests Articles & News Summeries, 18*(2), 192-196. 10.1080/09670877209413989

Taylor, M., McGregor, A., & Dawson, B. (2016). *Vulnerability of Pacific Island agriculture and forestry to climate change*. Rome: FAO.

Thien, S. J. (1979). A flow diagram for teaching texture-by-feel analysis. *Journal of Agronomic Education, 8*, 54-55. https://doi.org/10.2134/jae.1979.0054

Thomas, A. (2011). *Initial RSPO Certification Assessment Guadalcanal Plains Palm Oil Ltd (GPPOL), Honiara, Solomon Islands*. Singapore: BSI Group Singapore Pte Ltd. Retrieved from https://www.bsigroup.com/LocalFiles/en-ID/RSPO%20Public%20Summary%20Reports/2011/IAV%20Guadalcanal%20Public%20Summary%20Report%20050111Amended9.3.11%20Final.pdf

Thomas, G., & Balasimha, D. (1992). Canopy architecture, photosynthesis and yield of cocoa trees. *Café Cacao Thé, 36*, 103-108.

Thong, K. C., & Ng, W. L. (1978). *Growth and nutrient composition of monocrop cocoa plants on inland Malaysian soils.* Paper presented at the International Conference on Cocoa and Coconuts, Kuala Lumpur.

Toledo-Hernandez, M. (2021). Revealling the secret cocoa pollinators. Retrieved 07/02/2022 2022 from https://phys.org/news/2021-05-revealing-secret-cocoa-pollinators.html

Toramo, E., Desai, N., Amosa, F., Diczbalis, Y., & Dillon, N. L. (2019). Assessing morphological characteristics of elite Cocoa accessions (*Theobroma cacao* L.) in Makira Island, Solomon Islands. *Journal of South Pacific Agriculture, 22*, 30-41. https://repository.usp.ac.fj/id/eprint/12368/1/59-303-1-PB.pdf

Tosto, A., Zuidema, P. A., Goudsmit, E., Evers, J. B., & Anten, N. P. R. (2022). The effect of pruning on yield of cocoa trees is mediated by tree size and tree competition. *Scientia Horticulturae, 302*, 111275.

Trading-Economics. (2025). Cocoa. Retrieved 01/04/2025 https://tradingeconomics.com/commodity/cocoa

Trewren, K. (Ed.) (1992). *Research Bulletin No. 2: A guide to growing Cocoa in Solomon Islands*. Dodo Creek Station, Solomon Islands: Ministry of Agriculture and Lands.

Tri-Marine-Group. (2019). *Annual Sustainability Report*. Retrieved from https://trimarinegroup.com/2020/05/14/tri-marine-releases-2019-annual-sustainability-report/

Tropical-Cacao. (2024). How soil quality affects cacao growth and chocolate flavor. Retrieved from https://tropicalcacao.com/how-soil-quality-affects-cacao-growth-and-chocolate-flavor/

Tropical-Cacao. (2025, March 2). The ultimate guide to cacao farming: From seed to chocolate. Retrieved 01/04/2025 2025 from https://tropicalcacao.com/the-ultimate-guide-to-cacao-farming-from-seed-to-chocolate-2/

Trustrum, N., Whitehouse, I. E., & Blaschke, P. (1989). *Flood and landslide hazard northern Guadalcanal, Solomon Islands*. Palmerston North, New Zealand: Department of Scientific and Industrial Research.

Tsatsia, H., & Jackson, G. (2017a). Pacific Pests and Pathogens - Fact Sheets. In A. C. f. I. A. Research (Ed.), *University of Queensland and Secretariat of the Pacific Community*. ACIAR, Australia: PestNet.

Tsatsia, H., & Jackson, G. (2017b). Strengthening integrated crop management research in the Pacific Islands in support of sustainable intensification of high-value crop production. In A. C. f. I. A. Research (Ed.), *University of Queensland and the Secretariat of the Pacific Community*. ACIAR, Australia: Pestnet.

Uma, D., Gopal, N. O., Balakrishnan, S., Shoba, N., & Uchoi, A. (2018). Effect of different pruning levels and growth retardants on growth, yield and quality of cocoa (Theobroma cacao L.). *Journal of Pharmacognosy and Phytochemistry, 7*(4), 3354-3357.

Umaharan, P. (Ed.) (2018). *Achieving sustainable cultivation of cocoa*. Cambridge, UK: Burleigh Dodds Science Publishing Limited.

Uribe, A., Méndez, H., & Mantilla, J. (2001). Effect of balanced fertilization on cocoa yield. *Better Crops International, 15*(2), 3-5. https://cadenacacaoca.info/CDOC-Deployment/documentos/Effect_of_Balanced_Fertilization_on_cocoa_yield.pd

Urquhart, D. H. (1951). *Prospects of the growing of cacao in the British Solomon Islands, with notes on Malaya, Ceylon, and Java*. Bournville: Cadbyry Brothers Ltd.

USDA-NRCS. (2014). Soil Electrical Conductivity. In *Soil Health - Guides for Educators*. USA: Natural Resources Conservation Service.

Utomo, B., Prawoto, A. A., Bonnet, S., Bangviwat, A., & Gheewala, S. H. (2016). Environmental performance of cocoa production from monoculture and agroforestry systems in Indonesia. *Journal of Cleaner Production, 134*, 583-591.

Vadnjal, D., & Pelomo, M. (2014). *Solomon Islands Cocoa Value Chain Analysis*. Honiara, Solomon Islands: World Bank.

Valle, R. R., De Almeida, A. A. F., & Leite, R. M. D. O. (1990). Energy cost of flowering, fruiting, and cherelle wilt in Cacao. *Tree Physiol., 6*, 329-336.

van Vliet, J. A., & Giller, K. E. (2017). Mineral Nutrition of Cocoa: A Review. In Advances in Agronomy (Vol. 141, pp. 185-270). Wageningen, Netherlands: Elsevier Inc. Retrieved from https://www.sciencedirect.com/science/article/pii/S0065211316301237?via%3Dihub

van Vliet, J. A., Slingerland, M., & Giller, K. E. (2015). *Mineral Nutrition of Cocoa: A Review* (Report). Netherlands: Plant Production Systems Group, Wageningen University.

Voora, V., Bermudez, S., & Larrea, C. (2019). *Gloabal Market Report: Cocoa*. Canada: International Institute for Sustainable Development.

Wall, J. R. D., & Hansell, J. R. F. (1973). Soils of some Quaternary marine terraces in the British Solomon Islands Protectorate and some problems in their agricultural use. *New Zealand Journal of Agricultural Research, 16*(2), 271-286.

Wall, J. R. D., & Hansell, J. R. F. (1974). *The Bristish Solomon Islands Protectorate: Guadalcanal and the Florida Islands; Malaita and Ulawa (Land Resource Study 18)*. England Land Resources Division, Ministry of Overseas Development

Wall, J. R. D., Hansell, J. R. F., Catt, J. A., Ormerod, E. C., Varley, J. A., & Webb, I. S. (1979). The Soils of the Solomon Islands. *Land Resources Development Centre, 1*(4), 1-145.

Wall, J. R. D., Hansell, J. R. F., Catt, J. A., Ormerod, E. C., Varley, J. A., & Webb, I. S. (1979). *The soils of the Solomon Islands Volume 1*. England: Land Resources Development Centre, Ministry of Overseas Development.

Weinstein, M., Baram, S., Yermiyahu, U., Lieberman-Lazarovich, M., Tsehansky, L., Elmakias, A., . . . Graber, E. R. (2024). Nitrogen, phosphorus and potassium nutrition effects on flowering and reproduction in an F1 segregating population of the Theobroma cacao L. CCN-51 cultivar. *Scientia Horticulturae, 337* https://www.sciencedirect.com/science/article/pii/S0304423824007453?via%3Dihub

Weinstein, M., Baram, S., Yermiyahu, U., Tsehansky, L., Elmakias, A., & Graber, E. R. (2025). Nitrogen, Phosphorus and Potassium Deficiencies Impact the Transition from Juvenility to Maturity in Theobroma cacao L. *International Journal of Fruit Science, 25*(1), 36-47.

Wendling, M., Buchi, L., Ampsse, C., Sinaj, S., Walter, A., & Charles, R. (2016). Influence of root and leaf traits on the update of nutrients in cover crops. *SPRINGER LINK, 409*, 419-434.

Wessel, M. (1985). Shade and nutrition. In G. A. R. Wood & R. A. Lass (Eds.), (pp. 166-194). Harlow, United Kingdom.

Wessel, M., & Quist-Wessel, P. M. F. (2015). Cocoa production in West Africa, a review and analysis of recent developments. *NJAS-Wageningen Journal of Life Sciences, 74-75*, 1-7. https://www.tandfonline.com/doi/full/10.1016/j.njas.2015.09.001

Wong, C. C., Sharudin, M. A. M., & Rahim, H. (1985). Shade tolerance potential of some tropical forages for integration with plantations 2. Legumes. *MARDI Res. Bulletin, 12*(3), 249-269.

Wood, G. A. R. (Ed.) (1985). *Cocoa* (Fourth ed.). United Kingdom: Longman Group UK Limited.

Wood, G. A. R., & Lass, R. A. (Eds.). (2001). *Cocoa* (4th Edition ed.). Oxford, New York: Blackwell Science. https://onlinelibrary-wiley-com.ezproxy.massey.ac.nz/doi/pdfdirect/10.1002/9780470698983

World-Bank. (2020). *Household Agriculture, Fishing, Food Security and Vulnerability in Solomon Islands: Further Analysis of the National Agricultural Survey 2017*. World Bank Group. https://documents1.worldbank.org/curated/en/760351624439767823/pdf/Household-Agriculture-Fishing-Food-Security-and-Vulnerability-in-Solomon-Islands-Further-Analysis-of-the-National-Agricultural-Survey-2017.pdf

Xiao-yan, L., Ping, H., & Ji-yun, J. (2006). Advances in effect of potassium nutrition on plant disease resistance and its mechanism. *Journal of Plant Nutrition and Fertilizers, 12*(3), 445-450.

YARA. (2025). Soils, liming and salinity in cocoa production. Retrieved 05/06/2025 from https://www.yara.my/crop-nutrition/cocoa/soils-liming-and-salinity-in-cocoa-production/

Young, A. (1976). *Tropical soils and soil survey*. New York Cambridge University Press.

Appendices

Appendix I: Grower survey 1 Questionnaire

Part A: Background information

1. Name (optional): ……………………………………………………………………
2. Farm location
    a. Farm code: …………………………………………………………………
    b. Province: ……………………………………………………………………
    c. GPS Coordinates: ………………………………………………………….
3. Is the land used on rental or not?
    a. Yes (Go to question 4)
    b. No (Please select and go to Question 5)
        i. Freehold
        ii. Communal owner/guardian
        iii. Share farming
4. Type of lease (Select and go to Question 5)
    a. Native lease
    b. Crown lease
    c. Communal lease
5. Number of years involved in cacao farming: …….

Part B: Farm characteristics

6. Select cropping system and total farm area (Hectares)

Please tick cropping system used		Please select spacing used		Total Farm Area (Ha)
Only cacao		a. 3 m x 3 m		
Cacao under coconut		b. 3.5 m x 3.5 m		
Other __________________		c. Other ……………………………		

7. What cacao varieties and tree ages are grown on the farm?

Variety	Age	Area (Ha)	Area (Ha) harvested per year	Number of harvested per year	Amount (kg) harvested (wet) per year
Forastero					
Criollo					
Trinitario					
Amelonado					

8. Main activities carried out for the farm

Please, tick activities carried out in the farm			
1.Land preparation		7.Buying wet beans	
2.Planting		8.Fermenting	
3.Maintenance		9.Processing	
4.Applying inputs		10.Selling dry beans	
5.Harvesting		11.Farm modelling	
6.Selling wet been		12.Other ________	

9. What is the topography of the farm? (Please select)
   a. Flat (0-7°) Area: ………
   b. Rolling (8 – 15°) Area: …….
   c. Easy hill (16 – 25°) Area: …….
   d. Steep hill (> 25°) Area: …….

Part C: Farm management Practices

Pest management

10. Are there any pests present in the farm? YES/NO ……………………… (If NO, go to Question 6 b)
    e. Select the pest(s)

Pests	Please tick	Damage Type	Damage state				Frequency of damage per year	Time of the year
			Low	Moderate	Extensive	Complete		
Wood borers								
Pod borers								
Termites								
Longicorn								
Amblipelta								
Other _______								

    f. Select control method(s)

Control method	Please tick	Specific method/Chemicals	Application rate	Time of application
Zero management				
Phyto sanitation				
Chemical				
Biological				
Other (specify) _______________				

Disease management

11. Are there any diseases present in the farm? YES/NO …………………… (If NO, go to Question 7b)
    g. Select the disease present

Disease	Please tick	Damage Type	Damage state				Frequency of damage per year	Time of the year
			Low	Moderate	Extensive	Complete		
Black pod								
Canker								
Root rot								
Thread blight								
Pink disease								
Other__________								

    h. Select the control methods

Control method	Please tick	Specific method/Chemicals	Application rate	Time of application
Zero management				
Phyto-sanitation				
Chemical				
Biological				
Other (specify)				

Weed management

12. Select weed control methods used in the farm

Weed control method	Please tick	Specific	Application duration	Frequency per year	Time of the year
Hand weeding					
Slash & mulch					
Slash & burn					
Chemical					
Other (specify)					

Pruning and shade management

13. Select pruning and shade management practices applied in the farm

Practice	Select	Frequency per year
a. Shade control		
b. Cross branch removal		
c. Infected branch removal		
d. Growth control		
e. Other (Specify) ______________________		

Fertiliser use and nutrient management practices

14. Select fertiliser type used on the farm

A. Inorganic fertiliser	Select	Application rate and timing (kg/ha/application; month of application)	Method and location of application (i.e. distance from trunk)	Amount of fertiliser applied annually (kg/ha/year) and how many year has this been applied
i. Triple superphosphate				
ii. Muriate of Potash				
iii. Urea				
iv. Other _______________				
B. Organic fertiliser	Select			
i. Farm residues				
ii. Outside farm residues				
iii. Other organic residues				

C. How do you decide what type and how much fertiliser to use?

………

D. Are you an organic producer? ……. (If YES go to Question 10E)

E. Do you have organic certification? ……… (YES/NO)

15. Chemical tests conducted on farm. YES/NO …………………………. (If NO, go to PART D)

Soil Analysis	Select	Test Results	Frequency	How many cores of samples
Soil pH				
Bray I, Bray II, Olsen P, P retention				
Total N, Available N				
Exchangeable K, Ca, Mg and Na				
Sulphates				
Other ____________________				
Foliar tests				
Total N				
Total C				
Total S				
Na, K, Ca, Mg				
P				
Other ____________________				

Part D: Extension Support

16. Are there any agricultural services received? YES/NO ……………………

a. Type of assistance	Select	Select type of assistance received and go to Question 12b to select improvement programme and mention practices involved, and changes occurred		
Advisory services				
Training/Demonstration				
Tools/Materials				
Funds				
Other ____________________				
b. Improvement programme	Select	Practice(s)	Mention one/two improvement(s)	Years with programme
Amelonado hybrid cocoa subsidy scheme				
Foreign Investors and Church Missions				
SIG Cocoa Development Program				
PHAMA Program				
ACIAR Support				
Cocoa Livelihoods Improvement Program				
Rural Development				
PAR and IPDM				
Commodity Export Marketing Authority				
Private Sector				
Other				

THE END, THANK YOU!

Appendix II: Organic Byproducts Identification questionnaire

Background Information					
Name		Type of production			Years in production
Organization		(1)	(2)	(3)	
Individuals		(1)	(2)	(3)	
Address					

Byproducts Information																
List byproducts produced	Estimated volume (m^3) produced and available month/ year												Disposal method			
	J	F	M	A	M	J	J	A	S	O	N	D	Landfill	Burn	Sell (SBD$/m^3)	Other
(1)																
(2)																
(3)																
(4)																

Byproduct	**Delivery cost**		**Moisture content (%)**	**Chemical analysis/Nutrient content (Dry weight_____/Wet weight_____**									
	Free (Tonnage)	Hire (SBD$/ton)		Yes	No	N %	P %	K %	Ca %	Mg %	S %	B mg/kg	Others
1													
2													
3													
4													

Appendix III: Grower Survey 2

i) Cacao maintenance and improvement questionnaire

Part A: Background information

1. Name (optional): ……………………………………………..
2. Farm location
    a. Farm code: …………………………………………...
    b. Province: …………………………………………….
    c. GPS Coordinates: ………………………………………

Part B: Farm characteristics

3. Cacao varieties, establishment, re-working and yield

a. Cacao varieties and area			
i. Variety		ii. Area (ha) or number of trees and year of establishment	iii. Area and year of reworking
Forastero (A)			
Criollo (B)			
Trinitario (C)			
Amelonado (D)			
Total area (ha)			
No. of harvests (June 2021-May 2022)			
Typical wet bean yield per harvest			
Annual wet bean yield (kg) (June 2021-May 2022)			

Part C: Farm management practices

4. Pruning, and pests and diseases management practices

Please tick farm management practices and seasons implemented during past 10 years from 2020														
1. Tree management		J	F	M	A	M	J	J	A	S	O	N	D	State specific time of activity (Before, During or After harvests?)
a. No pruning														
b. Normal pruning														
i. Shade control														
ii. Cross branch removal														
iii. Growth control														
c. Intensive pruning														
2. Pests and diseases management														
a. Phyto-sanitation (removal of infected plant or plant part)														
b. Other (Other forms of methods to control pests/diseases)														

5. Constraints to pruning practices

1. What are the key constraints to practicing pruning and how do you respond to them?	
i. Key issue(s)/problem(s)	ii. Response(s)

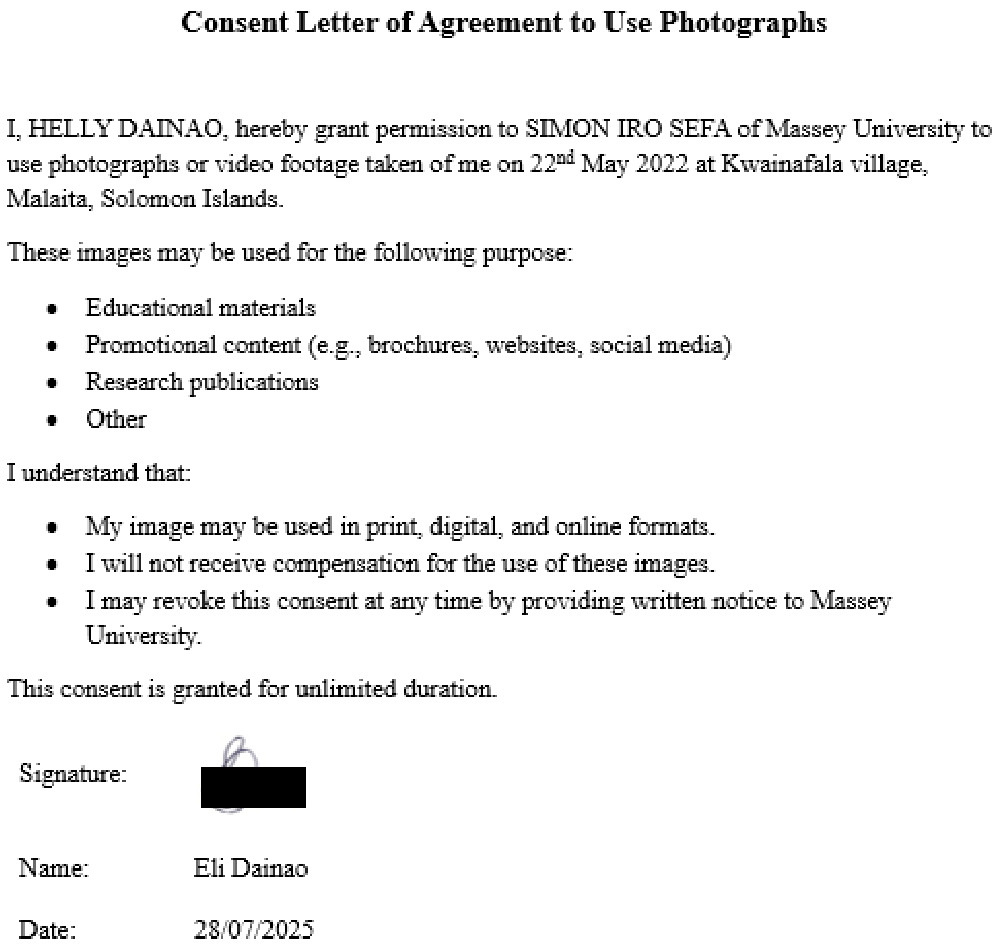
6. Plantation farm objectives

a. Please tick YES or NO if you have a strategy or policy in place for replanting or reworking (bud-grafting) of the plantation trees?		b. If YES, after how many years or at what age are you planning to do;	
Yes, I have a policy in place for replanting or reworking cacao trees		Replanting	Reworking
No, I do not have a policy for replanting or reworking my cacao trees			
c. Please tick constraints to why not doing reworking or replanting?		d. Please, state reason(s) for the constraint(s)	
i. I do not have the resources (recommended plant materials and/or tools)			
ii. I do not have knowledge and skills to do it			
iii. I have earned low income on this crop to support my livelihood			
iv. It demands time, money and labour			
v. I have changed my plan to do other things to get good income			
vi. Challenges on flooding or erosion or salt intrusion due to farm location			
vii. There are unresolved social issues (land disputes, theft, etc.)			
viii. Other ____			

ii) Harvest record sheet: May 2022 – April 2023

Month	Date of harvest	Amount (kg) of wet beans harvested		
		Good	Bad	Total
May				
June				
July				
August				
September				
October				
November				
December				
January				
February				
March				
April				

iii) Agreements



Consent Letter of Agreement to Use Photographs

I, HELLY DAINAO, hereby grant permission to SIMON IRO SEFA of Massey University to use photographs or video footage taken of me on 22nd May 2022 at Kwainafala village, Malaita, Solomon Islands.

These images may be used for the following purpose:

- Educational materials
- Promotional content (e.g., brochures, websites, social media)
- Research publications
- Other

I understand that:

- My image may be used in print, digital, and online formats.
- I will not receive compensation for the use of these images.
- I may revoke this consent at any time by providing written notice to Massey University.

This consent is granted for unlimited duration.

Signature: [redacted]

Name: Eli Dainao

Date: 28/07/2025

Consent Letter of Agreement to Use Photographs

I, ROBERT WAISU, hereby grant permission to SIMON IRO SEFA of Massey University to use photographs or video footage taken of me on 12th August 2022 at Niukapu village, Guadalcanal, Solomon Islands.

These images may be used for the following purpose:

- Educational materials
- Promotional content (e.g., brochures, websites, social media)
- Research publications
- Other

I understand that:

- My image may be used in print, digital, and online formats.
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Signature: [redacted]

Name: Robert Waisu

Date: 28/07/2025

Consent Letter of Agreement to Use of Photographs

I, DEBORAH IRO, hereby grant permission to SIMON IRO SEFA of Massey University, to use photographs or video footage taken of me on 31st May 2024 at the Soil Science Laboratory, Massey University, Palmerston North, New Zealand.

These images may be used for the following purposes:

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- My image may be used in print, digital, and online formats
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Signature: [redacted]

Name: Deborah Iro

Date: 01/09/2025