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Contents

1 Acknowledgments

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2 Executive summary

The Cambodian Upland Soils Project (CUSP) aimed to improve soil management in selected upland farming systems of southwest and southeast Cambodia to increase yields and returns for diverse crop options. In this study, soil and land management comprises characterisation of soil resources, identification of soil constraints to crop production and integrated site specific soil management to improve profitability and to control land degradation. The project was led by Murdoch University (MU) in partnership with the Cambodian Agriculture Research and Development Institute (CARDI), the Royal University of Agriculture (RUA) in Cambodia and the Department of Primary Industry and Regional Development, Western Australia (DPIRD).

Between 2018 and 2022 the project's key achievements included:

⇒ Introduction of new methodologies for soil and land suitability assessment and identification of main soil types and landscape patterns in representative upland regions

- Soil surveys of two districts which identified four new upland soils not described previously.
- Establishment of a Cambodian Soils Practitioners Stakeholder Group enabling coordination and knowledge sharing relating to soil survey, soil information management and method harmonisation.
- Development of a geographic framework of Cambodia for interpreting soil distribution in a landscape context. This spatial framework separates Cambodia into zones for soil landscape interpretation.
- Development of Land Use and Land Cover Change Analysis (LULCC) framework for upland study areas. This work placed emphasis on soil organic carbon under different land use.
- Development and calibration of Rapid Soil Analysis (Mid-infrared spectrometer, MIR and Ion selective electrode, ISE) techniques for CARDI laboratory enhancing capacity for soil chemical and physical analysis.

⇒ Identification of the soil and land constraints to crop production and soil management technologies for the upland regions

- Demonstrated crop response to P and K fertiliser additions compared to nil-fertiliser by farmer practice using satellite trials. Farmer-surveys revealed potential socio-economic and knowledge barriers to adoption.
- Development of a diagnostic tool for land suitability analysis of soil types.
- Application of field trials and pot trials that identified the variability of response of crops and soils in the study region to amendments of fertiliser for nutrient improvement, or lime for managing low pH conditions.

⇒ Introduction of tools and information that enable stakeholders to identify the main soil types, and their constraints to crop production

- Development of soil profile and soil classification tools and capacity. Codes books and datasheets developed for the Food and Agriculture Organization of the United Nations (FAO) standards and the World Reference Base (WRB) classification system. Capacity building of stakeholders through workshops and on the job training for stakeholders involved in soil survey activities.

- Translation of the Soil Constraints and Land Management Practices (SCAMP)[1] booklet into Khmer. Workshop for training stakeholders in the method of in-field soil observation and analysis to identify soil constraints.
- Soil and landscape reports for study regions which describe types, distribution, and chemical and physical characteristics.

⇒ Engagement with farmer groups to better understand farmer knowledge and perspectives of soil and soils constraints to crop production in upland regions

- Insight into farmers' perspective and understanding of soil type, soil related constraints, suitability of crop selection, soil management practices.
- Knowledge of soil fertility and fertiliser use for the study regions.
- Improved farmer knowledge of fertiliser use, agronomic crop management and profitability.

The key achievements of the project provide a foundation for further research and extension activities in the context of soil and crop management, availability of soil information, knowledge and capacity of stakeholder groups and monitoring and managing soil and land degradation.

[1] *Moody, P.W. and Phan Thi Cong (2008). Soil constraints and management package (SCAMP): guidelines for sustainable management of tropical upland soils. ACIAR Monograph No. 130, 86 pp.*

3 Background

Currently in Cambodia approximately 27 % of the 3 million ha of uplands are utilised by smallholder farmers, providing food security and improved livelihoods. High agricultural prices have been powerful drivers for agricultural growth and farmland expansion in recent decades on upland areas of Cambodia, rather than increases to crop productivity. However, the Royal Government of Cambodia (RGC) has recognised that continued expansion of cultivation into unused or degraded land is not environmentally sustainable and has prioritised intensification, improved yields and diversification of cropping in areas where upland farming is under development. In these rainfed uplands, crop yields and profits are vulnerable to low soil fertility, drought conditions and fluctuating markets. Smallholder farmers in extensive areas of the upland regions of Cambodia are hampered by poor crop production and unreliable yields. For improvement to crop yields, the smallholder farmers in these areas require cost effective soil and land management technologies to overcome nutrient deficiencies, low water storage, soil acidity and erosion risk, and these technologies need to be targeted to specified soil and landscape types.

Smallholder farmers typically operate under traditional farming systems with limited knowledge of soil constraints, crop management technologies, and are particularly vulnerable to crop failure and land degradation. There are significant yield gaps for upland crops (maize, peanut, mungbean, soybean, sesame) between farmers' practice and improved agronomic practices (Martin and Belfield 2007; Belfield and Brown 2009; Belfield et al., 2011; Sopheap et al., 2012a). Improving soil management to increase crop yields and returns for diverse crop options is a critical input to the development of resilient profitable and sustainable upland farming systems in Cambodia.

Low soil fertility is an inherent problem of Cambodian soils, with the majority of soils affected by N, P and K deficiency (Blair and Blair 2014). The nutrient content declines rapidly with continuous cropping, and is exacerbated by inadequate nutrient additions and inappropriate agronomic management that cause erosion, loss of organic matter and declining soil health, low soil water storage, and soil acidity (Bell and Seng 2005; Seng et al., 2005). In addition to soil nutrient deficiencies and acidity other constraints to crop production include hardsetting at sowing limiting crop emergence (Bell and Seng 2005; Seng et al., 2005; Hin et al., 2010).

At the projects inception there was minimal soil survey information available for upland areas reported other than the soil surveys conducted for five districts as part of ACIAR project SMCN/2001/051[2] (Bell et al., 2008)[3]. These surveys targeted upland areas with contrasting parent material. From this work it was recognised that the Cambodian Agronomic Soil Classification (CASC) (White et al., 1997), which was developed for the lowland – rice producing areas of Cambodia, does not allow identification of many soils in upland areas. One new Soil Group (Ou Reang Ov soil group) and one new phase of a Soil Group (Kompong Siem soil group, calcareous phase) were identified (Seng et al., 2007; Bell et al., 2008), but a key gap identified by ACIAR project SMCN/2001/051 (Bell et al., 2008) was the need for more extensive soil survey in the upland areas targeting different parent materials to identify a greater diversity of soil groups and identifying new CASC soil groups with distinctly different physical and/or chemical properties than previously identified soil groups and different constraints to crop production (Seng et al., 2007).

Similarly, at project inception there was a lack of land suitability assessment for the upland areas. While a methodology was developed by ACIAR project SMCN/2001/051 (Bell et al., 2008), land suitability assessment had only been completed by Cambodian Agricultural Research and

[2] *ACIAR project SMCN/2001/051 Assessing land suitability for crop diversification in Cambodia and Australia*

[3] *It should be noted that since the inception of CUSP the coverage of soil survey has been extended by General Directorate of Agriculture Department of Agricultural Land Resources Management (GDA-DALRM) considerably.*

Development Institute (CARDI) on three districts (Takeo District in Tram Kak Province, Ou Reang Ov District in Kampong Cham Province, Banan District in Battambang Province) (Vance et al., 2013) with few other reports (e.g., assessment of districts on the border of Thailand (RGC 2010) and a methodology paper by Mund and van Engelen (2005)).

The gaps in soil survey and land suitability assessment provided the rationale for the Cambodian Upland Soils Project (CUSP), including that: soils in the upland areas of Cambodia are not well described, constraints to crop production on specific soil types are not adequately determined and land suitability of soil types for crop production is not defined. Generalised advice on crop selection and management is not sufficient for smallholders or extensionists. Therefore, to increase crop productivity and minimise land degradation in the upland regions CUSP sought to describe and map key soils, identify soil-specific limiting factors to crop production and develop and promote cost-effective management techniques to overcome constraints identified.

The constraints to profitable field crop production in upland areas vary among landscape types and among soil types. Hence, there was a need to develop site specific soil and land management technologies in order to promote sustainable and profitable farm businesses in the uplands, and to minimise the risk of production losses and soil degradation. In addition, characterising and mapping constraints and determining land suitability was required as a critical enabling technology for improved field crop production in upland areas. For example, while fertiliser requirements for rice have been developed for each of the main lowland soils, such information is lacking for crops on upland soils of Cambodia. Further, increased capacity (including knowledge, expertise, resources and tools) of smallholder farmers, extension practitioners, researchers and policy-makers was required to identify and manage upland soils and facilitate better decision-making regarding crop selection and site specific land management practices. The longer term spin-offs of the research were expected to include: crop diversification and increases in productivity contributing to poverty reduction and improved livelihoods; policy development for sustainable land use; and, gaps identified for further research into soils in the upland regions.

The research strategy of the project was based on four approaches:

1. Identifying soil-landscape patterns in upland areas of Cambodia;
2. Investigating suitable methodologies to identify soil physical and chemical properties that will aid in identification of soil groups as well as soil constraints to crop production;
3. Developing an integrated site specific soil management approach to optimise production of field crops in upland areas (“crop” may include forages, depending on interests in the focus villages), and;
4. Developing the capacity of stakeholders to complete soil surveys and analysis (simple and/or rapid), interpret site specific factors limiting crop production, develop soil management technologies and implement appropriate soil management practices for specific soils.

4 Objectives

The project aimed to improve soil management in selected upland farming systems of southwest and southeast Cambodia to increase yields and returns for diverse crop options.

In this study, soil and land management comprised characterisation of soil resources, identification of soil constraints to crop production and integrated site specific soil management to improve profitability and to mitigate or prevent land degradation.

The researchable issues identified follow a logic of understanding soil and landscape resources, their limitations and how to address them.

1. What are the soil and land constraints to crop production in selected upland regions of southwest and southeast Cambodia?
2. How can more appropriate soil management technologies be adopted and adapted by farmers to alleviate site specific soil constraints (including nutrients) to crop production in upland regions?
3. Which approaches (e.g. tools, resources, communication materials) are most effective to identify soil types, landscapes and constraints to crop production in upland regions for different users?
4. How can emerging technologies, such as rapid soil assessment and digital soil mapping techniques, be used to identify new soil and landscape patterns and soil constraints to crop production in upland regions of Cambodia?

The project objectives were to:

1. Introduce new methodologies for soil and land suitability assessment and identify main soil types and landscape patterns in representative upland regions.
2. Characterise the soil and land constraints to crop production and identify soil management technologies for these regions.
3. Provide tools and information that enable stakeholders to identify the main soil types, and their constraints to crop production and select suitable soil management technologies.
4. Expand the knowledge base of soil resources and capability for soil resource management in Cambodia.

5 Methodology

Objective 1: Introduce new methodologies for soil survey and land suitability assessment and identify main soil types and landscape patterns in upland regions of Cambodia.

Activity 1.1 Review literature and available data for soil and landscape information for the uplands of Cambodia.

Within Cambodia several organisations complete soil and landscape analysis. This activity aimed to determine who collected soil survey information, where it was stored and if it could be added to the soil profile database of Activity 1.4. Initial compilation of information was through web-sources, meetings with stakeholders and literature searches. Whilst the organisations directly collecting information did not provide the data to the CUSP team, they did inform the team as to the areas surveyed, methodologies used and the progress of projects.

Activity 1.2 Determine the spatial extent of the key upland soils and their key properties and identify areas that have the potential for new upland soils.

Soil Survey Strategy

Aoral District, Kampong Speu Province and Dambae District, Tboung Khmum Province were selected for year 1 soil survey activities. These districts represent different soils and landscapes characteristic of upland areas in southwest and southeast Cambodia. A strategy for soil survey site selection in the two districts was produced incorporating the most useful imagery and GIS datasets to distinguish potential soil-landscape units at the district level. These were identified as geology, digital elevation model (DEM) derivatives of slope and multi-resolution valley bottom flatness (MrVBF).

The priorities for soil survey and land suitability assessment in Cambodia include the development of a National Soils Map for the whole country, development of agricultural zoning and land suitability and crop zoning. The project identified that the completion of a physiographic zone map of Cambodia may assist to define areas and tested two methods of automating definition of physiographic zones in Cambodia.

Physiographic Map of Cambodia

Consultation meetings between physiographic modellers and soil survey experts between November 2021 and Feb 2022 identified methods most likely to result in a reliable and simple physiographic map of Cambodia. Geology, climate derivatives, topography are key datasets.

The method was developed to create a simple physiographic map of Cambodia. The main purpose of the activity was to partition Cambodia into broad zones with similar landscapes and soil characteristics relevant for developing agricultural soil management extension materials for use at a district or province level. The major landscape patterns indicative of soil variation across Cambodia were grouped into Systems and Zones. The approach used was to apply unsupervised classification to remote sensing datasets to define geographic regions and interpret their physical characteristics by province, with a particular focus on Kampong Speu and Tboung Khmum Provinces as case studies. This geographic stratification of Cambodia will be a framework for future development of soil management manuals for local agricultural extension. Data inputs to the model included satellite imagery and modelled raster (gridded) datasets available for Cambodia that represent major environmental processes driving landscape and soil patterns. These include the major soil forming factors: climate, organisms, relief, parent material, and time. The full method used for the final maps of Agricultural Land Management Zones and Systems (subdivisions of Zones) for Cambodia, are available in CUSP report “Defining agricultural land management zones in Cambodia from remote sensing imagery” (Attachment 1).

Land Use and Land Cover Analysis

The Regional Planning Faculty of Royal University of Agriculture (RUA) completed studies to identify land cover change in Aoral District and Dambae District. The projects were completed by RUA students under the supervision of Regional Planning Faculty academic staff. Two Bachelor of Science students completed their final thesis component in 2018 and one Masters student completed their thesis from 2021 to 2023. Within each district a commune was selected for survey using drone techniques, after which the students completed supervised classification of Landsat 8 image.

Activity 1.3 Complete soil survey and landscape analysis of 2 districts targeted through the desktop study (Activity 1.2).

Aoral District, Kampong Speu Province and Dambae District, Tboung Khmum Province were selected for initial soil survey activities. These districts were selected to provide a link between the locations surveyed in SMCN/2001/051 and new locations through geology, soil fertility class and potential to have new soil groups or phases. The district surveys comprised of 3 phases, 1) Reconnaissance survey, 2) Full survey following site selection from spatial analysis (Activity 1.2), 3) Second survey filling in gaps after first draft of soil and landscape mapping of the district if required. A field based sampling strategy was completed for Aoral and Dambae Districts. Using the data layers from Activity 1.2, a sampling strategy was developed using conditional latin hypercube sampling, based on distribution of geology units, slope percent (in areas < 20 % slope), and landform position. Gower's index was applied to the input datasets to show similarity of the cells surrounding each location selected for sampling. This provided guidance to find a new location nearby, if the site was not able to be sampled. The sampling strategy developed was based on sample number and pragmatic constraints; 40 sample sites per district, restricted to within 500 m of road network. In cases where land tenure was not clear, sites may not have been visited, so additional sample sites were selected to cover soil – landscape units during the survey activity.

Guided by the sampling strategy, a free survey method described by McKenzie et al. (2008) was conducted across Aoral and Dambae districts. Detailed soil profile descriptions were completed, and horizons sampled, in areas of the landscape which were deemed to represent the different soil-landscape units. Further less detailed soil observations and landscape and surficial observations were made in the districts. Types and numbers of soil profile observations can be found in Section 7 and in the soil and landscape reports for each district.

Soil-landscape maps of Aoral and Dambae Districts were completed by combining the soil survey information (detailed pits and observations), a digital elevation model, Google earth and Bing aerial images and expert knowledge to create land unit maps. QGIS software was used to combine these data layers. Polygons of the new soil-landscape map units were digitised. The soil-landscape map was ground-truthed where possible by further observation of the soil-landscapes in the district to determine if the observed soil types were predicted in the soil-landscape map. The soil-landscape map was modified as required.

Soil classification was completed for detailed profile descriptions using Food and Agriculture Organization of the United Nations (FAO) descriptors (FAO 2006) and where possible classified to at least Reference Soil Group level in the World Reference Base (WRB) (IUSS 2022). Where applicable the CASC soil name was determined. Most soils in the district however fall outside the range of the CASC. Data from all soil profile observations have been recorded in the Cambodian Soil Database (CSD). Soil survey was completed by CARDI staff with Murdoch University (MU) or Department of Primary Industry and Regional Development (DPIRD) leads which provided on-the-job training in soil survey and soil classification using the FAO WRB.

Samples from whole horizons were dried and sieved to exclude coarse fragments and hard

segregations >2 mm, with the proportions of fine fraction (<2mm) and coarse fraction being recorded by weight percentage. Samples from fixed-depth intervals were dried, ground, and sieved to <2 mm. All samples were sub-sampled. These sub-samples were further ground to < 0.2 mm for analyses at CARDI using Mid-infrared (MIR) spectroscopy commissioned for this project. A selection of both sample types (<2 mm) were delivered to CSBP laboratory in Western Australia and analysed for various parameters as described by Rayment and Lyons (2010). Any remaining sample was stored at CARDI.
Tests included:

- Particle Size (Wet Chemistry Method – Indorante et al., 1990)
- pH in 1:5 water (4A1), pH in 1:5 0.01M $CaCl_2$ (4B1), EC in 1:5 water (3A1)
- Organic Carbon - Heanes (6B1)
- Phosphorus (Olsen) (9C)
- Aluminium ($CaCl_2$) (Bromfield 1987)
- Exchangeable cations for acidic soils (NH_4Cl) (15A1) or for alkaline soils (15C1)
- Exchangeable Acidity/Aluminium (15G1)
- Phosphorus Buffering Index (9I3c)
- Trace Elements (diethylene-triamine-penta-acetic acid (DTPA)) – Copper, Zinc, Manganese, Iron (12A1)
- Boron (12C2)
- Sulfur (KCl 40) (10D1)

In 2019 the project redirected the soil survey activity focus to complete a reconnaissance of soils in the regions with: large areas of newly cleared land with agricultural development, little recent soil survey activity and potential for new upland soils to be identified and described. In November 2019 a soil survey activity of North East Cambodia comprised a reconnaissance soil survey of Mondol Kiri, Ratanak Kiri and parts of Stung Treng Provinces. This activity was used as an on-the-job training in soil survey and soil classification using the FAO WRB. Murdoch University and Department of Primary Industries and Rural Development (DPIRD) staff led a team that included staff from CARDI, General Directorate of Agriculture - Department of Agricultural Land Resources Management (GDA-DALRM) and a student from RUA.

Capacity building in soil survey and soil classification was through a formal training course as well as on-the-job training during soil survey missions. The formal training course in soil survey and classification was completed over two days in February 2019 and was attended by participants from CARD, RUA, GDA-DALRM and National University of Battambang (NUBB). The course consisted of a day of lectures followed by a day of field work where two contrasting soil profiles were characterised. This complemented the on the job training the CARDI staff were involved in across the 4 survey activities in the first 2 years. Additional participants from RUA, GDA-DALRM and NUBB were invited.

Additional soil survey activities by CARDI staff were completed for project experiment sites and on a case-by-case basis for other research activities (See Section 6).

Activity 1.4 Update Cambodian Soil Database and add new soil profiles.

The soil profile database produced in SMCN/2001/051 was recommissioned for the project. The database was initially migrated to MSAccess (2016) and throughout the project was modified as required to maintain functionality by DPIRD staff (all codes updated, direct print report capability and templates for soil chemistry data upload). Within the database itself the codes were updated to the FAO soil classification WRB codes (2014-15 revision) and the revised Gazette of Cambodian Administration Areas. In conjunction with this the field booklets, soil survey site cards were also updated with any changes.

There were two updates of the field book and codes list – "Dataset and code definitions for the soil survey of Cambodia". 1) 2018 update for the FAO (2006) Guidelines for Soil Description (4th Edn). FAO, Rome 2006, and National Committee on Soil and Terrain (NCST, 2009) Australian soil and land survey field handbook (3rd Edn). (CSIRO Publishing: Melbourne). 2) 2023 Update for the World Reference Base for Soil Resources IUSS Working Group WRB. 2022. 4th Edition.

In addition to the work on the soil profile database a tablet-based soil survey data input tool has been created by RUA. This interface used the Open Data Kit software to collect and manage the information. This interface does not collect full profile descriptions but allows input of a refined set of variables that is likely to be used in simple soil profile description. This tool allows input of the data whilst in the field sites and benefits teams when completing soil survey activities, especially independently of the Australian collaborators as the data can be uploaded and viewed by all soil survey team members remotely. An accompanying simplified soil profile description booklet and hard copy sheet and codes description booklet were created. The tool is only available to project staff, with an accompanying training module the tool could be made available to a larger stakeholder group.

Throughout the project all new soil profiles (Activities 1, 2.3, 2.4) were added to the database. CARDI and Murdoch staff completed quality assurance checks (2019 and 2020) of the soil profile site data sheets entered into the database to ensure corrects codes were recorded and entered.

Activity 1.5 Develop rapid soil assessment methodologies and create calibration data set for the study areas.

Laboratory techniques – Mid-infrared spectroscopy and ion-selective electrode

Our approach was to build capacity in two complementary rapid soil analysis techniques to cover a broad range of soil properties. Mid-infrared spectroscopy is good for analysing soil attributes such as clay and organic carbon content whereas ion-selective electrode (ISE) is designed for ionic attributes such as pH, exchangeable potassium, and nitrate contents.

We facilitated sharing of knowledge, experience, and data by using the same MIR and ISE equipment and methods across ACIAR Projects in Southeast Asia.

Training in rapid soil analysis was carried out at three levels:

1. An overview seminar aimed at industry and government decision makers, University staff and students and colleagues from CARDI and GDA-DALRM to introduce the rapid soil analysis techniques, operation, capabilities, costs and benefits.

2. Hands-on training aimed at CARDI staff who will potentially use the facility. Training was carried out with an excess number of trainees for the job (4 to 5 for MIR and 5 for ISE) to allow for likely staff turn-over we usually experience in national institutions. We trained these staff members to prepare soil samples for analysis, operate the equipment, collect and upload MIR spectra and soil analysis data to an online data file. In addition, for MIR, we trained staff to select statistically representative soil samples for conventional analysis, use the conventional soil analysis to calibrate the MIR spectra for several soil properties and finally to use these calibrations to analyse soils.

3. On-the-job training where the trainees used the MIR and ISE techniques independently. We were there to support them during their first week of work to help resolve any technical difficulties faced during work. We continued to provide support when the newly trained staff members used MIR and ISE for soil analysis in the "production mode". The MIR and ISE training were carried out as separate events with MIR starting in May 2018 and ISE in March 2019. A follow-up MIR hands-on training was conducted in September 2023 to reinforce earlier training in calibration and soil analysis.

The proceedings of the MIR and ISE training were recorded in detail to provide enduring documents that trainees can refer to as instruction manuals to carry out these rapid analytical techniques independently (Attachments 2, 3).

Portable ISE for field testing

Field testing of the portable ISEs (Horiba LAQUAtwin-K-11) was performed at Kampong Speu, Aoral District in October 2019 to evaluate the logistics of using the instrument at a local village. This involved making and updating a list of materials required for soil analysis, subsampling and analysing soil samples. The soil samples were taken from the K and P replicated field experimental sites.

The Murdoch University team tested a portable K ISE sensor (Horiba LAQUAtwin-K-11) for rapid field measurement of soil K (2021-23). A selection of Western Australian soils with known Colwell K content were selected to assess the sensitivity, accuracy, reproducibility of the field-portable instrument.

Objective 2: Characterise the soil and land constraints to crop production and identify management technologies.

Activity 2.1 Review of the information describing soil and landscape characteristics, constraints and potential management strategies for improved crop production and sustainable land use in the uplands of Cambodia.

In this activity the approach was to complete a synthesis of existing grey and published literature to: 1) identify the soil constraints to upland crop production and the current research, technology and crop management techniques which have been found to successfully overcome constraints; and, 2) identify critical characteristics of soil and landscapes that may lead to land degradation.

Activity 2.2 Identify limiting factors to crop production in study areas through soil chemical and physical analysis, using traditional and rapid soils assessment methodologies.

Throughout the project soil chemical and physical properties were measured using traditional techniques and rapid soil technologies developed in Activity 1.5. The samples analysed were from soil surveys (Activity 1.3), satellite and experiment sites (Activity 2.4), soil nutrient decline and soil degradation study (Activity 2.3). In addition, the project collaborated with SLAM 2018/127[4], Centre for International Development (CIRAD), GDA-DALRM to access soils from different geographic areas to identify soil characteristics that can be estimated by the MIR methodology.
Interpretation of the soil physical and chemical data collected throughout activities is embedded within other activities to identify soil factors limiting crop production.

Activity 2.3 Determine the extent and nature of nutrient deficiency present in the study regions and test strategies to overcome

Glasshouse experiments that indicate amelioration techniques

The project identified that low soil pH was an issue for crop production in sandy soils of the upland regions. From early soil survey activities sites were identified to determine the affect of ameliorating low pH surface soils with lime amendments. Initially RUA Bachelor Students completed a pot trial under the direction of RUA and CARDI staff. In the CARDI glasshouses mungbean and maize were sown on 4 soil types treated with 5 lime rates (0 to 6 t/ha). Soils selected were the representative soils identified in Aoral and Dambae Districts by soil survey staff.

[4] *SLAM 2018/127Synthesis of learnings of sustainable intensification of agriculture in Cambodia*

After this a further two soils were investigated for response of mungbean to lime application by CARDI staff. This work included developing a protocol to determine the dose response curve for lime application to each soil to determine lime rates required to increase pH to non-limiting levels.

Assess rate of land degradation in the Aoral District of Cambodia

Concerns about soil and land degradation in the Aoral District arose after land clearing and suspected soil loss by erosion and fertility decline by loss soil organic matter and plant nutrients and soil acidification. The rate of soil and land degradation depends on terrain, soil type, land management and time since clearing. It is exacerbated by nutrient mining, excessive land cultivation and poor control of erosion.

The aim of this work was to determine the rate of soil and land degradation since clearing and to predict future land and soil conditions if current rates are or are not altered by better practices. This complements work on soil surveys where samples were characterised by rapid soil analysis techniques, farmers' interviews and field experiments to manage soil pH and nutrient deficiencies.

The study was completed in Prey Thom Village, Aoral District. Prey Thom has a defined grid layout. Satellite images show gradual clearing of these land lots from 2012. Satellite images were analysed for time of clearing and the information confirmed with farmer responses determine date of clearing and land use. The village and land was allocated to farmers in 2012. Satellite images show the site pre-clearing in April 2012, increasing number of strips of land cleared by 2015, and by 2019 most of the allocated.

For this approach we designed a sampling strategy that allowed comparison of two clearing times (initially cleared approx. 8 years, recently cleared approx. 3 years), targeted three soil types (identified in the community soils activity (Activity 4.2) as Chrab, Mixed Sandy, Kandeng), and replicated 3 times. At each selected site one soil profile to 50 cm was completed and a grid sampling strategy collected 25 surface samples. Soil samples were analysed with MIR and for pH, EC and K using the ISE. Data collection occurred from July 2021 analysis is ongoing after the final field trip in September 2023.

Activity 2.4 Develop options to overcome soil constraints to crop production incorporating the relevant nutrient, biological and agronomic management technologies in the study areas.

A facilitated workshop was used for the project team to design the field activities to begin to characterise the soil and land constraints to crop production in the target districts. The objectives of this work were to:

1. Develop capacity to address nutrient decline and deficiency to improve sustainability and profits.
2. Provide options to alleviate common deficiencies in P and K and increase profits and decrease land degradation Cambodia.
3. Assess the financial and sustainability risk of the new management practice.

We used formal replicated on-farm field trials and satellite trials (on-farm farmer participatory demonstrations) that were coupled with economic, risk and soil impact assessments to build capacity to develop the use of fertilisers in Cambodia. The soil impact assessments used nutrient (P and K) balance to assess the risk of soil nutrient depletion. The planning, design, implementation, communication and write up of this work involved CARDI and MU through a series of planning meetings, workshops and email discussions for participants to learn from one another and develop the work.

Satellite trials were used to demonstrate the benefits of ameliorating soil constraints across representative fields in the villages in a simplified manner, without replication and with less treatments. Aims were to: compare the effects of two P and K fertilizer rates with farmer practices on peanut yield on various soil groups, analyse the economic efficiency of the two different fertilizer rates and observe soil constraints for the crop growing.

Farmer participatory on-farm trials are a common approach to demonstrate the benefits of fertilizers. In our approach during the satellite trials, the host farmer volunteered to host the trials and field days, allocated a plot of land on their farm to the trial and the project team implemented the trial. The yield of the crop is then measured with the farmer and field-day guests to determine the impact of the fertilizer on crop production. Economic analysis is used to calculate and demonstrate the financial benefits of using fertilizers. In this analysis, the cost of fertilizers is compared with the increased yield and income that it generates. The economic risk of investing in fertilisers can be estimated from the probability of loss from multiple trials conducted with many farmers across many sites, seasons and years to give confidence in using the appropriate fertiliser practice.

The satellite trials focused on relevance to local farmers. This influenced the size of plots, the crop selected, rates of fertilisers used, type of analysis conducted on the data and simplicity of treatments. This approach precludes the use of soil test to determine the level and type of fertiliser used. Soil test data are almost never available to farmers to base their decision on. Instead, we used the knowledge that deficiency of P and K is common to decide which fertilisers to used. On-farm satellite trials compared the effects of two rates of P and K fertilizers (added with N) with the farmer's dominant practice (T1) of using no fertilizer (Table 1) on peanut yields. Fertiliser treatments were at a lower rate (T2) of P and K fertilizers and twice this rate (T3). Rates of P and K added in T2 were made by calculation of the total P and K removed by a 3 t/ha peanut crop, with the assumptions of a harvest index of 0.5 and P efficiency of 75 % (Wright and Middleton 1991; Martin and Belfield 2007; USDA 2018). Fertiliser P and K treatments used were modified from 2021 to include locally available forms of fertilisers (triple superphosphate (TSP) changed to diammonium phosphate (DAP)) applied at rates that should be both effective, affordable and accessible to local smallholder farmers. In addition to the basic treatment, from 2021, gypsum treatments were used to ensure adequate supply of Ca and S and evaluate their benefits in peanut production. We repeated the trials across many farmers, sites, soils, seasons and years (Table 2) to ensure that the methodology used is robust and scientifically sound and the results are credible and reliable. Satellite trials were implemented in the main wet season (MWS) in 2019 and from 2020 to 2022 in the early wet season (EWS) and MWS.

Farmer field days were utilised to present the results to farmers and gain their opinion of best treatment (voted after viewing crop) and begin dialogue for the next years activities (Table 3). Over time the satellite trails were expanded due to increased interest of participating farmers, and in 2021 included a new village. In all year's peanut was the primary crop planted, however in 2020 the crops were expanded to include watermelon and sweet potato as farmer opinion in 2019 was that more crops be included in the study. Post 2020 the crop sown returned to peanut only. In 2022, sites were included in Dambae District, Tboung Khmum Province. Detailed methods of the satellite trials can be found in the protocols and annual reports for satellite trials.

Table 1. Basic treatments used for satellite trials across all years and seasons (Main wet season (MWS) and Early wet season (EWS).in 2019 to 2022

	2019 MWS[1]	2020 MWS and EWS[1]	2021 MWS and EWS[2]	2022 MWS and EWS[2]
T1	0N-0P-0K	0N-0P-0K -0 gypsum[3]	0N-0P-0K -0 gypsum	0N-0P-0K + 0 gypsum
T2	15N-15P-20K	15N-15P-20K 110 gypsum	27N-15P-20K 110 gypsum	27N-15P-20K + 110 gypsum
T3	15N-30P-40K	15N-30P-40K 110 gypsum	27N-30P-40K 110 gypsum	27N-30P-40K + 110 gypsum
T4	N/A	N/A	N/A	27N-15P-20K + 0 gypsum
T5	N/A	N/A	N/A	27N-30P-40K + 330 gypsum

[1]2019 and 2020: Urea (46N-0P-0K), TSP (0N-20.7P-0K), Muriate of Potash (MOP) (0N-0P-49.8K)
[2]2021 and 2022: Urea (46N-0P-0K), DAP (14N-17P-0K), MOP (0N-0P-49.8K)
[3]Gypsum ($CaSO_4$)

Table 2. Satellite trial year, host, location 2019 to 2022

Year	Season	Number of Host farmers	Gender	Village, Commune, District
2019	Main wet season	5	3M 2F	Prey Thom, Rasmey Samaki, Aoral[1] Tang Robang, Hoang Samnom, Aoral
2020	Early wet Season	6	2M 4F	Prey Thom, Rasmey Samaki, Aoral Tang Robang, Hoang Samnom, Aoral
	Main wet season	5	3M 2F	Prey Thom, Rasmey Samaki, Aoral Monorom, Hoang Samnom, Aoral
2021	Early wet Season	10	3M 7F	Prey Thom, Rasmey Samaki, Aoral Tang Robang, Hoang Samnom, Aoral Monorom, Hoang Samnom, Aoral
	Main wet season	8	5M 3F	Prey Thom, Rasmey Samaki, Aoral Tang Robang, Hoang Samnom, Aoral Monorom, Hoang Samnom, Aoral
2022	Early wet Season	8	2M 6F	Prey Thom, Rasmey Samaki, Aoral Tang Robang, Hoang Samnom, Aoral Monorom, Hoang Samnom, Aoral
		3	3M 3F	Kouk Srok, Dambae[2]
	Main wet season	6	3M 3F	Tang Robang, Hoang Samnom, Aoral Pos Vaek, Rasmey Samaki, Aoral
		2	2M 0F	Kouk Srok, Dambae

[1]Aoral District, Kampong Speu Province

[2]Dambae District, Tboung Khmum Province

Table 3., Farmer attendance to field days at crop maturity 2019 – 2022.

Year	Season	Number of farmers	Gender	Village, Commune, District
2019	Main wet season	40	15M 25F	Prey Thom, Rasmey Samaki, Aoral
2020	Early wet season	28	12M 16F	Tang Robang, Hoang Samnom, Aoral
		23	5M 18F	Prey Thom, Rasmey Samaki, Aoral
	Main wet season	20	5M 15F	Monorom, Hoang Samnom, Aoral
		30	9M 21F	Prey Thom, Rasmey Samaki, Aoral
2021	Early wet season	22	4M 18F	Tang Robang, Hoang Samnom, Aoral
		28	8M 20F	Monorom, Hoang Samnom, Aoral
	Main wet season	25	9M 16F	Tang Robang, Hoang Samnom, Aoral
		25	10M 15F	Monorom, Hoang Samnom, Aoral
2022	Early wet season	28	12M 16F	Monorom, Hoang Samnom, Aoral
		32	7M 25F	Tang Robang, Hoang Samnom, Aoral
Total		301	96M 205F	

[1]Aoral District, Kampong Speu Province
[2]Dambae District, Tboung Khmum Province

Early in 2022 the CARDI team identified that the project had withdrawn from Dambae District (partly due to COVID restrictions) after activities in 2019. It was decided that the project would reengage with farmers in Dambae and complete the soil fertiliser and fertiliser use survey (Activity 4.1) and install a set of fertiliser satellite trials. The team also decided to complete replicated field trials to assess fertiliser use efficiency in both Dambae and Aoral Districts to complement the satellite trials completed.

There are significant yield gaps between farmers’ practice and improved agronomic practices. This experiment aimed to assess fertiliser response to commonly occurring nutrient deficiencies in two contrasting districts of Cambodia.

A formal on-farm replicated field experiment was attempted at four sites, two sites in each of the Aoral and Dambae Districts in the main wet season 2022 (July to November). Soils at Aoral District were a sand at site 1 and a sandy loam at site 2. Soils at Dambae District were a clay loam at site 3 and a gravelly clay loam at site 4. A randomized complete block design with six fertilizer treatments and four replications was used (Table 4). The treatments were structured so that kernel yield response to P and K could be calculated from several treatment combinations so that variability, consistency, and predictability of response could be assessed.

Table 4. Nutrient rate of each fertilizer treatments applied as urea, diammonium phosphate (DAP) and muriate of potash (MOP). All treatments received 27 kg N/ha as urea and 110 kg gypsum/ha to ensure adequate supply of calcium and sulphur to the peanut crops.

Treatment no.	Nutrient (kg/ha)	
	P	K
T1	0	0
T2	15	0
T3	15	20
T4	15	40
T5	30	20
T6	30	40

Activity 2.5 Develop site specific management technologies for the soil-landscapes of the study regions.

In conjunction with Activities 2.2 and 2.5, MU researchers focussed on identifying information to incorporate into a framework for land capability classification (LCC) for non-rice crops in Cambodia. Information sources for this activity was from the previous LCC for non-rice crops in Cambodia which was developed in SMCN/2001/051 and reported in Bell et al. (2005a and 2005b). The LCC developed by CUSP also uses a number of frameworks to assess capability for growing upland crops such as the Fertility Capability Classification (FCC) (Sanchez et al., 2003; Bell et al., 2007) and variations as reported in FAO (1976, 1984), van Gool et al. (2004) and Sys et al. (1993). In addition, the Soil Constraint and Management Practices (SCAMP) document (Moody and Kong, 2008) was also used to assess soil and land attributes and their effect on crop growth.

Objective 3: Provide tools and information that enable stakeholders to identify the main soil types, and their constraints to crop production

Activity 3.1 Develop simple tools for in-field soil-landscape assessment.

The decision support framework, SCAMP (Moody and Cong 2008) was identified as a tool to link the outputs from soil and landscape mapping to site specific soil management guidelines. The SCAMP methodology is a technical document designed for researchers and extension staff with expertise in soil interpretation. The project team identified this document as a resource that may be used in Cambodia in its current form, or a revised form. The project investigated the SCAMP document and other documents (e.g. Soil Tip) currently available in Cambodia in a workshop designed to teach the next users how to use SCAMP and Soil Tip. When Soil Tip and SCAMP are compared, SCAMP is a full package from soil description to assessment of soil suitability, whilst Soil Tip only covers basic soil description. This was followed by an evaluation activity. The project team become aware that SCAMP in its current form may not be appropriate for all stakeholder groups and if appropriate the tool should be used and/or revised for training of next users and/or farmers. Workshops of activities with CARDI and GDA-DALRM completed further evaluation of the tool and recommendations.

In addition to the SCAMP document the project team has been developing materials for use by stakeholders for the: identification of constraints to crop production and management technologies to overcome them. This targets constraints to crop production identified in the Community Soils Mapping activity (Activity 4.1) that farmers identified as well as issues identified in the Soil Survey activity related to crop production and land degradation. A series of project planning workshops (online and in-person) occurred from October 2021 to March 2023 where the participants discussed priority topics for farmer field day training.

Activity 3.2 Develop a framework for documentation of upland soils as a version of the Cambodian Agricultural Soils Classification (CASC).

For each study area the project sought to, 1) create information that describes the main upland soils, how to identify them, their expected spatial extent, their key management issues and appropriate management techniques and 2) collate the information in a booklet or factsheet, which also incorporates the tools developed for in-field soil landscape assessment, developed in 3.1 above.

The CASC is the name given to the soil classification for rice soils developed in the publication *The Soils Used for Rice Production in Cambodia* (White et al., 1997). This common naming system has been well accepted, and it is proposed to expand this classification, either as an expansion of the original rice soil publication, or as a standalone companion publication for the upland soils of Cambodia. Based on the upland districts surveyed so far, several new soils have been identified, and a framework has been developed for reporting on these new soils. Current consensus between CARDI and GDA-DALRM is that the upland soils should be described in a separate document. The project team developed a framework for this using soils identified in the three surveys locations to date 1) Dambae District, 2) Aoral District and 3) Reconnaissance survey of North East soil survey. This can be expanded to incorporate other soils surveys from previous or future surveys, ultimately creating an upland soils manual as a companion to the rice soils manual.

Objective 4: Develop knowledge of soil resources and capability for soil resource management

Activity 4.1 Develop an understanding of which tools, knowledge and approaches to building capacity are most effective to identify soil types, landscapes and constraints and improve soil management practices

During the project, 263 smallholder farmers (154 females and 109 males) from six villages in Aoral District, Kampong Speu Province and Dambae District, Tboung Khmum Province participated in the research. Initially, farmers participated in semi-structured interviews and focus group discussions designed to understand farmers' current farming systems including the constraints to crop production, their access to inputs and the available extension advice and support. Three targeted activities were then carried out: 1) *community soils workshop* designed to capture farmers understanding of the soil types in their village; 2) *gender analysis* that aimed to understand the gender dimensions of any new technologies/practices/tools promoted through the project and their impacts and extension preferences and access; and, 3) *soil fertility and fertiliser use survey* that examined farmers understanding of soil fertility; documented the extent of fertiliser use; and, investigated the constraints to fertiliser use.

In year one of the project four representative case study villages were selected in consultation with local authorities and traditional leaders from the target districts (identified as part of Activity 1.3). Criteria for selection of villages included that they were in upland locations with diverse soils. Selected villages included Prey Thom and Tang Robang in Aoral District, Kampong Speu Province and Svay Popeah and Srae Veaeng in Dambae District, Tboung Khmum Province. In year five of the project two additional villages (Kouk Srok and Krasang) were identified for Satellite Trials (Activity 2.3) and included in activities thereafter.

Community Soils Activities (CSA)

The baseline survey which took the form of Community Soils Activities (CSA) rather than detailed household survey was conducted in Aoral District, Kampong Speu Province and Dambae District, Tboung Khmum Province in September 2018 and January 2019 respectively. Community soils activities, particularly mapping, have been used for a range of purposes including to:

- Understand farmer (local, traditional) knowledge of different soil types and management skills
- Develop a shared understanding/common language
- Compare or validate farmer soil knowledge and 'expert' soil knowledge – similarities and differences
- Combine farmer and scientist indicators and diagnostics to develop criteria for assessing soil quality/soil fertility or soil-specific technologies
- Relate farmer knowledge to the socio-economic, cultural and agro-ecological context in which it has developed
- Develop practical solutions to soil management constraints
- Improve adoption and utility of management practices

For the CUSP, the aims of this activity were to:

- Inform farmers about the project

- Know farmers' perspective/understanding of: soil type, soil related constraints, suitable crops for particular soils and soil management practices
- Know the local language/terminology – to use in tools, discussions, future work

In the CSA, participants were asked to identify the soil types in their fields and village, they were then asked to agree on the main soil types and describe the properties of each of these soils including their fertility, fertiliser requirements and crop suitability. In the process, farmers ranked their soils from most fertile to least fertile. In order to cross-reference the descriptions and names of the soils with soil themselves the groups were then asked to handle soil samples collected previously. Each participant handled the samples separately, in some instances mixing them with water and creating ribbons or balls with the sample, this facilitated further discussion about the soils, the group then agreed on the soil type for each sample. Participants then located the different soils on a village map.

Gender and Extension Analysis

As a follow on from the community soil activity and as part of the Gender Awareness component of the project (Activity 0.5) a gender and extension analysis was completed to better understand the roles that women and men play in agriculture and the gender dimensions of any new technologies/practices/tools promoted through the project and their impacts. The specific aims of the analysis were to:

- Understand women and men farmers demand for and adoption of soil management information, tools and technologies, in order to understand how they might affect the uptake of CUSP outputs.
- Understand the extension networks and activities that farmers are part of to better understand potential scaling strategies for CUSP outputs.

The analysis involved focus group discussions and interviews with farmers in CUSPs four target villages and key informant interviews with Provincial Department of Agriculture Forestry and Fisheries (PDAFF) staff in Kampong Speu and Tboung Khmum Provinces. The analysis was led by Cambodian gender consultant Chenda Sem with guidance from gender expert Josie Huxtable.

Fertiliser and Fertiliser Use Survey

The CSA and gender analysis focused on understanding the context, including: local soils knowledge and capacity for soil management (baseline community soils survey); and women and men's demand for soil management information, tools and technologies (gender and extension analysis). Based on the findings of this work the project identified a need to further understand: 1) farmers understanding of soil fertility; 2) fertiliser use practice and in particular constraints to fertiliser use.

In 2021/22 the soil fertility and fertiliser use survey was completed in Aoral and Dambae Districts. Farmers in each district were surveyed and key informant interviews with provincial agricultural officers in Kampong Speu and Tboung Khmum Provinces and input suppliers were conducted.

The survey was used to examine farmers understanding of soil fertility and fertiliser use practice. The survey was divided into three parts. The first part asked participants about their perspective of soil fertility including whether they thought yields and soil fertility were increasing or decreasing, the cause of any changes and what makes a soil less fertile or more fertile. Part two of the survey explored farmers understanding of common crop symptoms (e.g., curling, discolouration, leaf damage) and whether they attributed any of these to nutrient deficiencies using the International Plant Nutrition Institute (IPNI) photographic tool. The final part of the survey asked farmers about their fertiliser use practice including whether they used fertiliser on their lowland rice crops and/or upland crops. The reasons for not using fertiliser were probed further to identify the major barriers to fertiliser use.

A semi-structured interview schedule was used for the interviews with the agricultural officers and included questions about their perspective of the barriers to smallholder fertiliser use and soil fertility management and the kinds of tools/activities that might encourage farmers to manage their soil fertility/soil health. These interviews were also used to further explore some of the claims regarding constraints to fertiliser use. A structured survey was used for interviews with input suppliers; they were asked questions about their stock, sales, suppliers, and customers in order to ascertain whether access and affordability were constraints to fertiliser use.

Activity 4.2 Engage and communicate with stakeholders in the case study areas.

The project engaged stakeholders in activities designed to inform the development of tools for in-field soil landscape assessment and develop their capacity to improve crop productivity through new understanding of soil related constraints to crop production and improved soil management practices. However, as these represent significant activities in their own right they are presented as Activity 4.3.

Activity 4.3 Develop stakeholders' capacity to improve crop productivity through new understanding of soil related constraints to crop production and improved soil management practices.

Activities were designed to develop stakeholders' capacity to improve crop productivity. Central to this were activities that also informed the development of simple tools for in-field soil-landscape assessment (Activity 3.1). The activities were developed on an annual basis in conjunction with stakeholders. The final activities completed were:

- Community mapping exercise to identify village soil types.
- Soil fertility and fertiliser use study to further understand: 1. farmers understanding of soil fertility; 2. constraints to fertiliser use.
- Participatory review of existing simple tools for soil identification.
- Satellite trials of crops and management strategies based on identified soil types/constraints.
- Training workshops on soil management practices.
- Workshop on tools developed.
- Farmer field days to showcase the trials and tools to the broader community.
- Targeted training workshops in the tools developed e.g. development practitioners, extension providers, local traders.

Each activity is described and reported in detail in other Objectives and full reports are available as attachments.

It should be noted that initially the mode of engagement was to be through stakeholder forums however, after year 1 of the project there were some concerns that stakeholder forums were not going to be a useful mode for engaging with farmers. There were a number of constraints to establishing stakeholder forums: 1) it is difficult to establish a group and engage farmers on Cambodia using this method; and, 2) it is especially difficult to engage Cambodian farmers using this method without a local partner and/or a sufficient incentive (i.e., where groups do work there are benefits in terms of marketing produce and/or savings). The project had good early engagement with farmers involved in trials and other activities, but communities and local staff did not support the idea of a formal 'group' or forum.

6 Achievements against activities and outputs/milestones

Objective 1: Introduce new methodologies for soil survey and land suitability assessment and identify main soil types and landscape patterns in upland regions of Cambodia.

no.	activity	outputs/ milestones	completion date	comments
1.1	Review literature and available data for soil and landscape information for the uplands of Cambodia. This will include information from adjacent countries.	• Data sources compiled in a database. • Review of existing information collated and synthesised into a report. • Soils information identified uploaded into the Cambodian soils database.	July 2020	Report and spreadsheet "Review of Soil Information in Cambodia" completed (Attachment 4). Whilst the stakeholder organisations directly collecting information did not provide the data to the CUSP team, they did inform the team as to the areas surveyed, methodologies used and the progress of projects.
			July 2022	Literature review "Geology and landscape evolution of Cambodia" (Attachment 5)
			March 2022	Facilitated Cambodian Soil Survey Practitioners joint meeting on Advances in Soil Survey and Soil Classification in Cambodia. Co- hosted by CARDI as part of CUSP project GDA-DALRM and MU. Key CUSP presentations • Soil Database – Development of soil database for central storage of Cambodian soil data (Dr Hin Sarith) • CARDI Soil Survey Activity, method, and achievement (Mr Lim Vandy/ Dr Hin Sarith) • Proposal to develop an upland soils manual - fact Sheets (Noel Schoknecht) • SCAMP – What is it and how can it be used to improve knowledge of soils in Cambodia? (Dr Hin Sarith & Dr. Wendy Vance) • Cambodia Soil Data Audit – Creating a catalogue of Cambodia soil profile data (Noel Schoknecht)

				Project staff contributed to the research paper from Dr Hin Sarith's PhD research. Hin, S., Bell, R.W., Newsome, D., Vance, W., Seng, V. (2023). Origin and Properties of Deep Sands of Southeastern Cambodia: Some Preliminary Findings. In: Hartemink, A.E., Huang, J. (eds) Sandy Soils. Progress in Soil Science. Springer, Cham. https://doi.org/10.1007/978-3-031-50285-9_2. The research was funded by the ACIAR through Projects SMCN 2001/051, and writing progressed during SMCN 2016/237.

no.	activity	outputs/ milestones	completion date	comments
1.2	Determine the spatial extent of the key upland soils and their key properties and identify areas that have the potential for new upland soils.	Report of the likely spatial extent of upland soil types and their key properties. • Collect spatial information. • Compile GIS layers and soil survey information to be used in the analysis.	August 2017	GIS layers for Cambodia have been collected. These include layers of soil surveys, geology, elevation and topography. The layers have been sourced from ACIAR project SMCN/2001/051 and Open Development Cambodia. Satellite imagery of Landsat 8 and Sentinal have been located for the study regions. The Shuttle Radar Topography Mission (SRTM) has been used for the DEM and derivatives. Climate and bioclimatic variables were sourced however these are only useful at national scale, and not useful to assist in creating a soil sampling strategy at the district level. Useful layers to distinguish between soil-landscape units are geology, DEM derivatives of slope and multi-resolution valley bottom flatness (MrVBF). 2016 Landsat 8 imagery was classified to distinguish between agricultural land and forest.
		• Report on the likely spatial extent of soil-landscape units in the each district.	July 2018 2021 2023	The draft Aoral District map was produced. 12 new sampling points were selected to infill the Aoral District survey sites. Aoral District report and map (Attachment 6) Dambae District report and map (Attachment 7)
		Report on the physiographic zones of Cambodia defined by the spatial layers of elevation, geology, landuse and selected satellite images	Nov 2021 to Feb 2022	Consultation meetings between November 2021 and February 2022 identified methods most likely to result in a reliable and simple physiographic map of Cambodia. Geology, climate derivatives, topography are key datasets.

			December 2022	Report on physiographic zones This resulted in a grouping of Systems and Zones developed for Cambodia which represent the major sources of soil variation across Cambodia. Output: 1. Report - Defining agricultural soil management zones in Cambodia from remote sensing imagery 2. Map of Soil Management Zones (Attachment 1)
		Working with GDA-DALRM, review the Crocker soil map with available physiographic and soil data to determine a methodology to create an improved national soil map that includes physiographic attributes. This new map could then be used to determine broad physiographic regions of Cambodia.	2021 April 2023	The CUSP Australian team provided review of the DALRM-GDA draft of “The World Reference Base Classification of Cambodian Soils”. Produced by GDA-DALRM. Presentation of - Defining agricultural soil management zones in Cambodia to visiting GDA-DALRM staff Dr Seng Vang and My Phy Chhin to start consultation on the report and map. Presented by Dr K Holmes.
		Provide recommendation on priority areas for further survey which target and identify regions with Upland soils that have potential for new Upland soils to be identified and described. Yr 4, m 10	October 2019	Advice paper - Proposed new survey work for North Eastern Cambodia. Attachment 8
		RUA led Land Use and Land Cover Change detection (LULCC) activities in Aoral and Dambae	2019	A study of LULCC detection was completed in Haong Samnam Commune, Aoral District in Kampong Speu and Dambae District of Tboung Khmum. The projects were completed by Royal University of Agriculture, Bachelor of Science students for their final thesis component. The students used Landsat 8 images and drone survey techniques. In the Aoral District the commune selected had a significant decrease in semi-evergreen forest from 2013 to 2017, showing an increase in barren land, paddy fields, deciduous forest and sugar plantations. In Dambae District the largest increase was in the area of rubber plantations.

			2022	Land Use and Land Cover analysis study aimed to complete land use change maps. Mr Ty Sopanha (RUA) completed a land use and land cover map in Reaksmei Sameakki and Haong Samnam commune, Aoral District, Kampong Speu Province. Landsat 8 datasets are used within the period of 2015-2020 processing through Random Forest Algorithm using R Program and QGIS. There are 7 classes of land use and land cover are identified for mapping. A LULCC map of 2020 has been classified. A ground truthing mission in 2022 was completed to further validate the maps and refine the analysis.

no.	activity	outputs/ milestones	completion date	comments
1.3	Complete soil survey and landscape analysis (see Section 5 for detail)	Report of soils and landscapes of new surveyed districts.	2021 2023 2020	Final report for Aoral District (Attachment 6) Final report for Dambae District (Attachment 7) Trip report of reconnaissance soil survey of Mondol Kiri, Ratanak Kiri and parts of Stung Treng Provinces (See Section 7, Activity 1.3).
		Reconnaissance survey completed of target districts – Survey districts/locations identified completed Yr 1, m 3	July 2017 Nov 2018	A reconnaissance survey was completed of two target districts, Aoral District, Kampong Speu Province and Dambae in Tboung Khmum Province.
		Field-based sampling strategy completed for target districts Yr 1-3, m 5	2018	Field based sampling strategy was completed for Aoral and Dambae districts. Using the data layers from Activity 1.2.
		Field survey campaigns completed Yrs 1-3, m 8	March 2018 Feb 2019 Nov 2018	Field survey campaign completed in Aoral District, Kampong Speu Province Field survey campaign completed in Dambae District, Tboung Khmum Province
		Reports for each District aligned with the Mid-term review and Final project review	2019 2021	Draft soil and landscape map of Aoral district Two draft reports have been prepared for the mid-term review: Soil and Landscape Report of Aoral District and Soil and Landscape Report of Dambae Report

		Report for each new Soil Group identified for the CASC	2023	Identification of 4 new upland soils which are described in fact sheets (Attachment 9). See Activity 3.2. These fact sheets provide a template for further characterisation of new upland soils and the potential publication of an upland soils manual describing the characteristics and management of the main upland soils of Cambodia as a companion and complement to the CASC (White et al., 1997).
		Complete a reconnaissance soil survey of Mondol Kiri, Ratanak Kiri and parts of Stung Treng Provinces.	November 2019	Soil survey activity of North East Cambodia comprised a reconnaissance soil survey of Mondol Kiri, Ratanak Kiri and parts of Stung Treng Provinces.
		Complete soil profile analysis of all field experiment sites and land degradation study sites	2022	Aoral District, Kampong Speu Province The CARDI team completed 18 new soil profile descriptions as part of the land degradation study.
		RUA Led activity - Tablet-based soil survey data input tool	2018 - 2019	A tablet-based soil survey data input tool has been created by RUA. This interface used the Open Data Kit software to collect and manage the information. An accompanying hard copy data sheet and codes description booklet were created. The interface was implemented to collect data for a 'simple' soil profile analysis. The 'simple' analysis collects a smaller set of attributes is more suited to the SCAMP style of soil profile assessment and can be completed by most stakeholders with knowledge of soil survey, without being professional soil surveyors. The interface was updated after initial testing. However, it was not widely implemented during the project as most soil survey activities use the 'complete' soil survey techniques.

no.	activity	outputs/ milestones	completion date	comments
1.4	Update CSD and add new soil profiles.	Updated CSD. Yr 1, m 8	2018 to 2023	All new soil profiles and point source observations collected for the project were entered into the current Cambodian Soil Database. (n=221)
			Updated 2018 Final Version 2023	Field booklet "Dataset and code definitions for the soil survey of Cambodia" (Attachment 10)
			Updated 2018 Final Version 2023	Soil survey site card used by CARDI has been updated. Version changes as above.
			November 2019	Murdoch and DPIRD staff completed on the job training with CARDI staff on the use of the database.
			2019	CARDI staff recorded anomalies in the database entry which need to be rectified in a modified MSACESS database
			2020	Migrated database to in 64 bit operating system. The update to codes in the database completed.
			2020	Soil chemical data from CSBP for CUSP uploaded to the database. Protocol and table template which will allow future uploads of chemical data implemented.
			June 2021	Dr Sarith Hin (CARDI, Deputy Director) presented a seminar to GDA-DALRM and UBB staff on the soil database.
			2022	All new profiles entered for CUSP were checked for quality and consistency in data entry. As part of this work the classification for the WRB was finalised for the CUSP profile sites.
			March 2022	Facilitated Cambodian Soil Survey Practitioners joint meeting on Advances in Soil Survey and Soil Classification in Cambodia. Described above in Activity 1.1.

no.	activity	outputs/ milestones	completion date	comments
1.5	Develop rapid soil assessment methodologies and create calibration data set for the study areas.	Rapid soil measurement equipment commissioned	MIR Equipment commissioned in May 2018 and ISE in March 2019	MIR and ISE equipment purchased in Australia and carried to Cambodia. After commissioning and training, the MIR and ISE equipment are now in routine use at CARDI.
		Protocols for soil preparation and MIR.	May 2018	Protocols for the operation of the MIR, OPUS software and sample preparation were completed. (Attachment 2) All project soil survey and selected archived soil samples have been scanned for MIR analysis. 100 soil samples representative of the spectra obtained for all scanned samples have been identified and samples were shipped to Australia and analysed by conventional means at CSBP soil and plant analysis laboratory, Perth Western Australia. The data were used to calibrate the MIR spectra for numerous soil properties.
		Protocols for soil preparation and ISE.	March 2019	A draft protocol for the analysis of soil by ISE has been produced during the training course in March 2019 and circulated to CARDI colleagues for comments CARDI's laboratory continued to generate soil data for activity 1.3 and activities in Objective 2. (Attachment 3)
		CARDI staff trained in MIR and ISE	MIR – May 2018 ISE – March 2019	Theoretical, practical and on-the-job training activities Five CARDI Soil and Water team members were trained in the operation of the MIR, sample preparation, OPUS software operation, data handling and storage in a 2-week hands on program with presentations and demonstrations. Five CARDI Soil and Water team members were trained in the operation of the ISE and sample preparation, in a 2-week hands on program with presentations and demonstrations. Laboratory staff at CARDI are now confident in analysing soil pH, extractable potassium, ammonium and nitrate using ISEs. Training completed and CARDI now has the capacity to use MIR and ISE routinely for rapid soil analysis. No. = 5690 MIR, 1542 ISE K, 3183 pH.
			2020	Portable ISE probes were demonstrated and used in the SCAMP training course.

		Calibration libraries for the study regions of the upland areas.	Initial calibration June 2020 Updated calibration September 2023	Soils from Aoral and Dambae Districts were used for initial (n=66) and an updated (n=92) calibration for selected attributes. Calibration library for 22 soil attributes developed and use to analyse 5960 soil scans.
		CARDI staff trained in MIR calibration and soil analysis using these calibrations.	September 2023.	Hands on-training conducted at CARDI to refresh practicing MIR calibration and analyse soils. Four CARDI Soil and Water team members were trained.
		Protocol development for field testing of soil Nitrate, K and pH using the portable ISE devices.	February 2023	Both field and laboratory testing completed.
		Field testing of portable ISE devices	October 2019	Field testing of the portable ISE was performed at Kampong Speu, Aoral District in October 2019 to evaluate the logistics of using the instrument at a local village.
		Implementation of portable ISE methods with stakeholders	Not implemented as method was not suitable.	The portable ISE lacked sensitivity, accuracy and reproducibility to be used as a reliable method.
			2022	178 samples from soil profiles samples were scanned by near-infrared spectrometer (NIR) at Murdoch University. The same wet chemistry analysis dataset from CSBP used for the MIR was utilised for calibration of the NIR spectra.
			October 2019	CARDI Flame photometer – items required for the recommissioning of the Flame photometer were purchased by CARDI via Murdoch University. Dr Mike Wong, Ms Kim Sokheng and Ms Mouy Keang recommissioned the equipment. CARDI WP4C – soil potentiometer training and demonstration was conducted by Dr Wendy Vance with participants Ms Kim Sokheng and Ms Mouy Keang, Mr Sun Kethya.

PC = partner country, A = Australia

Objective 2: Characterise the soil and land constraints to crop production and identify management technologies.

no.	activity	outputs/ milestones	completion date	comments
2.1	Review of the information describing soil and landscape characteristics, constraints and potential management strategies for improved crop production and sustainable land use in the uplands of Cambodia. This review could include information from adjacent countries.	Review of the existing research and information compiled as report.	2019 2019 2022 2020 to 2022	Researcher My Vichhey Nell (RUA) completed a review of material. As part of Cross Project (SLAM 2018/127) compiled information on response of low pH soil to Lime amendments and crop yield improvements. (Attachment 12) The project staff contributed to the review paper : Bell RW, Seng V, Vance WH, Philp JNM, Hin S, Touch V, Denton MD. Managing Sands of the Lower Mekong Basin to Limit Land Degradation: A Review of Properties and Limitations for Crop and Forage Production. *Soil Systems*. 2022; 6(3):58. https://doi.org/10.3390/soilsystems6030058 The research was funded by the ACIAR through Projects SMCN 2001/051, SMCN 2012/075 and SMCN 2016/237. Reviewed information for use in the development of the “Land Capability Assessment Methodology”

no.	activity	outputs/ milestones	completion date	comments
2.2	Identify limiting factors to crop production in study areas through soil chemical and physical analysis, using traditional and rapid soils assessment methodologies.	Report that identifies soil limiting factors to crop production across soils in the study area. • Reports for each District aligned with the Mid-term review and Final project review	2017	In the reconnaissance survey completed in November 2017, 13 sites were sampled for soil fertility assessment at depths of 0-20 cm and 20-50 cm. These samples were analysed for soil pH and EC by the CARDI lab. Further analysis of the chemical and physical properties of these soils occurred with the aim of selecting soils to be used in pot trials for activity 2.3.
			2019	First phase of this activity was progressed with all soil samples collected in soil survey activities having undergone MIR analysis. After commissioning of the ISE the samples from all soil survey activities were analysed for pH and K.

			2020	The soil analysis was completed on selected soil profile samples through CSBP analysis for MIR calibration. Samples also analysed for pH and K in the CARDI lab. Key observations from the data are that in the two districts: • Most topsoils are marginal to deficient in phosphorous. • Potassium and sulphur deficiencies may occur frequently. • Topsoil and subsoil acidity are a problem likely to be worsen by agricultural intensification if remedial measures are not taken.
			2021	Progress of soil analysis – as of 2021, 527 samples were analysed for pH and K by the ISE. 579 samples were processed with the MIR with estimates for various soil and physical properties derived. The Soil and Landscape reports of Dambae and Aoral utilised this data to identify the limiting factors to plant growth in the main soil groups.
			2022	Reviewed land characteristics and land qualities in relation to land suitability for upland crops and developed criteria for assessment of Cambodian upland soils and landscapes. Documents included were ACIAR SMCN 2001/051 land suitability assessment, Sys et al. (1993), Land suitability rating for economic crops (Thailand publication), SCAMP (Moody and Cong 2007), Commonwealth Scientific and Industrial Research Organisation (CSIRO) Brunei (consultancy), ACIAR projects in Philippines and Myanmar (SMCN/2014/075; SMCN/2009/031). See Activity 2.5 for tool development for land suitability assessment.

no.	activity	outputs/ milestones	completion date	comments
2.3	Determine the extent and nature of nutrient deficiency present in the study regions and test strategies to overcome	Soil nutrient status for key soil types quantified and recommendations for amelioration reported.	2018 onwards	After commissioning the ISE and MIR equipment at CARDI soil samples were able to be analysed for the soil survey, satellite trials and pot trials completed in the project.
		• Report of available fertiliser inputs.	March 2022 and 2023	Activities of Fertiliser and Fertiliser Use Study in Objective 4 audited the available fertilisers in Aoral and Dambae Districts.

		• Diagnostics test of nutrient status of key soils completed (pot trials). • Glasshouse trials completed.	August 2019	RUA Bachelor Students completed a pot trial under the direction of RUA and CARDI staff. In the CARDI glasshouses mungbean and maize were sown on 4 soils types treated with 5 lime rates (0 to 6 t/ha). Soils selected were the representative soils identified in Aoral and Dambae Districts by soil survey staff. Submission of thesis reports was August 2019.
		CARDI pot trials	2022	Experiment completed lime requirement pot trial on mung bean with two low pH soils was established. CARDI Soil and Water Group
			September 2023	Follow up experiment completed on soil with possible Manganese toxicity at low pH. CARDI Soil and Water Group
			December 2023	Data collated – report draft completed
		• Report on the efficacy of organic and inorganic fertiliser inputs on soil nutrient status of the key soil types. Reports aligned with the Mid-term review and Final project review		Nutrient management experiments were completed in the satellite trials in activity 2.4. Glasshouse experiments focussed on overcoming low pH conditions with lime application. No work was completed on inorganic fertiliser options.
		Report on soil nutrient decline and soil degradation for 1 sites.	Feb 2021	Online project team workshop to develop the protocol (CARDI and MU)
		• Site sampling and field work	July 2021 August 2021 September 2023	First field trip to identify the 18 plots to sample and sample of 6 sites (CARDI) Second field trip for collection of samples from remaining 12 sites. Farmer interviews (CARDI) Field trip to confirm grouping of soil types from the 18 fields selected (CARDI and MU)
		• Laboratory analysis completed • Report completed	August 2022	MIR, K, pH analysis completed Data analysis and report ongoing

no.	activity	outputs/ milestones	completion date	comments
2.4	Develop options to overcome soil constraints to crop production incorporating the relevant nutrient, biological and agronomic management technologies in the study areas.	Successful options for site specific management for key soil and crops identified.		Activities listed below
		Initial farmer and sites selection completed; soil and landscapes characterised for constraints.	2019	Soil survey and community soils activity (CSA) for Objective 4 was completed for Aoral and Dambae Districts in 2018. Follow up meeting with the villages involved in CSA recruited interested farmers with target soils sites for MWS 2019 experiment and satellites trials.
		Planting choices and experimental design finalised for each year. In Yr 1 completed by	2019 March 2019 – 2023 March 2019 - 2023	A workshop of project staff determined the 2 experiments to be completed in each of the locations, 1) Determining crop types that are best suited to the local land characteristics through crop type trials, and 2) Ameliorating soil by providing better nutrition to crops Satellite trial designs completed for MWS start in 2019 and EWS start 2020 onward. Experimental site design completed for MWS start in 2019 and 2022.
		Experimental sites sown to correspond with early wet season and main wet season in 2018~~.~~	2019 June to October 2022	Experiment sites sown in 2019 in Aoral District - Crop type experiment not successful and not reported. Experiment on the effect of P and K application on peanut crop in upland soil in Aoral and Dambae Districts, Cambodia
		Satellite trails implemented in early wet season and main wet season Yrs 2-~~4~~5	2019 to 2022	Satellite trials started in 2019 after soil survey activity in 2018. Satellite trials completed in Aoral District 2019 to 2022 and Dambae District in 2022. In 2019 Main wet season only, 2020 onwards early and wet season trials.
		Final reports for experiments completed in Yrs 2-5 Interim results reported at Annual meetings.	June 2020 to 2023	Scientific reports for all satellite trials completed annually. (Attachments 14, 15 & 21) Submitted to annual reports and completed monitoring and evaluation reports as required.
			November 2022	Abstract and Posters presented at TropAg conference (Satellite trials)
			July 2023	Posters presented at Soil Science Australia 2023 conference (Satellite trials and 2022 Experiment)

no.	activity	outputs/ milestones	completion date	comments
2.5	Develop site specific management technologies for the soil-landscapes of the study regions.	Report on site specific management technologies for key soil types in upland regions. Information from the report will feed into the framework developed in Activity 3.2.	November 2022	Developed a Land Capability Assessment Methodology. Developed an excel spreadsheet tool to rate a soil profile and its accompanying chemical, physical and terrain data using a comprehensive set of qualities for land suitability classes of 1 (good) to 5 (unsuitable).

PC = partner country, A = Australia

Objective 3: Provide tools and information that enable stakeholders to identify the main soil types, and their constraints to crop production

no.	activity	outputs/ milestones	completion date	comments
3.1	Develop simple tools for in-field soil-landscape assessment	Tools developed to aid key stakeholder groups to identify main upland soils Collect resources that explain visual soil assessment techniques and simple methods for soil identification. Methods identified and drafted for visual soils assessment and soil identification to use in 1. Tool for technical audience 2. Tool for farmer groups Draft tools tested with stakeholders (Activity 4) Tools modified Tools retested Final documentation of tools	2018	Tools identified that explain visual soil assessment techniques, 1) The decision support framework - SCAMP (SMCN/2002/085) (Moody and Phan Thi Cong 2008), 2) SoilTip (CARDI), 3) NUBB training booklet.
			October 2019	Dr Phan Thi Cong led a workshop for the training and evaluation of SCAMP by project staff in October 2019. This was a 3 day workshop, 2 days in seminars/workshop activities and 1 day field training.
				SCAMP document translated to Khmer and printed (ACIAR publication funding). SCAMP translation was completed by ACIAR and was proofed by Dr Seng Vang and staff at GDA-DALRM.
				Workshops completed to identify material (in addition to SCAMP) for stakeholders to: identify constraints to crop production and management technologies to overcome them.
			August 2022	Small working group participated in the SCAMP workshop - Requirements to disseminate the SCAMP package effectively – Stakeholder groups
			2023	Tools to be modified and re-tested, but project team undecided about which format would be most useful for which audiences.

no.	activity	outputs/ milestones	completion date	comments
3.2	Develop a framework for documentation of upland soils as a version of the CASC.	1. Framework of a booklet or factsheet.	2019	A short discussion paper outlining the current situation and possible options for including the upland soils identified into a soil manual for Cambodia was prepared. A template for Soil Fact Sheet was drafted for stakeholder comment. This first example of identifying and reporting on a new Soil Group for the CASC which identifies upland soils in contrast to the original soils identified in the CASC which is based on lowland rice soils. (Attachments 9 & 13)
			2021 & 2023	As part of drafting the soil survey reports for the two districts the soils that are not represented in the CASC and which are considered as new upland soil types have been identified.
		2. Booklet or factsheet for study areas that describes the upland soils using the CASC (Upland CASC) with extended information of identification, interpretation and management. Draft report at annual meetings Final report	March 2021 September 2022	The concept of the development of upland soil manual - Fact Sheets was presented to the Cambodian soil to stakeholders in March 2021 and September 2022.
			Nov 2023	Final draft fact sheets have been prepared for four soils, one in Aoral District and three in Dambae District. These are the start of an upland soil manual for the entire country and it is recommended that fact sheets for other soils are created as the soils are identified in the regional survey progr4am. Ultimately these fact sheets can be combined into an upland soils manual as a companion publication to the rice soils manual. This work will also link with the recently published World Reference Base soils of Cambodia publication (DALRM 2022).

Objective 4: Develop knowledge of soil resources and capability for soil resource management

no.	activity	outputs/ milestones	completion date	comments
4.1	Develop an understanding of which tools, knowledge and approaches to building capacity are most effective to identify soil types, landscapes and constraints and improve soil management practices	*Ethics approval completed*[5]	2018	Ethics approval through Murdoch University finalised for Objective 4 activities
		Four representative case study villages are selected	2018	Four case study villages selected; Prey Thom and Tang Robang Villages in Aoral District and Svay Popeah and Srae Veaeng Villages in Dambae District.
		Baseline survey and key informant interviews completed,	June 2019	The baseline survey took the form of a community soils activity that investigated farmer understanding of the soil types. (Attachment 16)
		Annual data collection /analysis (including gender analysis) completed	Sept 2018 Jan 2019 Oct 2019 July 2021 June 2022	Community soil activity Aoral District Community soil activity Dambae District Gender analysis activity completed Fertiliser study Aoral District Fertiliser study Dambae District
		Gender analysis report	August 2018 February 2020	Gender analysis team engaged Gender and Extension Analysis completed in Prey Thom and Tang Robang Villages in Aoral District and Svay Popeah Srae Veaeng Villages in Dambae District. Report (Attachment 17).
		Annual summary report produced	Annually 2019 to 2023	Submitted to annual reports and completed monitoring and evaluation reports as required.
		End-line survey and key informant interviews completed	March 2022 March 2023	Soil fertility and fertiliser use study – Aoral District (Attachment 18). Soil fertility and fertiliser use study – Dambae District (Attachment 19). Final surveys took the form of soil fertility and fertiliser use studies for each district. Soil fertility and fertiliser use study aimed to further understand: 1. farmers understanding of soil fertility; 2. constraints to fertiliser use.
		Communication of findings	2021 2022	A Case study was submitted to the Global Soils Partnership Network. Co-authored by MU, CARDI and GDA-DALRM staff. Title - Developing climate-smart land use and land management through community learning in newly developed rural areas of southern Cambodia (Attachment 22). Findings from the community soils activity and soil fertility and fertiliser use study were presented at TropAg 2022.

[5] *Not an initial milestone*

no.	activity	outputs/ milestones	completion date	comments
4.2	Engage and communicate with stakeholders in the case study areas.	Stakeholders are engaged in each village/district	2018	Detailed planning for the community soils activity took place in 2017. Field visits in 2017 enabled initial engagement with stakeholders within communities. Following this engagement with community stakeholders continued throughout the projects activities. Through initial case study activities, the project recruited farmers for satellite trials. Using these sites for farmer field days the project continued engagement with a core group of farmers and extended the project activities into neighbouring villages in subsequent years.
		Schedule stakeholder activities for next 12 months	Annually	Detailed planning for each activity was completed annually. CUSP project team workshops were used to plan each project activity. Pre-2020 these were 1 day planning workshops. Post 2020 these were online Zoom meetings.
		Annual review meetings	Annually	Contributions were made to annual review reports and meetings as required. Project activities were also presented during online meetings and to external stakeholder meetings and conferences.

no.	activity	outputs/ milestones	completion date	comments
4.3	Develop stakeholders' capacity to improve crop productivity through new understanding of soil related constraints to crop production and improved soil management practices.	Community mapping exercise Community soils map	Jan 2019 June 2019	Activity completed (see Activity 4.1) Report completed (Attachment 14)
		Review of existing soils identification/assessment tools completed	Oct 2019	Investigated the use of the SCAMP document and other documents (e.g. Soil Tip) currently available in Cambodia in a workshop designed to teach the next users how to use SCAMP and Soil Tip. Further evaluation of tools completed as part of Activity 3.1
		Targeted training workshops (ISE and MIR training activities are listed in Activity 1.5)	22 May 2018	An introduction to the use of mid infrared spectrometer for soil analysis (Mike Wong)
			21 to 25 Oct 2019	SCAMP Training (Dr Kong, W Vance, M Wong)
			20 to 21 Feb 2019	Master class in soil survey (N Schoknecht, W Vance, S Hin)
			June 2021	Cambodian Soil Database seminar (S Hin)
			March 2019	Overview Seminar followed by ISE and MIR laboratory visit and demonstration
			December 2023	Soil Constraints and Management in Cambodia, Lecture Prof Richard Bell

			Annually	From MWS 2019 to MWS 2023 satellite trials were completed in Aoral District. MWS 2023 Dambae District was included. Farmer field days conducted to coincide with harvest of satellite trials.
			Oct 2021 March 2022 March 2023	Project workshops to develop training activities for farmer field days.
			April 2023	Training course: developed “Technology Packages for Peanut Cultivation and Sustainable Soil Fertility Management for Smallholder Farmers in Cambodian Uplands (Attachment 20) Focus – Fertilizer requirements N-P-K and soil pH. Aoral District 1. Pos Vaek village with 30 participants (22 female) 2. Tang Robang village with 30 participants (25 female). Dambae District 1. Kouk Strok village with 30 participants (4 female) Srae Veaeng village with 30 participants (7 female).
		Videos on key topics developed		Not completed Work is ongoing to develop materials for use by stakeholders for the: identification of constraints to crop production and management technologies to overcome them. Development of these tools has been delayed due to a focus on other activities and further consideration of the most appropriate tools to develop for end- and next users. The project intends to hold further discussions with PDAFF about the kind of SCAMP related tools they would find useful for building their own capacity and farmer capacity.

7 Key results and discussion

Objective 1: Introduce new methodologies for soil survey and land suitability assessment and identify main soil types and landscape patterns in upland regions of Cambodia.

Activities 1.1 Review literature and available data for soil and landscape information for the uplands of Cambodia

Information on soil survey methods and codes used was collated as well as the types of surveys, location and data storage methods. As a result of this the project completed a report and spreadsheet which reviewed the soil information available in Cambodia ("Review of Soil Information in Cambodia" (Attachment 4). Since this report the coverage of soil survey activities was extended by GDA-DALRM through FAO[6] and Asian Food & Agriculture Cooperation Initiative (AFACI) collaborations leading to the publication of the Word Reference Base Classification for Cambodian Soils (DALRM 2022) and associated map. The FAO TCP[7] project delivered Cambodian Soils Information System (CamSIS) which went offline sometime in 2021. The FAO hoped to reactivate the system in late 2023.

From this activity, it was recognised that stakeholders would benefit from standardisation and harmonisation of soil survey methodology and reporting, and multi-agency use of the soil database. To support this the project facilitated a workshop where stakeholder organisations that actively work in soil survey and land suitability assessment could discuss the best way to 1) Standardise soil survey protocols to the same framework (FAO basis); and, 2) Integrate the multi-agency soil survey data into the soil database to create a multi-organisation repository of soils survey data.

Representatives from the key stakeholder agencies (CARDI, GDA-DALRM, NUBB, University of Heng Samrin Thboung Khmum and MU) participated in the Cambodian Soil Survey Practitioners meeting (March 2022). Stakeholders presented their recent soil survey activities, methods used and data storage. Following this the group discussed options to progress the harmonisation of methods and use of shared database which can then be used in decisions on land management, land suitability assessment and soil mapping. As part of this workshop there was a facilitated discussion to come to an agreement between agencies regarding: 1) standardisation of the methods used for soil survey across agencies; and, 2) multi-agency uses of the soil database developed in ACIAR projects. To progress the recommendations and actions there is a need to assist agencies in capacity building and developing a framework for soil survey methodologies, and continued development of the database. Other key activities identified through stakeholder engagement meetings with GDA-DALRM was to update the Cambodian Soil Database with GDA-DALRM soil profile information; select a target set of samples form GDA for MIR analysis; share CUSP soil profile information to assist GDA-DALRM with developing the Cambodian Soils Map using the FAO WRB. The recommendations from the stakeholder workshop were that these activities would require the formation of technical working groups to discuss further work and to handle further technical development.

These activities have identified a number of key gaps. The project identified a need for a data audit of the current soil profile data held within different institutions as the first step to advancing the CSD to become a tool that houses all Cambodian soil survey information. There is a need for

[6] DARLM Soil Project Working Group soil project was supported by AFACI/RDA of the Republic of Korea and strongly coordinated by FAO in the framework of ASP/GSP.

[7] Technical Co-operation Programme. National soil information and land suitability evaluation system for Cambodia. TCP/CMB/3602.

repositories of soil information for use in digital soils mapping, land suitability maps, soil attribute maps, and to support policy makers. Understanding the soils organisational network, what soil information and data is available, key knowledge/information pathways and harmonization of methodologies, will support development of a government-led soil information system and soil strategies.

Activity 1.2 Determine the spatial extent of the key upland soils and their key properties and identify areas that have the potential for new upland soils.

Agricultural Soil Management Zones and Systems

The diversity and complexity of soils and landscapes across an entire country can make the communication of relevant, understandable soil and land management information difficult. At present, Cambodia's lowland rice production soils and related landscape processes are well characterised, however this is not the case with upland regions. To enable simpler communication of soil and land management issues division or stratification of the country into zones containing a smaller range of properties as a spatial framework is necessary. This geographic stratification of Cambodia provides a framework for future development of land management manuals for local agricultural extension.

Nine environmental rasters were selected to represent major controls on agricultural soils: 5 landform variables, the geology map reclassified as more general geochemistry units, the Aridity Index, an indicator of precipitation seasonality, and surface water for a dry and a wet month. Temperature information was not included because it did not vary much at the available spatial resolution, and was accounted for indirectly in the Aridity Index as evapotranspiration. Land cover surfaces were available, but predominantly reflect human activities rather than environmental gradients controlling soil qualities. These were not included but will likely be useful for developing soil management recommendations in the future. The national soil maps were not included for geographic zoning, but were used to evaluate the final products.

Eight Zones were defined as higher level groups of the original 20 Systems (Figure 1 (Zones) and Figure 2 (Systems)). The original environmental rasters (untransformed) were summarized within each major Zone to describe the local environment and help identify the major differences between zones (Table 5).

<u>Zone evaluation with reference maps</u>

Evaluation of the Zone and Systems maps with existing soil-landscape maps was a first step toward assessing their plausibility and accuracy. We checked how well the polygon boundaries of the field maps align with System boundaries, and whether the relationship between the different maps change over the landscape. A rigorous validation of the maps required verification on the ground to check how well they capture geographic patterns across the country, and whether the boundaries align with physical landscape changes. In Upland areas seven district soil maps were used in the analysis. In lowland areas the Lowland Rice Soils map (White et al., 2006) was used. In addition, 2 case studies were completed for 1) Kampong Speu Province (KP), 2) Tboung Khmum Province (TK).

Overall in upland areas, the Systems align with the hand drawn polygons well in areas with high relief and on bedrock, and typically define the break in slope between alluvial plains and steeper slopes. The boundary between Lowlands [200] and Plains [100] (lowest lying areas) also compares well in Dambae, Tram Kak, Ou Reung Ov, and Ponhea Krek. The distinction between Alluvial Plains [230 and 210 teal] and Lowlands – old alluvium [300 green] is reasonably well captured in Dambae and Aoral. Lowlands [200] are separated from Basalt Hills [600] in Dambae and Ponhea Krek.

The new maps do not distinguish well between subdivisions within the lowest lying Floodplains [100], which cover large areas of Banan, Kong Pisei, and Tram Kak. The Ponhea Krek local mapping has several subdivisions which are all classified as Systems in the Alluvial Plains [200] Zone.

The lowest lying areas may not be well captured by Systems because they contain very little variation in the environmental characteristics used for defining Zones and Systems (e.g. climate, terrain attributes).

The Rice Soils map (White et al., 2006) has four subdivisions, distinguishing between areas that grow rice in the wet or dry season, in deep or shallow water. All of these units are mapped as Floodplains [100], with small amounts of the Alluvial Plains [200] Zone (. The largest Rice Soil area (Shallow water wet season) includes small percentages of other Zones, which reflects the much broader and more diverse area included in this unit. The rainfed upland rice unit is the most diverse, with only 60 % of its area falling into the Floodplains [100]. However, this unit is small (150 sq km). The Rice Soil Map was published in the early 2000's, and the authors were unlikely to have used remote sensing products or a high resolution digital elevation model as base maps. The polygons are generalized and the map scale is small (~ 1:1,000,000), which reduces the correspondence between the polygons and the raster-derived Zones. There is likely to be important geographic variation within Zone [100] that has not been captured in these new Systems.

<u>Limitations and potential improvements</u>

Unsupervised classification worked well to explore regional soil-landscape variation across Cambodia. This statistical approach to define units from independent environmental datasets produced common spatial groupings with distinctive physical differences visible both in the maps and in summary statistics. We chose the final geographic units by comparing the maps with local soil landscape maps available for small areas of the uplands and the rice ecosystem maps in the major river valleys. These initial System and Zone maps can be improved by (1) localized modifications to the map unit legends and recommendations, (2) identifying or developing improved environmental rasters to input to modelling, and (3) applying different modelling approaches, acknowledging that some will require training datasets which are not currently available.

There is room for improvement in all aspects of the study, including the choice of input rasters, classification algorithm and parameter selection, definition of the units and hierarchical system, and method for accuracy evaluation. New or alternative data sources will be needed for progressing several of these aspects of the study. Remote sensing products are continuously improving through global efforts to model earth systems, and should be regularly reviewed for use in Cambodia. Many of the most promising classification approaches being developed in the digital soil mapping community require training data for supervised classification; if these could be developed for Cambodia, it would be worth exploring other modelling approaches. Another way to improve unsupervised approaches such as used in this study is to identify independent data for evaluating the final maps. Perhaps data currently being collected by forestry or agriculture in Cambodia could be utilized for these purposes.

We used available environmental datasets to devise a national context for understanding soil landscape differences. Existing datasets are useful, but cannot deliver a perfect output. Understanding the fundamental processes driving soil development and subsequently patterns in the landscape patterns will be needed to interpret the large variability in Cambodia's soil resources, and as this knowledge grows, mapping requirements will change also. Developing a geographic framework for Cambodia may require an iterative process where the technical approach and map applications evolve together.

This project is an initial effort to map the whole of Cambodia, and more detailed maps will be required at the district level for relevant agricultural extension. However, the System and Zone maps can help to identify similar regions and avoid duplication of effort, provides geographic boundaries to focus district level localized mapping projects, and helps national agencies identify where investment in new soil research is most needed (Attachment 1).

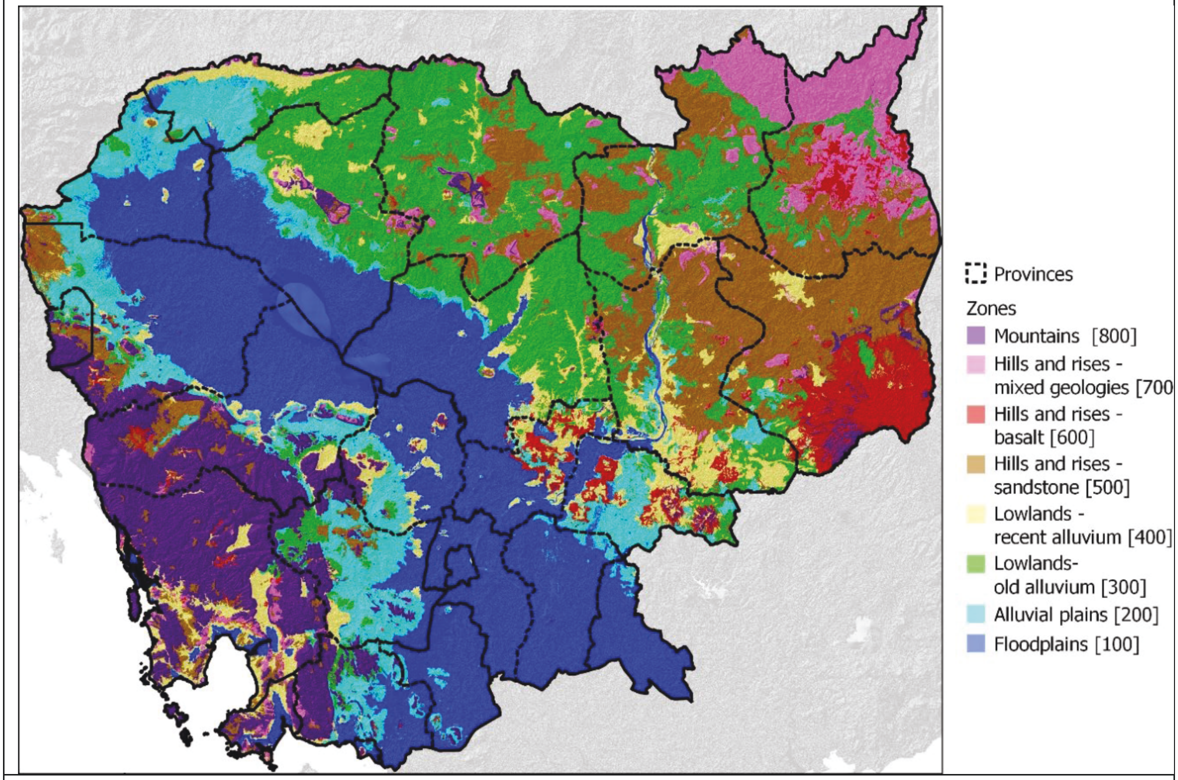

Figure 1. Agricultural soil management Zones (8 in total).

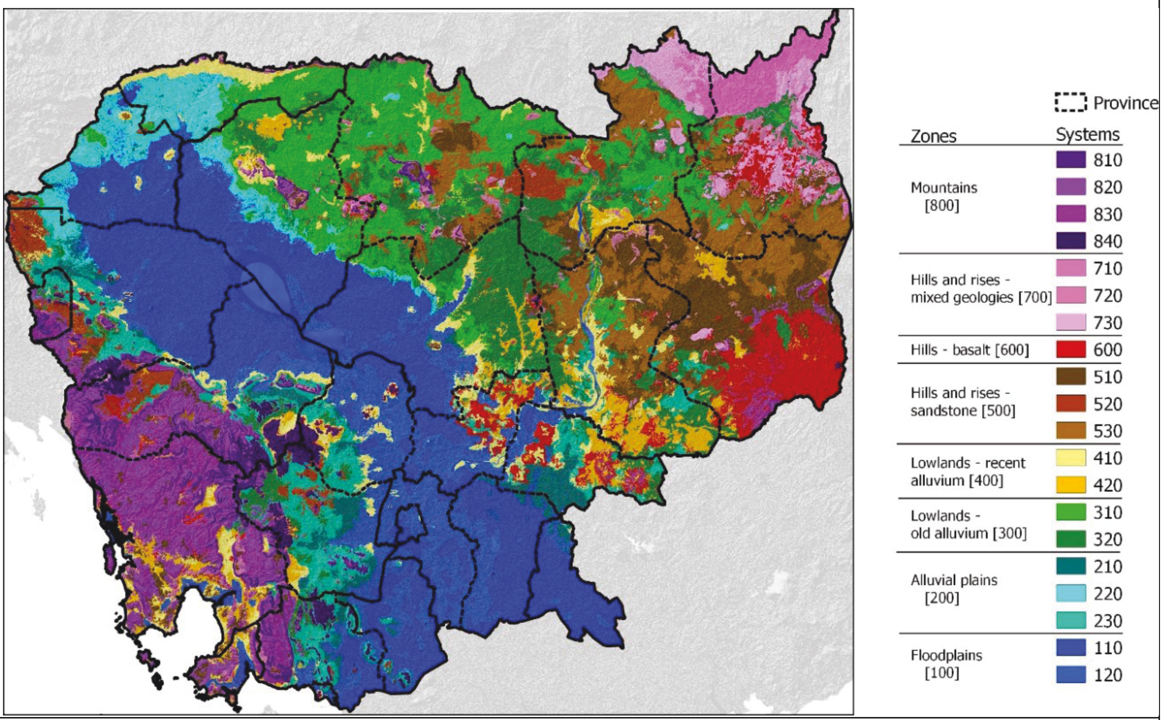

Figure 2. Agricultural soil management Systems (20 in total), subdivisions of the eight Zones shown in Figure 1.

Table 5. Agricultural soil management zones (Figure 1)

Zone		Definition	Description
Mountains [800]		Climate: Aridity index indicates wide range, low seasonality. Includes wettest regions of Cambodia. Inundation: Negligible Landforms: Mountains and steep hills on weathered rock; high peaks and ridgelines, extreme slopes Geology: Mostly Sandstone, some felsic igneous Reference Soil Groups: Leptosols (68 %), Acrisols (19 %), and Cambisols (9 %). Dominant reference soils: Dystric Leptosols (57 %)	This zone comprises the mountainous areas that are common in the south-west of Cambodia, and similar terranes that occur in scattered areas in the northern and eastern parts of the country. The mountains are mainly comprised of sedimentary sandstone, although other igneous rocks (commonly granite, rhyolite and dacite) or metamorphic rocks (such as hornfels) may also occur. Soils are generally shallow and stony. This zone includes some of the wettest areas in Cambodia, with an average annual rainfall greater than 2000 mm. Land use is mainly limited to nature conservation or forestry.
Hills and rises – mixed geologies [700]		Climate: Second least arid area in Cambodia, but strongest seasonality. Inundation: Present (main river) Landforms: Smooth, large hills, with locally high relief, and hilly/dissected terraces; moderate peaks and ridgelines, some steep slopes. Geology: Felsic igneous and metamorphic bedrock, plus sandstones; some mafic areas. Reference Soil Groups: Leptosols (45 %), Acrisols (24 %), and Ferralsols (10 %). Dominant reference soils: Loamic Dystric Leptosols (37 %)	This zone comprises hilly areas on a range of geologies, other than basalt and sandstone, that are widespread throughout the country. The steepest areas are mainly comprised of sedimentary sandstone, although other geologies such as igneous rocks (commonly granite, rhyolite and dacite) or metamorphic rocks (such as hornfels) may also occur. Soils are generally shallow and stony. Rainfall is variable, wetter in the south-western and north-eastern areas, and more strongly seasonal than other parts of the country. Land use is mainly limited to annual and perennial upland crops, animal husbandry, forestry or nature conservation.
Hills and rises – basalt [600]		Climate: moderate aridity and low seasonality Inundation: Negligible Landforms: Smooth hills, with some local high relief, interspersed with broad valleys and plains; Gentle peaks and ridgelines, some moderate slopes Geology: basalt bedrock (mafic igneous) Reference Soil Groups: Ferralsols (33 %), Leptosols (26 %), and Acrisols (17 %). Dominant reference soils: Rhodic Haplic Ferralsol (17 %)	This zone consists of typically rounded hills and rises on basalt. It is common in the eastern half of Cambodia, most notably in Kampong Cham, Tboung Khmum, Mondul Kiri and Ratanakiri Provinces. Aridity decreases and seasonality increases as elevation increases towards the east. The far south-east basalt hills and rises have the highest elevation and milder maximum temperatures Soils are usually red or brown, clayey and well structured. These soils are fertile compared to most soils of Cambodia and are generally deep. Their effective soil volume varies according to the prevalence of iron-nodules

			present, with some containing significant amounts of ironstone gravel. Many of the soils currently classified as Ferralsols may be Nitisols based on their structure and free iron contents. This zone supports a range of upland annual and perennial crops and animal husbandry. The deeper red variants usually support rubber plantations.
Hills and rises – sandstone [500]		Climate: more arid than Basalt Hills, and moderately seasonal (NE influence?) Inundation: Negligible Landforms: Dissected and smooth terraces and high plains; low hills interspersed with broad valleys (found in E and W); some moderate slopes Geology: Sandstone with some shale Reference Soil Groups: Acrisols (60 %), Leptosols (13 %), and Cambisols (13 %). Dominant reference soils: Ferralic Plinthic Acrisols (17 %)	This zone consists of typically rounded hills and rises on sandstone. It is common in the eastern and northern areas of Cambodia, but also occurs in scattered areas throughout the rest of the country. The soils are variable, but typically have a clayey subsoil and contain large amounts of iron oxides and iron-rich gravels. Land use is varied, and may include a variety of annual and perennial upland crops, animal husbandry, forestry and nature conservation.
Lowlands – recent alluvium [400]		Climate: more arid and low seasonality Inundation: Negligible Landforms: Active upper catchment floodplains, sandbars, river terraces; depositional areas higher in the landscape, mountain valleys, active alluvial fans, low slopes Geology: Dominated by young alluvium, mix of other bedrock types may be present. Reference Soil Groups: Acrisols (49 %), Cambisols (11 %), and Ferralsols (8 %). Dominant reference soils: Gleyic Acrisols (14 %)	This zone includes alluvial deposits in valley floors, river terraces and alluvial fans within landscape uplands and upper reaches of major river systems, and sandy and silty relict alluvial deposits subsequently uplifted by volcanic activity, forming colluvial slopes that fringe hills throughout the country. Soils are variable, but usually have a sandy or loamy surface with a clayey subsoil. Land use is varied, and may include a variety of annual and perennial upland crops, rice production in lower areas, animal husbandry and forestry.
Lowlands – old alluvium [300]		Climate: more arid, slight bimodality, and moderately seasonal (NE influence?) Inundation: Negligible Landforms: Stable terraces and plains, some dissected; low slopes Geology: dominated by old alluvium Reference Soil Groups: Acrisols (71 %), Cambisols (13 %), Leptosols (6 %). Dominant reference soils: Haplic Acrisols (17 %)	Widespread throughout the northern half of Cambodia, this zone includes subdued slopes, terraces and plains on older alluvial materials. Soils are variable, but usually have a sandy or loamy surface with a clayey subsoil but are not regularly waterlogged or inundated. Rainfall is variable. Land use is diverse, and includes cropping for rice and other annual crops, perennial tree crops, animal husbandry and forestry.
Alluvial plains [200]		Climate: Arid and very low seasonality Inundation: Significant in wet season	This zone comprises the widespread plains and footslopes that commonly separate the uplands from the floodplains.

		Landforms: Alluvial or lacustrine plains; transition zone between plains and other landscape features , very low slopes Geology: Dominated by old alluvium Reference Soil Groups: Acrisols (67 %), Cambisols (13 %), Leptosols (7 %). Dominant reference soils: Gleyic Acrisols (29 %)	The geology is mainly old alluvial material. Soils are variable, but usually have a sandy or loamy surface with a clayey subsoil and are often seasonally waterlogged. Rainfall is variable. Land use is mainly cropping, often for rice but also may include other annual or perennial crops.
Floodplains [100]		Climate: Most arid and very low seasonality Inundation: Extensive Landforms: Lowest part of the landscape, lake plain, valley bottoms, extremely low slopes Geology: Young alluvium and water bodies Reference Soil Groups: Acrisols (47 %), Gleysols (19 %), permanent water (8 %). Dominant reference soils: Order Gleyic Acrisols (28 %)	This zone includes widespread plains with the lower parts extensively inundated in the wet season. These plains incorporate a major part of Cambodia, stretching from the north-west, to the southern boundary. It also includes the large inland lake, the Tonle Sap and the Mekong floodplain to Kratie Province. The geology is mainly recent alluvial material. Soils are variable, but usually have a sandy or loamy surface and a clayey subsoil and are typically seasonally waterlogged. Rainfall is variable. Apart from the urban areas such as Phnom Penh, land use is mainly cropping, typically for rice.

Activity 1.3 Complete soil survey and landscape analysis of 2 districts targeted through the desktop study (Activity 1.2).

Field survey campaigns were completed in Aoral District, Kampong Speu Province and Dambae District, Tboung Khmum Province. In Aoral District, 35 sites were visited, and soil profiles from 13 exposures and 8 pit excavations were examined in detail and sampled for MIR and chemical analysis. A further 14 sites were briefly described from small intact cores extracted by soil spear and from observations of surface and landform features. In Dambae District, detailed soil profile descriptions were completed on 25 profiles, and horizons sampled, in areas of the landscape which were deemed to represent the different soil-landscape units. An additional 35 less detailed soil observations and 16 landscape and surficial observations were made in the district.

The project finished the survey of Aoral District and Dambae District in early 2019. As an alternative to whole district survey it was decided that the project concentrate on identifying upland soils across larger areas of uplands which are yet to be surveyed to identify new upland soils. The project completed soil survey of the upland areas of North and North East of Cambodia in November 2019, as there was little recorded soil data for this part of the country, despite significant clearing and development for agriculture. This region was identified as one with potential for new upland soils to be identified and described. This activity aligned the project with the priorities for soil survey and land suitability assessment in Cambodia of GDA-DALRM, which include the development of a National Soils Map for the whole country, and development of agricultural zoning and land suitability assessment. The soil survey activity of North East Cambodia comprised a reconnaissance soil survey of Mondol Kiri, Ratanak Kiri and parts of Stung Treng Provinces. Twenty-seven upland soil sites were selected along a transect through these provinces. The sites were described, and in many cases sampled, to gain a representative sample of soils likely to be present across these provinces and throughout the north-east of Cambodia more generally. Fifteen sites were described in detail from existing exposures and sampled at fixed depth increments according to CUSP protocols. All sites were classified to the FAO World Reference Base (WRB 2015) and the CASC. All samples were returned to CARDI laboratory for processing and analysis by MIR. A further 12 sites were described briefly from small intact cores, shallow exposures and from observations of surface and landform features.

Soils and Landscapes of Aoral District, Kampong Speu Province

Upland agriculture is expanding rapidly in Aoral District with clearing of substantial areas of forest on sloping land for a range of agricultural activities. Large areas have been granted as concession lands which are used for growing sugar cane, and range of annual and perennial crops and forestry.

The soils of the district are diverse and poorly understood, and to maximise the sustainable use of these lands the soil properties and management implications need to be better understood. Whilst knowledge of lowland soils associated with rice production are well known, knowledge of the upland soils has stagnated with little new information being reported since the study of Crocker (1962). The soil survey activities were reported in Soils and Landscapes of Aoral District, Kampong Speu Province (Attachment 6).

The landscape was divided into 15 map units using broad geomorphic and geologic parameters, and the described soils within these units (Figure 3, Table 6). The most represented soil within this district are described in Table 7. Within the soil analysis completed the soil groups do have variation in pH, Al content, nutrient levels and phosphorus buffering index. This leads to notable differences in these properties between soil groups may lead to soil having issues of one or more of the following: low pH, Alumiunium or manganese toxicity, low overall soil fertility, Zn deficiency, K, P, B, S deficiency.

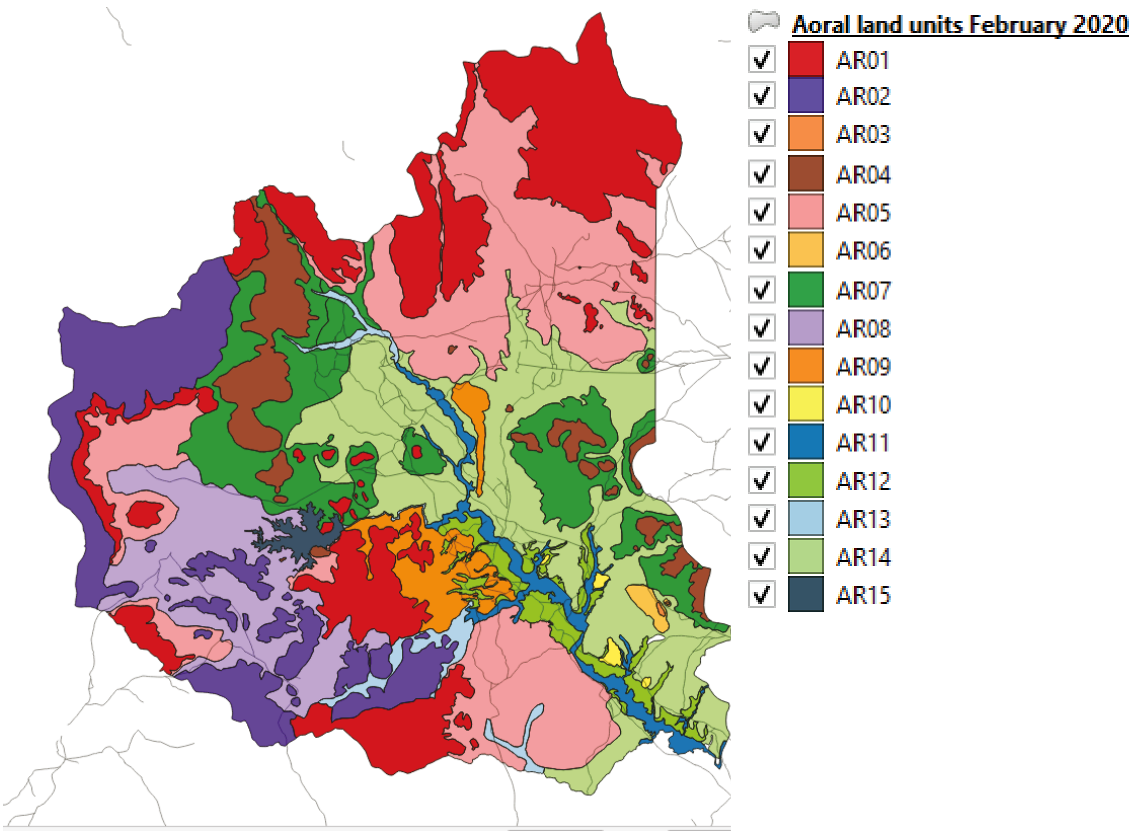

Figure 3. Aoral District Soil-landscape map

Table 6. Aoral District map units

Geomorphic unit	Geology	Map unit description	Soil description	Soil classification: Dominant WRB	Map unit label
Hills and mountains	Granite, Rhyolite, dacite and diorite	Large hills and mountains up to 1800m high, with narrow valleys. Includes low hills outcropping in undulating plains and rises	Bare rock on crests and ridges; skeletal gritty sands on rises and upper slopes; Deeper gritty sand with developed A horizons in narrow valleys	Major soils expected: Skeletic LEPTOSOL (arenic) Lithic Skeletic REGOSOL (arenic)	AR01
	Sandstone	Low hills, hills and mountains up to 1000 m high	Bare rock and skeletal soil on crests, rises and upper slopes; Shallow and rocky sands and loams of variable depth on slopes.	Major soils expected: Skeletic LEPTOSOL (arenic) Lithic Skeletic REGOSOL (arenic)	AR02
	Limestone	Small but rugged limestone hills	Bare rock, reddish loams and clays	Major soils expected: Lithic Eutric LEPTOSOL (clayic) Nudilithic LEPTOSOL	AR03
	Shale, hornfels and other metamorphic rocks	Low hills and hills	Shallow stony soils and rock outcrop. Deeper yellow to brown loamy to clayey soils in fractures in rock	Major soils expected: Lithic LEPTOSOL (loamic) Skeletic LEPTOSOL (clayic)	AR04
Footslopes of hills **Undulating hills**	Granite and other acid intrusive igneous rocks	Long gentle slopes below granite hills and mountains. Gently dissected with more or less parallel shallow drainage lines and low interfluves. Includes narrow alluvial flats for rice growing.	Deep pale to yellowish brown granitic sands. Often gritty. Possible siliceous hardpans below 1 m. May include floaters of bedrock and occasional bedrock outcrop.	Gritty granitic sands: Dystric ARENOSOL (colluvic) Sands with siliceous hardpan within top 1.0 m: Petric Dystric DURISOL (arenic) In lower slopes and depressions with clayey subsoil development: Abruptic LIXISOL (clayic) Abruptic ACRISOL (clayic)	AR05
	Limestone	Gentle slopes fringing limestone hills	Reddish clayey soils of variable depth, often containing floaters of limestone rock.	Dolomitic CAMBISOL (clayic, chromic) Calcaric CAMBISOL (clayic, chromic)	AR06

	Sandstone, shale, hornfels and other metamorphic rocks	Gentle to moderate slopes fringing hills	Yellow to brown clayey soils, often stony and over fractured rock. Soil depth highly variable.	Stony soils: Cambic, Brunic or skeletic LEPTOSOL (loamic or clayic) Deeper soils over fractured rock: Leptic or Haplic CAMBISOL (loamic or clayic) Leptic or abruptic LIXISOL (clayic)	AR07
Rises and undulating plains	Sandstone	Undulating plains and rises on weathered sandstone	Variable sandy surfaced soils, often with a clayey subsoil. May include iron indurated layers.	ACRISOL (clayic) LEPTOSOL (loamic) Haplic PLINTHOSOL (colluvic)	AR08
	Sandstone, shale, hornfels and other metamorphic rocks	Undulating plains and rises on fractured bedrock	Variable soils, but often loamy to clayey with a texture contrast over fractured rock. Rock usually within 1 m	Leptic or abruptic LIXISOL Leptic or abruptic ACRISOL	AR09
	Unconsolidated sediments	Sandy rises	Deep sands, often gravelly. Maybe be clayey and gritty at depth.	Dystric ARENOSOL (colluvic) Abruptic LIXISOL (clayic) Abruptic ACRISOL (clayic)	AR10
Valleys and plains	Active floodplain and levees	Oxbows, levees, flooded plains, river channel	Variable soils, usually young. Brown silty loams on levees.	FLUVISOL CAMBISOL	AR11
	Alluvial plain	Almost level plains near to river channels. Rice paddies.	Grey silty loam and clays	LUVISOL LIXISOL FLUVISOL	AR12
	Narrow valleys	Narrow valley floors amongst hills and rises	Variable soils	FLUVISOL LUVISOL	AR13
	Old alluvial plains – partly dissected	Extensive areas of old alluvium on gently undulating plains.	Variable soils, often with a sandy or loamy surface over clay.	Abruptic or Haplic LIXISOL (arenic, loamic or clayic) Dystric ARENOSOL (colluvic)	AR14
Water	Permanent water bodies	Lakes and dams	Not characterised		AR15

Table 7. Representative soil profiles in the district grouped into the main Reference Soil Groups (WRB 2015). Detailed description in Attachment 6.

ARENOSOL	
Description	These deep sandy soils are common on the gently undulating to undulating footslopes below the granitic hills. They are pale grey to yellow or brown in colour, often with a pinkish tinge, and usually gritty with angular quartz from the weathered granite. Dystric ARENOSOL (colluvic) Dystric ARENOSOL (colluvic) overlying siliceous hardpan below 1.0 m
Summary	Deep, coarse sandy, acidic and generally infertile soils
Texture class	Typically sandy throughout, with coarse sand
Organic Carbon	Low levels of organic carbon at the surface (<1 %) and usually very low levels (<0.5 %) in the subsoil.
pH & Al toxicity	Typically acidic at the surface (<pH_{Ca} 6.0) and strongly acidic (<pH_{Ca} 5.0) in the subsoil. In some soils Aluminium levels were very low indicating that aluminium toxicity would not be an issue at these low pHs, however some soils had significant aluminium levels (>1 mg/kg) which would indicate aluminium toxicity as a potential problem.
EC	Very low conductivity indicating they are non-saline.
CEC	Expected cation exchange capacity (CEC) across all cations is very low, indicating very low soil fertility.
Phosphorus Buffering Index (PBI)	Very low (36-70) to low (71-140) range. In some subsoils with higher clay contents PBI may be moderate.
Macronutrients	Sulfur, potassium, phosphorus and boron levels are all low indicating possible deficiencies in these elements.
Micronutrients	Cu, Fe and Mn) levels are satisfactory with the exception of Zinc which is low, however manganese toxicity may be an issue in very acid soils.
Management considerations	This group comprises deep sandy soils with low water holding capacity and generally low fertility. Soils under agriculture production are typically low in organic carbon. When they are first cleared of native vegetation they may have deep organic rich surface layers, but these are soon lost by erosion or oxidation. They are however deep and well drained and, with the exception of the soils with a silcrete hardpan, of deep rooting depth. They can perform well for agricultural crops providing they are provided with sufficient water and nutrients. They have a high risk of leaching of nutrients, and exposed topsoils are at risk of both water and wind erosion. Soils with a silcrete hardpan will have reduced rooting depth and available water and are likely to be of lower productivity.
DURISOL	
Description	These moderately deep sandy soils occasionally occur on the gently undulating to undulating slopes below the granitic hills. They are pale to yellowing in colour, and often gritty with angular quartz from the weathered granite. They overly a siliceous hardpan within 1 m from the soil surface. Petric Dystric Durisol (Arenic)
Summary	Sandy soils over siliceous hardpan within 1.0 m of the soil surface.
Texture class	Particle size analysis shows that the soils are typically sandy throughout, withy coarse sand dominating the sand fraction. In this district these soils often occur at the

	footslopes of granitic terrain, and the sand particles are often very angular, imparting a gritty feel.
Chemical properties	Chemical properties are expected to be similar to the ARENOSOLS RSG. Soil physical properties of the subsoils are expected to be a key limiting factor in this group. Low soil sampling intensity of this soil group.
Management considerations	This group comprises shallow sandy soils over a siliceous hardpan with very low water holding capacity, generally low fertility and low productivity. Soils under agriculture production are typically very low in organic carbon, especially in the subsoil. The presence of a siliceous hardpan reduces rooting depth. They can perform satisfactorily for shallow rooted agricultural crops providing they are provided with sufficient water and nutrients. They have a high risk of leaching of nutrients, and exposed topsoils are at risk of both water and wind erosion.
CAMBISOL	
Description	These shallow to moderately deep stony soils are common on the slopes adjacent to hills of sedimentary rocks. Fractured bedrock is often encountered within the top 1 m. Shallower versions of this soil are classified as LEPTOSOLS. Leptic CAMBISOL (clayic) -
Summary	A broad range of soils with limited soil formation and a lack of clear diagnostic features, but not sandy throughout. Cambisols have a cambic horizon which demonstrates some profile differentiation in terms of soil colour, clay increase and structure. Regosols have no diagnostic horizons.
Texture class	Typically loamy to clay loamy in the surface horizon/s. Subsoil textures are usually clay loamy to clayey.
Organic Carbon	Low to moderate levels of organic carbon at the surface (<2 %) and low levels (<1 %) in the subsoil.
pH & Al toxicity	Typically acidic (<pH_{Ca} 6.0) in the surface horizons, and neutral to alkaline (pH_{Ca} >6.0) in the subsoil. Aluminium levels are generally low and aluminium toxicity is unlikely.
EC	Very low conductivity indicating they are non-saline.
CEC	Cation exchange capacity across all cations is usually moderate, with a CEC of 5-10 common. Calcium is the dominant cation. Soils are general of low to moderate fertility based on their base status.
Phosphorus Buffering Index (PBI)	Moderate to high (>140) range, and highest in the clayey subsoils.
Macronutrients	Sulfur, phosphorus and boron levels are all low indicating possible deficiencies in these elements. Potassium is the exception and is in the low (<70 mg/kg) to moderate (70-200 mg/kg) range. This may be related to the chemistry of the parent material.
Micronutrients	Cu, Fe and Mn levels are satisfactory with the exception of Zinc which is sometimes low.
Management considerations	This group comprises variable loamy to clayey soils that have low to moderately fertility and moderately productive. When they are first cleared of native vegetation they may have deep organic rich surface layers, but these are soon reduced by erosion or oxidation. They are of highly variable depth, and often contain fractured bedrock at shallow depth, although this may not significantly reduce rooting depth for perennial crops as roots can penetrate along the fracture lines. They are well suited to a variety of upland agricultural crops, especially perennial fruit or nut tree crops. They are also well suited to agroforestry, especially in steeply sloping areas.

LIXISOL/ACRISOL	
Description	Grey to brown soils with a distinct clay increase down the profile are widespread n the undulating to flat plains on old alluvium, and gentle slopes on a variety of rock types. Mottling is common in the subsoil. Abruptic LIXISOL (clayic) Grey to brown clayey soils with mottled subsoils common on the alluvial plains. Haplic LIXISOL/ACRISOL (clayic)
Summary	Sandy or loamy topsoils over a clay enriched subsoil occurring within 1.0 m from the soil surface. In the subsoil more than half of the exchangeable cations are calcium, magnesium, sodium or potassium and exchangeable aluminium is generally low. Total cation exchange capacity is also low. These soils were provisionally identified as ACRISOLS in the field, but the data indicates that the many of these clay enriched soils are likely to be LIXISOLS. Further analysis is required to determine the likely distribution and occurrence of LIXISOLS versus ACRISOLS. Ferric phase, high levels of ironstone coarse fragments or segregations occur throughout the profile.
Texture class	typically sandy to loamy in the surface horizon/s with an argic subsoil horizon/s with a texture of clay loam to clay.
Organic Carbon	moderate levels of organic carbon at the surface (<2 %) and usually low to very low levels (<0.5 %) in the subsoil. Aluminium levels are generally low at the surface, increasing with depth. Soils with lower exchangeable aluminium levels will classify as LIXISOLS, the ones with higher exchangeable aluminium will classify as ACRISOLS. Aluminium toxicity is unlikely to be an issue as the pH is neutral in the subsoil layers with higher Al levels.
pH & Al toxicity	They are typically acidic (<pH_{Ca} 6.0) to strongly acidic (<pH_{Ca} 5.0) in the surface horizons, and neutral (pH_{Ca} >6.0) in the subsoil.
EC	All soils have a very low conductivity indicating they are non-saline.
CEC	Cation exchange capacity across all cations is often low, with a CEC of <5 common. The topsoil and clayey subsoil may have a moderate CEC of between 5-10. In the layers with a higher CEC, calcium is the dominant cation and pH is usually neutral. Soils are general of low fertility based on their base status.
Phosphorus Buffering Index (PBI)	moderate to high (>140) range, and highest in the
Macronutrients	Sulfur, phosphorus and boron levels are all low indicating possible deficiencies in these elements. Potassium is the exception and is in the low (<70 mg/kg) to moderate 70-200 mg/kg) range. This may be related to the chemistry of the parent material.
Micronutrients	(Cu, Fe and Mn) levels are satisfactory with the exception of Zinc which is sometimes low.
Management considerations	This group comprises variable loamy to clayey soils that have low to moderately fertility and moderately productive. When they are first cleared of native vegetation they may have deep organic rich surface layers, but these are soon reduced by erosion or oxidation. They are of highly variable depth, and often contain fracture bedrock or ironstone gravel at depth. They are well suited to a variety of upland agricultural crops, especially perennial fruit or nut tree crops. They are also well suited to agroforestry, especially in steeply sloping areas.

Soils and Landscapes of Dambae District, Tboung Khmum Province

Soil-landscape patterns of Dambae District are the consequence of sequential Pleistocene to Holocene basalt flows with variable chemical composition and the Pleistocene to Holocene sedimentary regime of the Mekong alluvial system, whose topography and drainage characteristics have been altered by recent tectonic adjustment. The combination of landform and soil distribution contributes to soil-landscape map units, which are shown for Dambae District in Figure 4, and summarily described in Table 8. (Attachment 7).

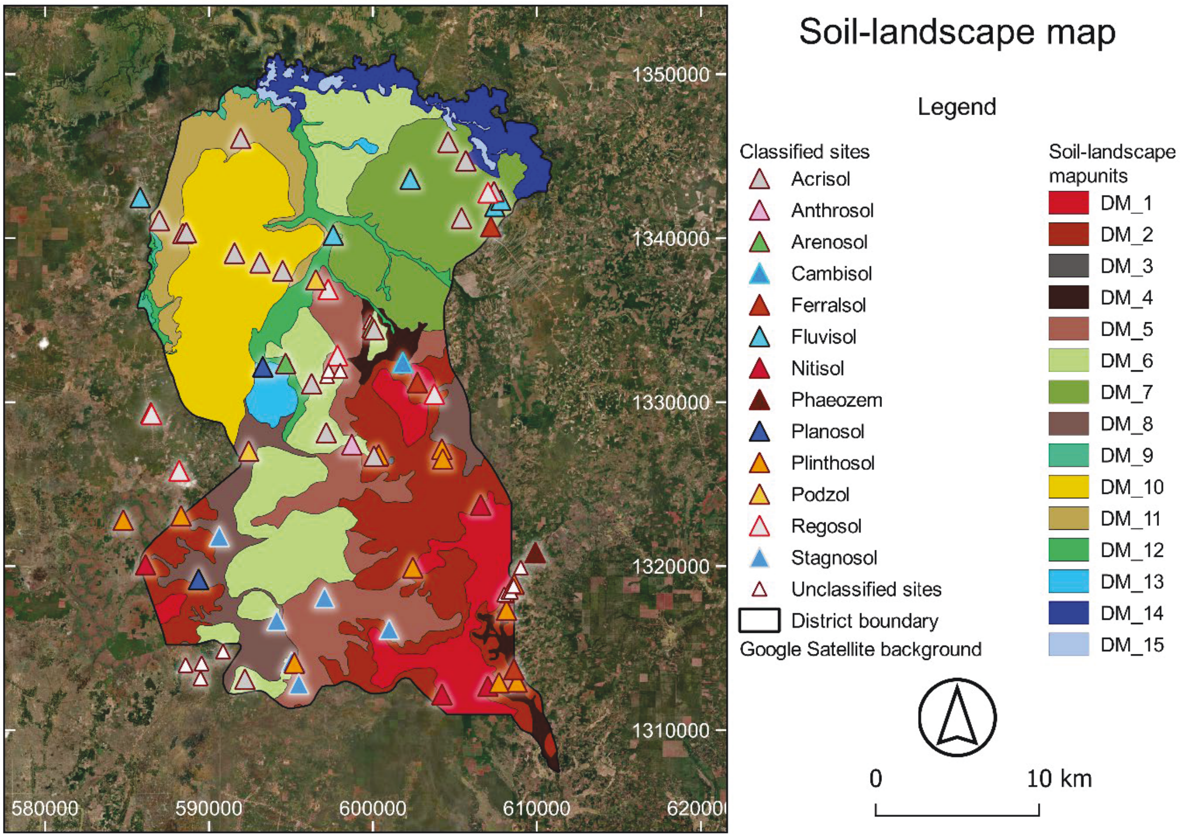

Figure 4. Dambae District Soil-landscape map.

Table 8. Dambae District map units

Map Unit label	Map Unit Name	Proportion of district (%)	Summary Description
DM_1	Basalt plateau	7.3	Gently undulating basalt plateau and upland hillslopes with Nitisols and minor red Ferralsols
DM_2	Basalt slopes	16.6	Slopes proximal to plateau with Pisoplinthic Plinthosols and Pisoplinthic Ferralsols
DM_3	Hornfels steep hill	<0.1	Steep rises and low hills with exposed rock outcrop and mixed skeletal soils, often clayey on lower slopes
DM_4	Basalt narrow valleys	2.0	Narrow valley with Vertisols and Phaeozoms, often with basalt gravel, stones and boulders
DM_5	Basalt and colluvial footslopes	10.7	Broad footslopes and alluvial plains with grey clay soil with common gravel, stones and boulders
DM_6	Alluvial plains and footslopes	15.4	Colluvial footslopes with soils of mixed origin: a complex of Acrisols and Cambisols, often Pisoplinthic, and minor Phaeozems
DM_7	Uplifted alluvium	12.0	Alluvium up-warped by volcanic doming and containing relict alluvial channels with extensive river stone and cobble beds; minor basalt flows and occasional groundwater seeps at interface between basalt flows and relict alluvium
DM_8	Broad alluvial plains	6.4	Extensive alluvial/colluvial plains between sandy and basalt rises
DM_9	Alluvial terrace	0.4	Active floodplains on major tributaries containing loamy-surfaced alluvium
DM_10	Alluvial paleoplain - level	13.2	Broad, level terrace of Pleistocene sediments with Prey Khmer fine sandy phase dominant
DM_11	Alluvial paleoplain - Eroding surface	5.8	Eroding slopes between relict alluvial plain and river channels with Prateah Lang, Krakor and minor Prey Khmer soil
DM_12	Alluvial channels	3.6	Oxbows, levees, flooded plains and channels
DM_13	Lake bed	1.3	Lacustrine deposits
DM_14	Mekong Floodplain	4.4	Terminal backslope of Mekong floodplain with Bakan soils
DM_15	Water and vegetated wetlands	0.8	Water and Permanent Swamps

Reconnaissance soil survey of Mondol Kiri, Ratanak Kiri and parts of Stung Treng Provinces

The majority of soils described during the reconnaissance soil survey of Mondol Kiri, Ratanak Kiri and parts of Stung Treng Provinces have been previously identified in published soil surveys of the Ou Reang Ov and Ponhea Krek Districts of Kampong Cham Province and a survey currently underway in the Dambae District, Tboung Khmum Province.

The geology of upland Mondol Kiri and Ratanak Kiri Provinces are dominated in area by basalt flows, which form similar soils to other Cambodian hillside and upland soils derived from basalt (Labansiek, Ou Reang Ov, and Kompong Siem in the CASC). Smaller upland areas of these provinces are composed of coarse and intermediate sedimentary rock, granite and minor metamorphic rock (Figure 5).

Deep red loamy to clayey deep friable soils on basalt Ferralsols and Nitisols (WRB) Labansiek (CASC) Example: SMC237 Site 181	Brown loamy to clayey soils with abundant Fe gravels Ferric Cambisols (WRB) Ou Reang Ov (CASC) Example: SMC237 Site 191	Dark clayey soils in lower parts of landscape Phaoezems (WRB) Kompong Siem (CASC) Example: SMC237 Site 174

Figure 5. Profile images of dominant soils present on extensive basalt uplands in the Mondul Kiri and Ratanak Kiri Provinces.

Photo: On the job training: (L to R) Paul Galloway (back to camera), Khat Piseth, Nall Vichhey, Lim Vanndy and Heng Huor. Photograph taken by team member Sim Ra.

The granitic and metamorphic hills generally have poorly-developed soils (Leptosols-WRB). These have only been briefly described (Figure **6**).

Two new soil types were identified in areas derived from sandstone and alluvial deposition.

1: Sand to sandy loam over gravel over gravelly sandy clay loam to clay in depositional areas. This soil is formed on siliclastic sediments (sand silt and minor clay) on old alluvial plains. They are well drained in the upper metre and can be poorly drained and waterlogged in the lower profile.

2. Sand over clay on hillslopes and plains, derived from sandstone.

		
Shallow loamy soils over metamorphosed sediments Leptosol (WRB) No Suitable Group (CASC) Example: SMC237 Site 180	Sand to sandy loam over gravel over gravelly sandy clay loam to clay Ferric Acrisols (WRB) No suitable Group (CASC) Example: SMC237 Site 186	Sand over clay. Abruptic Acrisol (WRB) Has similarities to Prateah Lang (CASC) Example: SMC237 Site 189

Figure 6. Profile images of previously undescribed soil types present in the Mondol Kiri and Ratanak Kiri Provinces.

Photo: The survey team, from L to R: Noel Schoknecht, Lim Vanndy, Khat Piseth, Roeun Somoeun, Paul Galloway, Heng Huor, Nall Vichhey. Photograph taken by team member Sim Ra.

Field survey incorporated significant training in site and soil description and classification to World Reference Base (FAO, 2015) standards. New surveyors Mr Heng Huor and Mr Nall Vichhey significantly improved skills throughout the trip. Experienced surveyors Mr Lim Vanndy and Mr

Khat Piseth received refresher training. The combined training resulted in improved site completion rates as skills improved throughout the trip.

Activity 1.4 Update CSD and add new soil profiles.

Throughout the project all new soil profiles (Activities 1, 2.3, 2.4) were added to the soil database. Soil chemical data from CSBP for CUSP project sites was uploaded to the database. An update to the database by DPIRD now allows a protocol and table template which will allow future uploads of chemical data. CARDI and Murdoch staff completed quality assurance checks (2019 and 2020) of the soil profile site data sheets entered into the database to ensure corrects codes were recorded and entered. Within the database itself the codes were initially updated to the FAO soil classification WRB codes (2014-15 revision) and then in 2023 to the updated to the 4th edition (IUSS 2022) and the revised Gazette of Cambodian Administration Areas. In conjunction with this the codes and methods within the field booklets and soil survey site cards were also updated ("Dataset and code definitions for the soil survey of Cambodia" Attachment 10). The project is considering how the database can be utilised (input profiles, print reports, data sharing) by CARDI and GDA-DALRM in the short term, possibly other stakeholders in the future. The recommendations from the Soil Survey Practitioners meeting (March 2022) provides guidance on the process required to advance this. In November 2019, Murdoch and DPIRD staff completed on the job training with CARDI staff on the use of the database. Stakeholders were presented with information on the development of the soil database for central storage of Cambodian soil data in the presentation by Dr Hin Sarith at the March 2022 meeting. The GDA-DALRM soil survey codes and survey data were sourced to determine how the data can be incorporated into the current database. The data collected by GDA-DALRM in the recent FAO TCP project did adhere to the FAO Guidelines to Soil Descriptions similar to the "Simple Profile Description" used in CUSP. There are some differences in codes used and these anomalies should be removed from both organisations (CARDI and GDA-DALRM) codes with the implementation of a standardised framework.

Activity 1.5 Develop rapid soil assessment methodologies and create calibration data set for the study areas.

Overview MIR Seminar

A half-day seminar was held at CARDI on 22 May 2018 and was attended by 12 people from CARDI (8), RUA (2) and MU (2). The 3-hour seminar was delivered in 3 formats to engage the audience's interest: presentation, demonstration and a video. The seminar was opened by Dr. Seng Vang, who was the current Deputy Director of CARDI. The content of the seminar was as follows:

- Welcome and Introduction to Cambodian Upland Soil Project (Dr Veng Seng)
- Presentation: What is MIR Spectroscopy? (Mike Wong)
- Video: Operating the MIR Equipment
- Presentation: MIR Calibration Strategies (Wendy Vance)
- Visit to MIR Lab to demonstrate measurement
- Presentation: MIR Calibration (Mike Wong)
- Demonstration: MIR Calibration and soil property estimation (Mike Wong/Wendy Vance)
- Presentation: Role of Rapid Soil Analysis in digital soil mapping (Wendy Vance)
- Close

The anticipated outcome of the seminar was that decision makers and general audience have a better understanding of what MIR Spectroscopy can do for them, and the benefits and costs compared with conventional methods of analysis.

Hands-on MIR training

Hands-on training was targeted at potential users of MIR at CARDI. It was conducted in Phnom Penh on 22 May to 25 May 2018 and was attended by 5 participants. The focus of the hands-on approach was to maximise practice and improve confidence. This was supported with presentations on the theory and practice of MIR and demonstrations. The participants were trained in:

- Sample preparation using soils from Aoral District. The participants trained in sub-sampling, drying, grinding, sieving soil to <0.5 mm (later changed to 0.2 mm) and re-drying soils for MIR scanning.
- Each participant practiced installing the MIR instrument and the associated MIR OPUS software on their personal computers.
- Each participant practiced registering the software and modifying the tool bars to facilitate sample scanning, display of spectra, calibration and soil analysis.
- Data preparation for MIR Calibration, loading the calibration spectra in the OPUS Software, adding the list of available soil data (component list) for calibration, saving the spectra and component list as a Method, developing calibrations for each component for soil analysis. This exercise initially used data available from Myanmar.
- Discussed effect of humidity on the equipment and practiced daily check of desiccants and humidity level in the equipment.
- Each participant operated the MIR to measure MIR reflectance of soil samples from the Aoral District and saved the MIR Spectra in a dedicated directory.

A follow-up refresher training in MIR calibration and soil analysis was conducted in September 2023. This is because calibration is a one-off activity and initial training was done using scans and soil test data for Myanmar soils. This training provided the opportunity to train using Cambodian data.

On the Job MIR training

CARDI allocated two staff members (Ms Kimsokheng and Ms Mouy Keang) to run the MIR Laboratory in the "production" mode to start analysing the Aoral samples. They were supported in their first week of work (28-31 May 2018) to help build confidence and resolve any analytical/technical problems that can arise during the day to day running of the laboratory. Issues addressed included: monitoring and cleaning soil spillage on MIR mirrors, contamination of sample cups by manual handling, variability in replicated measurements traced to inadequate grinding. The sandy soils of Aoral required further grinding from <0.5 to < 0.2 mm to achieve reproducible spectra. Subsequently Ms Kimsokheng and Ms Mouy Keang have trained Mr Sun Chankethya in the operation of the MIR.

Protocol for MIR

The MIR Protocol documented the operating procedures to analyse soils by MIR. This protocol described procedures for soil sampling and preparation, scanning samples by MIR and developing and using calibrations for soil analysis. The protocol was tested for completeness, clarity and accuracy by asking trainees to use it on its own to analyse soil samples independently.

Overview ISE Seminar

The seminar entitled "Rapid Soil Analysis using Mid-Infrared Spectroscopy (MIR) and Ion Selective Electrodes (ISE)" was presented at CARDI's Auditorium on Tuesday 19 March 2019 (Figure 4). The aim was to introduce a broad audience, including policy and decision makers, to what MIR and ISEs are and what they can do in rapid soil analysis to support rapid and cost-effective data acquisition for (1) mapping and managing baseline soil fertility and (2) determining soil test data to underpin fertiliser and lime decisions. The inclusion of MIR in the seminar topic was at the request of colleagues from the Royal University of Agriculture. The seminar was attended by 23 people from CARDI (11), Royal University of Agriculture (5), General Directorate of Agriculture (5) and private consultants (2). The seminar was followed by a laboratory visit to demonstrate soil potassium analysis by ISE to the seminar attendants.

Hands-on ISE training

This training was targeted at potential users of ISE at CARDI. It was conducted in Phnom Penh on 11 March to 15 March 2019 and was attended by 5 participants The focus of the hands-on approach was to maximise practice and improve confidence in soil analysis using ISE. This was supported with presentations on the theory and practice of ISE and demonstrations. The participants were trained in:

- Preparing extracting and standard solutions for ISE measurements
- Setting up the ISE for measurement using standard solutions
- Using soils from Aoral, the participants trained in extracting samples for ISE measurement.
- Each participant operated the ISE to measure soil pH, exchangeable K and soil solution nitrate.

On the Job ISE training

The second week of training (Monday 18-Friday 22 March 2019) consisted of supervised analysis of project soil samples for exchangeable K in a "production mode". Soil batches consisting of 20 samples each were measured in duplicate within half a day. Training focused on the preparation and logistics of analysis, direct data recording, data checking and reporting.

Protocol for ISE

The ISE Protocol documents the instructions to analyse soils using ISE. It was tested for completeness, clarity and accuracy by asking trainees to use it to analyse soil samples.

Testing field-portable ISE for timely local data

Field testing of the portable ISEs (Horiba LAQUAtwin-K-11) was performed at Kampong Speu, Aoral District in October 2019 to evaluate the logistics of using the instrument at a local village. There were no problems using the portable ISE in the field but the potassium concentrations in soil extract was often just at or above the lower limit of detection of 4 ppm K (<80 ppm Colwell K).

The Murdoch University team further tested a portable K ISE sensor (Horiba LAQUAtwin-K-11) for rapid field measurement of soil K (2021-23. The field-portable ISE could not measure soils with <80 ppm Colwell K. This detection limit is significant because this is the typical concentration below which a response to K may be expected in crops with high K requirements. The method as tested may be useful to identify soils where K may be needed but the severity of K deficiency would not be known unless current method is improved to increase sensitivity and ability to measure soils with lower K concentrations. In further tests, the field-portable ISE did not have the accuracy and reproducibility required for fertiliser recommendation. The instrument is unstable and its sensitivity decreased rapidly after analysing a few soil samples.

Application of MIR and ISE

CARDI now has the capability to analyse soils rapidly and cost-effectively by MIR and ISE. So far, 1333 soil samples were scanned in four replicates to obtain 5332 MIR spectra and run through the calibration to estimate all attributes in Table 9. These attributes were estimated with varying levels of accuracy depending on the goodness of the calibration. The coefficient of determination (r^2) is the proportion of variation in the MIR estimates accounted for by variation in the measured data. Higher values approaching 100 % indicate better MIR estimates. The root mean square error of cross validation (RMSECV) is the absolute error (sign removed by taking the square of the error) of the calibration. It must be interpreted in relation to the values of the attributes being estimated. For example cation exchange capacity (CEC) has a RMSECV of 1.20 meq/100g whereas the value for organic C is 0.121 %, the median value was 1.53 meq/100g for CEC and 0.56 % for organic C. The residual predictive deviation (RPD) (SD/RMSECV) gets around this problem by considering standard deviation. Residual predictive deviation values of 3 and above are considered to be the result of very good MIR estimates. Residual predictive deviation values of 2-3 are considered good, 1.5-2 as indicator and < 1.5 poor. These RPD classes are arbitrary. Using this approach parameters considered to be predictions of analytical quality (RPD >3) were clay %, sand %, coarse sand %, CEC, effective CEC (ECEC) and total organic carbon (TOC). Parameters considered good quality estimates were pH(H_2O), DPTA Mn and Cu. Amongst the parameters that could be used as indicators only, was pH ($CaCl_2$). A better approach is to ask (1) what I am going to use the data for and (2) what level of error can I accept to determine whether an MIR estimate is worthwhile. In some cases, an indication whether we are facing a deficiency may be sufficient. Initial calibrations were made in 2020 and these calibrations were updated as more conventional soil analysis became available. On going work is investigating the benefits of including more soil samples in the calibration.

The CARDI laboratory now has the capacity to measure available potassium and available nitrogen via ISE. The analysis of potassium, nitrate and ammonium will be most useful for rapid turnaround of soil analysis for field trials related to soil fertility requirements and can be used for general soil nutrient analysis. In addition, the equipment can be used to test fertiliser for quality in regards to percentage of N and K. By working independently, our CARDI colleagues can analyse 20 soil samples for extractable potassium in duplicate during a morning. The ISE analysis further enhances the capacity of the laboratory for rapid soils analysis, in conjunction with the MIR which was introduce in year 1 of the project.

CARDI has used the ISE facility and the MIR to analyse project soil samples taken at each sample site in the projects satellite and field experiment sites.

Table 9. Assessments of calibration of soil attributed by MIR

Attribute	Test calibration sample range	r^2	RMSECV	RPD	Number of Principal components	Goodness of calibration
Cation exchange capacity (meq/100g)	0.18-44.5	97.6	1.26	6.4	8	Very good
Exchangeable Ca (meq/100g)	0.05-25.54	96.4	0.94	5.3	8	Very good
Clay (%)	7.5-94.1	95.9	5.19	4.9	4	Very good
Organic C	0.025-2.83	94.9	0.121	4.4	5	Very Good
Exchangeable Mg (meq/100g)	0.05-18.64	94.0	0.74	4.1	7	Very Good
Sand (%)	4.67-86.85	93.2	6.58	3.8	4	Very good
ECEC (meq/100g)	0.32-44.52	87.9	2.55	2.9	7	Very Good
DTPA[1] Cu (mg/kg)	0.1-2.65	83.8	0.2	2.5	7	Good
DTPA Mn (mg/kg)	0.4-384.44	82.1	20.5	2.4	9	Good
Sulphur (mg/kg)	0.25-68.5	77.9	2.71	2.1	6	Good
DTPA Zn (mg/kg)	0.04-5.51	77.2	0.26	2.1	6	Good
pH(H_2O)	4.5-9.1	76.7	0.42	2.1	10	Good
Boron (mg/kg)	0.05-0.68	76.0	0.06	2.0	10	Good/Indicator
pH($CaCl_2$)	3.9-7.9	75.8	0.4	2.0	7	Good/Indicator
Exchangeable K (range <190 PPM)	0.02-1.5	73.0	18.5	1.9	7	Good/Indicator
Exch Al	0.01-5.85	72.0	0.51	1.9	10	Good/Indicator
PBI	7 -2418	67.6	353	1.8	9	Indicator
Electrical Conductivity (dS/m)	0.005-1.66	61.0	0.013	1.6	4	Indicator
Base Sat	6.6-100	59.4	22.1	1.6	4	Indicator
DTPA Fe (mg/kg)	0.05-118	54.9	10	1.5	8	Poor
Olsen P (mg/kg)	0-0.68	43.7	3.9	1.3	8	Poor
Exchangeable Na (meq/100g)	0.024-4.8	18.9	0.46	1.1	3	Poor

[1] diethylene-triamine-penta-acetic acid (DPTA)

Objective 2: Characterise the soil and land constraints to crop production and identify management technologies.

Activity 2.1 Review of the information describing soil and landscape characteristics, constraints and potential management strategies for improved crop production and sustainable land use in the uplands of Cambodia.

Initially a search of relevant material was completed with RUA research assistant My Vichhey Nall compiling a short review. This report and the accompanying excel metadata sheet was then use in other activities to assist in experiment design and identifying limiting factors for the land capability study. Information has been collected and compiled for various activities throughout the project and contributed to Bell et al. (2022) in collaboration with SLAM/2012/075[8].

Activity 2.2 Identify limiting factors to crop production in study areas through soil chemical and physical analysis, using traditional and rapid soils assessment methodologies.

Interpretation of the soil physical and chemical data collected throughout activities is embedded within other activities to identify soil factors limiting crop production.

Activity 2.3 Determine the extent and nature of nutrient deficiency present in the study regions and test strategies to overcome

Reports on glasshouse experiments and the land degradation study are ongoing.

Activity 2.4 Develop options to overcome soil constraints to crop production incorporating the relevant nutrient, biological and agronomic management technologies in the study areas.

Fertilizers are essential for increasing crop yields and improving food security and poverty in Cambodia. They can also help halt recent expansions of upland farming into forest land through deforestation; forest cover declined from 48 to 40 % from 2014 to 2022 (ODC 2016; 2023). The newly established upland farming system is characterised by low inputs, low and declining yields, and profits compared with paddy rice cropping. This low use of inputs has led to land degradation by SOM loss, erosion, soil acidification and nutrient mining. There is a risk that the current upland farming system may be drawn into a cycle of poverty due to loss of soil fertility and inability to address this issue due to inability of farmers to invest and profit from on-farm investments. Policy makers recognise the need to replace deforestation and current farmer practice with better agronomy underpinned by better use of fertilisers to increase productivity and sustainability. Adoption of fertiliser use will require capacity building of technical staff and farmers and on-farm approaches are very effective.

There is a lack of local site-specific data on crop yield response to fertilizers and other factors that influence crop production. This lack of evidence can make it difficult to convince farmers to adopt fertilizer use. Several approaches can be used to demonstrate the benefits of fertilizers in development work. Formal field trials are a tried-and-tested approach that involves conducting controlled experiments in farmers' fields to compare the yields of crops that are fertilized with different types and amounts of fertilizer. This approach can be very effective in demonstrating the benefits of fertilizers e.g. N, P, K, S responses, but it is very expensive, time-consuming, hard to implement. It mostly does not work in development settings.

Reported challenges in conducting formal replicated field trials to inform fertilizer use in development work highlight the need for innovative approaches to assess the benefits of

[8] *SLAM/2012/075 Management Practices for Profitable Crop-Livestock Systems in Cambodia and Lao PDR*

fertilisers. The key area of our work was developing a more farmer-friendly and easier to implement and communicate method for collecting data on crop yields, fertilizer use, and other factors that may influence crop production to assess profits, risks and sustainability of the proposed fertiliser practice.

Here, we report the use of an example of a formal field trial and on-farm trials with economic and risk analysis to communicate the benefits of fertilizers to farmers and other stakeholders. We used a partial nutrient (K and P) input-output balance to evaluate the sustainability of the practice and likely residual benefits of the fertilisers.

Results for 2019 – 2022 satellite trials

Overview of crop yields and response

The analysis of the satellite trials for Aoral and Dambae District peanut crops, treatments T1 to T3 from 2019 to 2022 are reported here. Each single suite of treatments per site was considered a replicate, these numbers can be found in Table 2 above. Differences in soil conditions, rainfall and other factors meant there was considerable variability in dry kernel yields among sites, seasons, and years (Figure 7). Compared with the farmer's common practice of using no fertiliser (T1, 1.42 t/ha), additions of P and K fertilizers improved peanut kernel yields significantly in T2 and T3. The effects of season (early or main wet seasons) or season rainfall on dry kernel yields were not significant.

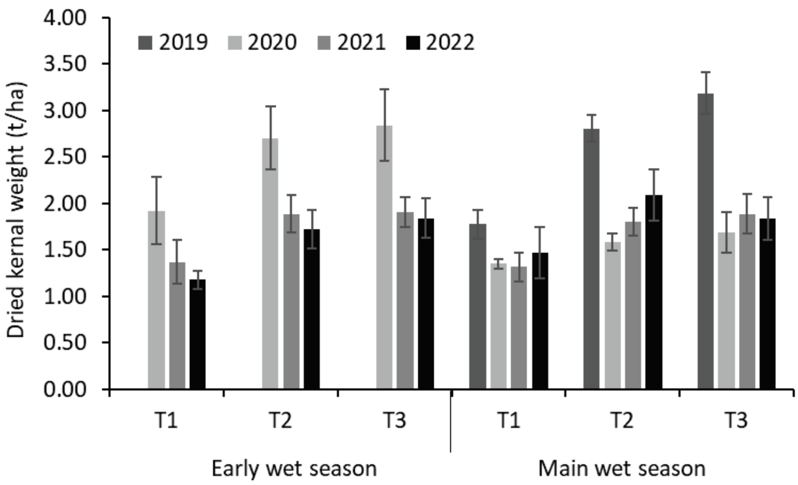

Figure 7. Mean dry kernel yields in 2019 to 2022 as influenced by common upland farming practice of no-fertiliser use (T1) and two increasing rates of fertiliser (T2 and T3).

Available P (Olsen P in ppm P) in representative topsoil soils was consistently low (< 4 ppm). Available K (exchangeable K in ppm K) ranged from adequate to high (> 100 ppm K) to low and deficient (<75 ppm K) (Figure 8). Yield response was calculated as yield (t/ha) of T1 (no fertiliser) relative to the site maximum (maximum of T1, T2 and T3). In this case, low values indicate a high response and values approaching 100 % indicate low response to fertiliser applications. Whilst results varied across sites, deficiency of P, typical of the Aoral District ensured reliable response to T2 and T3 over T1. The biggest responses occurred in plots where low P (<2 ppm P) coincided with low K (<75 ppm K).

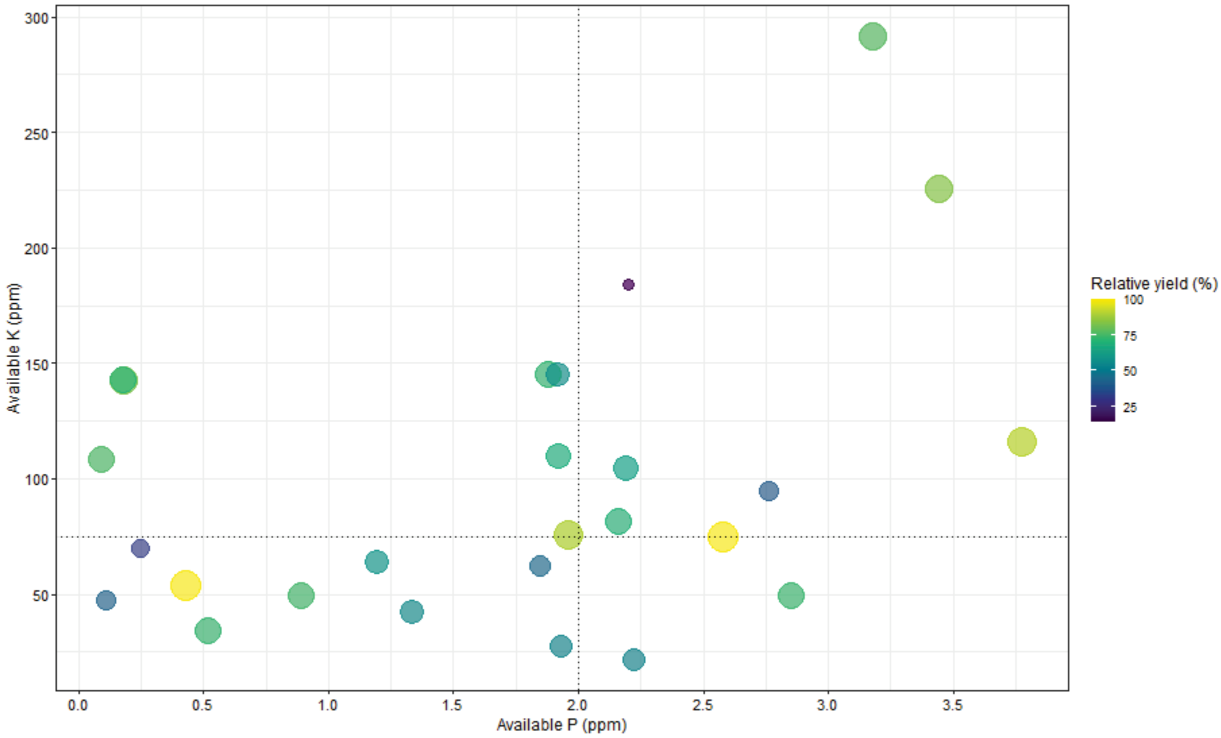

Figure 8. Yields of T1 relative to the site maximum (maximum of T1, T2 and T3). Smaller relative yields equate to larger responses to fertiliser treatment. Dotted lines indicate boundaries of the low P on the x-axis (<2 ppm P) and low K on the y-axis (<75 ppm K).

Economic Benefits of Using Fertilizers

The four year (2019-2022) average total expenditures, harvest income and profits from T1, T2 and T3 are shown in (Figure 9). Whilst the expenses varied slightly from year to year depending on local market forces and costs we chose to keep the labour and seed costs consistent across years. Data of the expenses was collected at purchase of inputs, and labour costs were estimated for all activities based on the time and number of people required to complete an activity. The expenses consist of 1158 $/ha for labour and 675 $/ha for seeds. In comparison, the corresponding average cost of fertilisers increased from 2019 to 2022 from 240 $/ha to 315 $/ha for T2 , and 348 $/ha to 466 $/ha for T3. For this analysis between season and years, the only difference in expense between T1, T2 and T3 was the cost of fertiliser. The traditional farming practice was profitable and there were opportunities to increase this profit with fertiliser use.

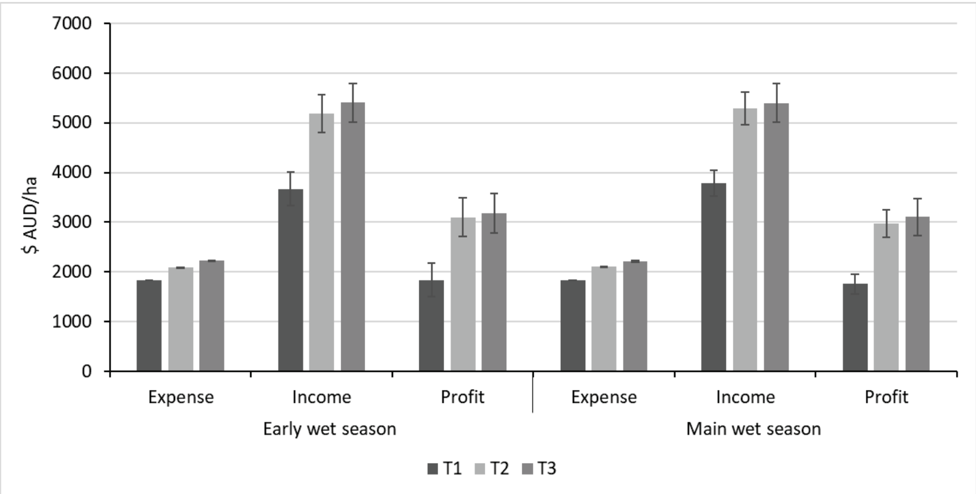

Figure 9. Mean total expense, income and profits over 4 years of on-farm satellite trials

The marginal profits of each fertiliser increment from T1 to T2 and from T2 to T3 shows sharply diminishing returns from increasing fertiliser rates to T3 (Figure 10). Marginal profits from using T2 was strong and reliable. Increasing fertiliser rate to T3 results in low and unreliable marginal profits characterized by occurrences of loss.

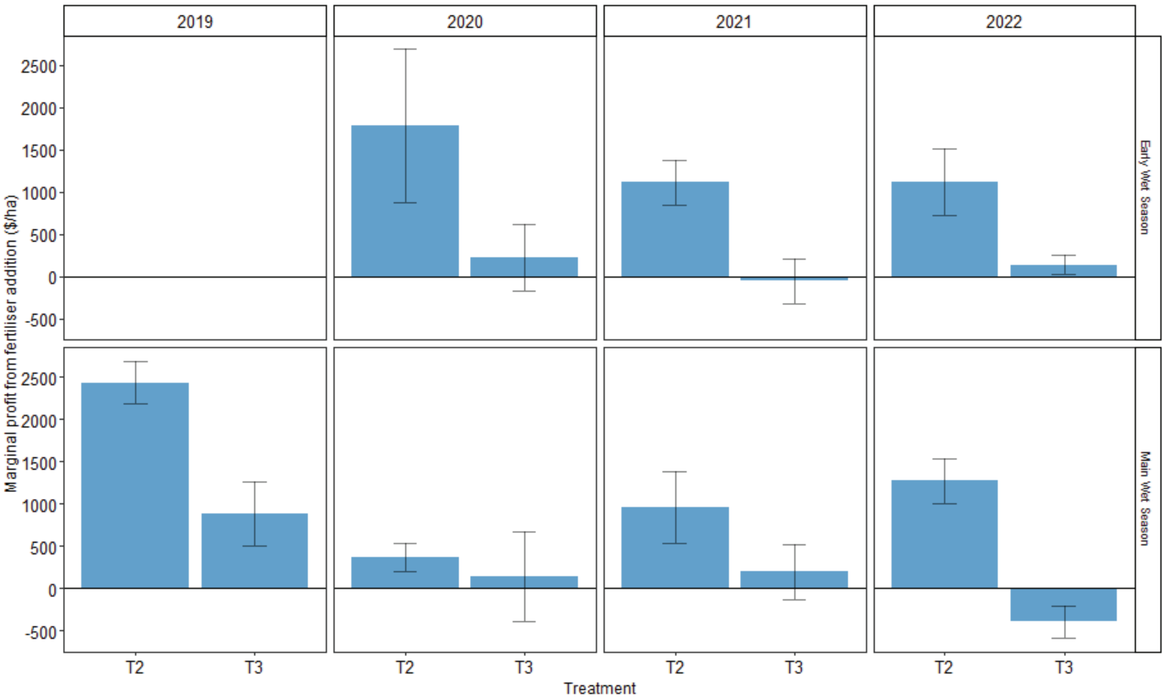

Figure 10. Mean and SE of annual marginal profits from using fertilisers compared with the next lower fertiliser treatment (T2 = Profits of (T2 – T1) and T3 = Profits of (T3 – T2). The top row represents the EWS and bottom row the MWS. In 2019, there was no EWS trials.

Farmers are interested in their site-specific marginal profits (or loss) from adopting the use of fertilisers for upland crops (Figure 11). This approach to presenting the data also allows the overall risk from investing in fertilisers to be assessed based on the probability of loss measured across the years, seasons and sites.

At the lower fertiliser rates (T2), 47 sites were profitable and 6 made a loss. The mean marginal profits from fertiliser use was 1067 $/ha (n=53). When losses occurred, the average loss was - 533 $/ha (n=6). The losses were mostly small except at site 2 in the EWS of 2020 which was - 1250 $/ha and site 3 which was - 810 $/ha in the MWS of 2021. The frequency of loss from using the T2 fertiliser treatment was 6 out of 53 trials or 11 %. The overall majority (94 %) of farmers gained from using the lower fertiliser rate irrespective of season and sites.

At the higher fertiliser rate (T3), 28 sites were profitable but 25 were making a loss. The average marginal profit at the higher fertiliser rate was 107 $/ha (n=53). This is much lower than the marginal profit of using the lower rate of fertiliser. The risk of making a marginal loss (25 out of 53 sites) was much higher (47 %). In these cases, higher investment risks were not offset by higher profits.

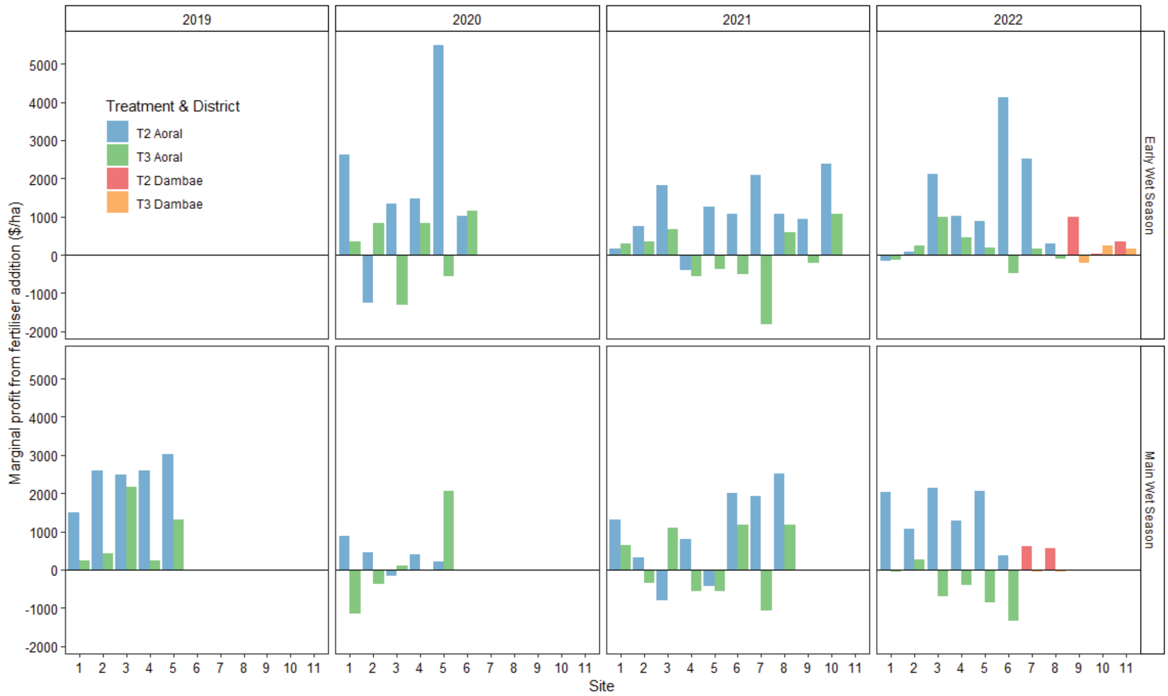

Figure 11. Site-specific marginal profit from using fertilisers compared with the next lower fertiliser treatment (T2 = Profits of (T2 – T1) and T3 = Profits of (T3 – T2). Each pair of bars represents profits or loss at one site. These sites were different each year and season. The top row represents the EWS and bottom row the MWS. In 2019, there was no EWS trials. Dambae District sites were added in 2022 and in EWS were sites 9, 10 and 11, in MWS were sites 7 and 8.

Sustainability of farming practices based on T1, T2 and T3

K balance

The four year (2019-2022) average input of K in fertilisers, removal in harvested kernels and balance from T1, T2 and T3 are shown in (Figure 12). The annual mean K balance (kg K/ha) based on fertiliser inputs of K minus removals in harvested kernels only is always negative for T1 across the four experimental years, sites and seasons (Figure 13). Using T2, results in a neutral to positive annual balance assuming that K is only removed in harvested kernels. Using T3 resulted in positive balances as greater rates of K was not offset with equivalent increases in yields and K removal. From a site-specific perspective (Figure 14), T1 is also always negative and T3 always has positive K balances. T2 is most likely to be neutral to positive and sustainable if K is only removed as harvested kernels and the other crop residues are retained on the land.

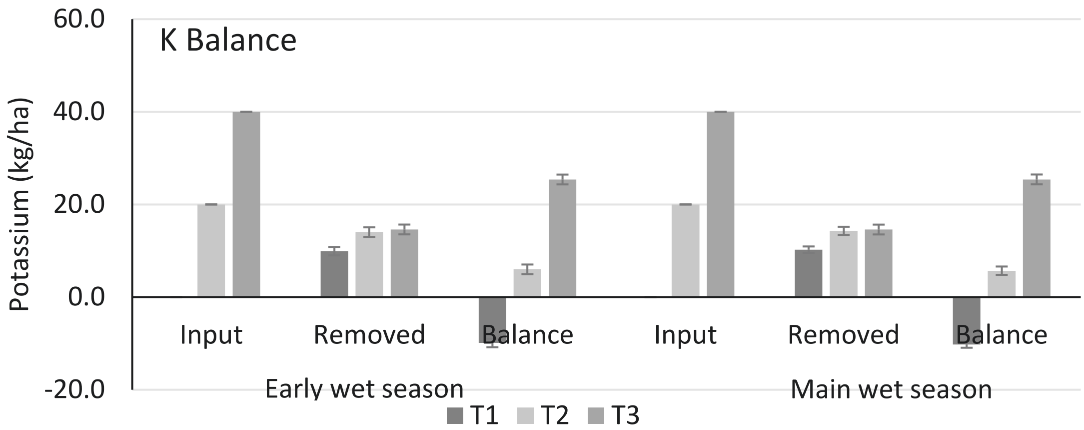

Figure 12. Four year (2019-2022) averaged K balance in the satellite trials

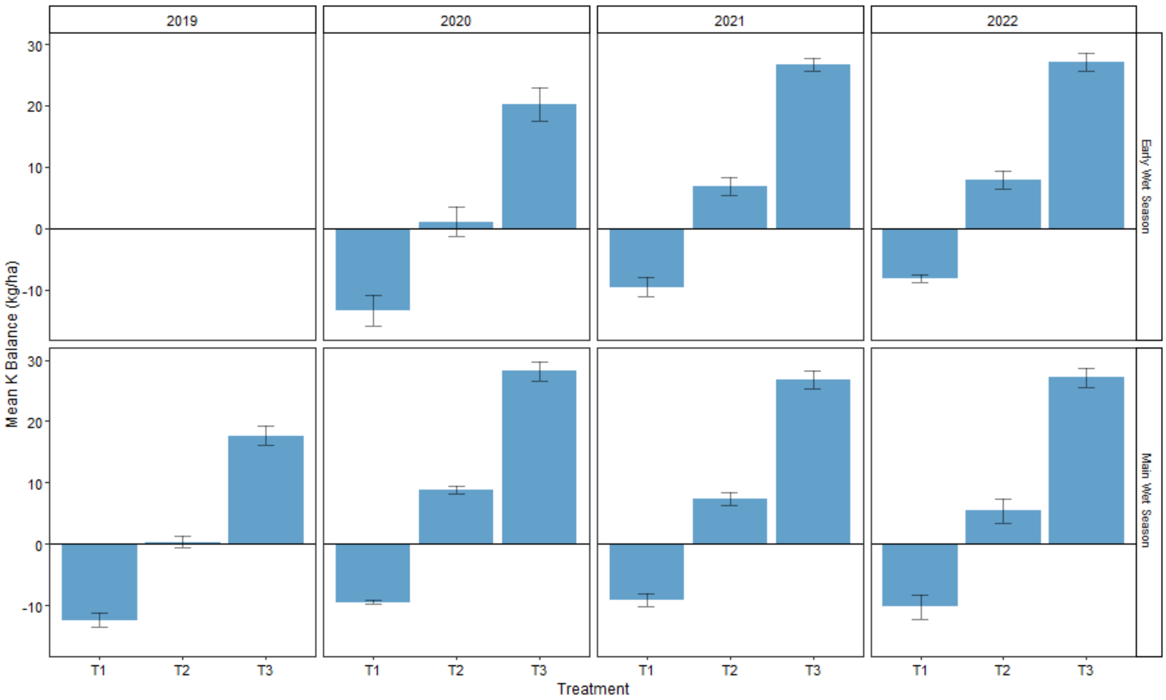

Figure 13. Mean annual K balance for T1, T2 and T3 for the early wet season (top rows) and main wet season (bottom row). In 2019, there was no EWS trials.

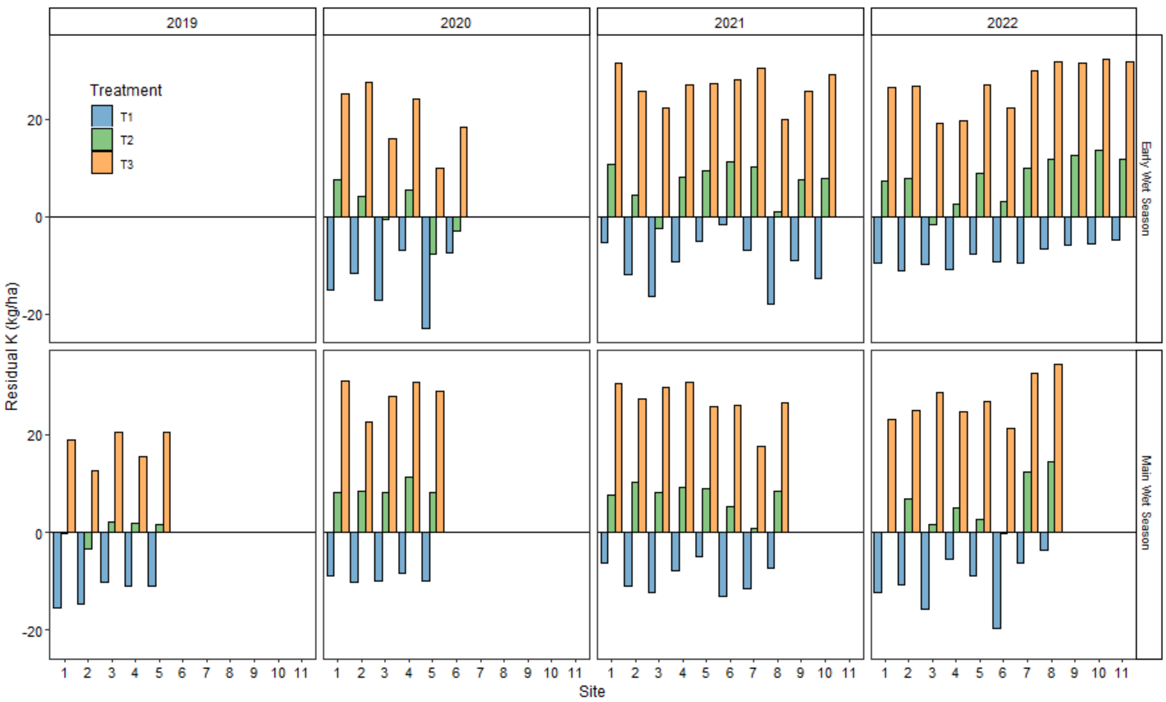

Figure 14. Site-specific K balance assumed to be residual in soil (Kg K/ha) for 2019-2022. Each set of three bars represents three treatments at one site. These sites were different each year and season. In 2019, there was no EWS trials. Dambae District sites were added in 2022 and in EWS were sites 9, 10 and 11, in MWS were sites 7 and 8.

P balance

The four year (2019-2022) average input of P in fertilisers, removal in harvested kernels and balance from T1, T2 and T3 are shown in (Figure 15). Phosphorus deficiency prevalent in the Aoral District is exacerbated by the practice T1 (Figure 16) which is mining P from the low soil reserves. T2 and especially T3 are more sustainable as they are building up the soil reserves of P (Figure 14) when P is only removed in kernels. From a site-specific perspective also, T1 is always negative and T2 and T3 always have positive P balances (Figure 17). T2 and T3 are sustainable and will build up soil P if P is only removed as harvested kernels and the other crop residues are retained on the land.

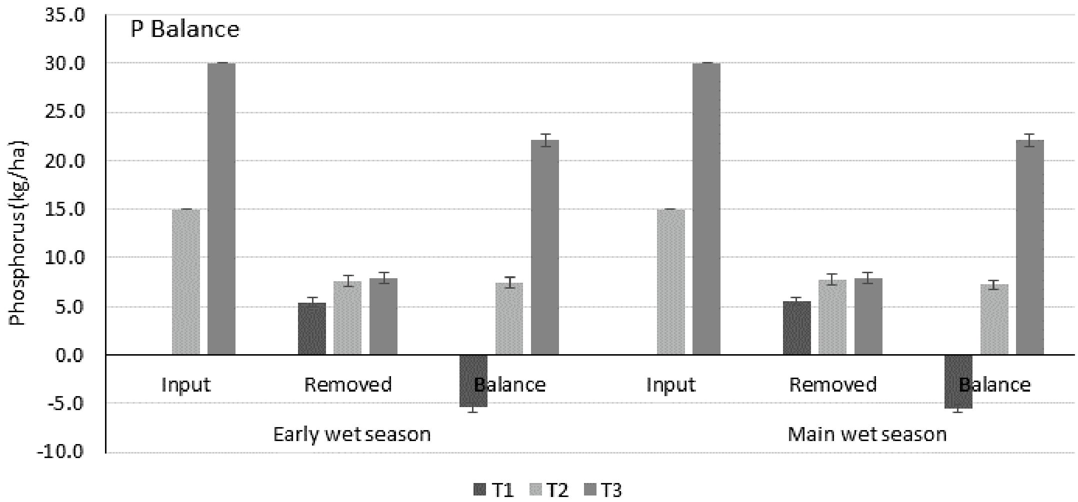

Figure 15. Four-year mean P balance for the early wet season and main wet season

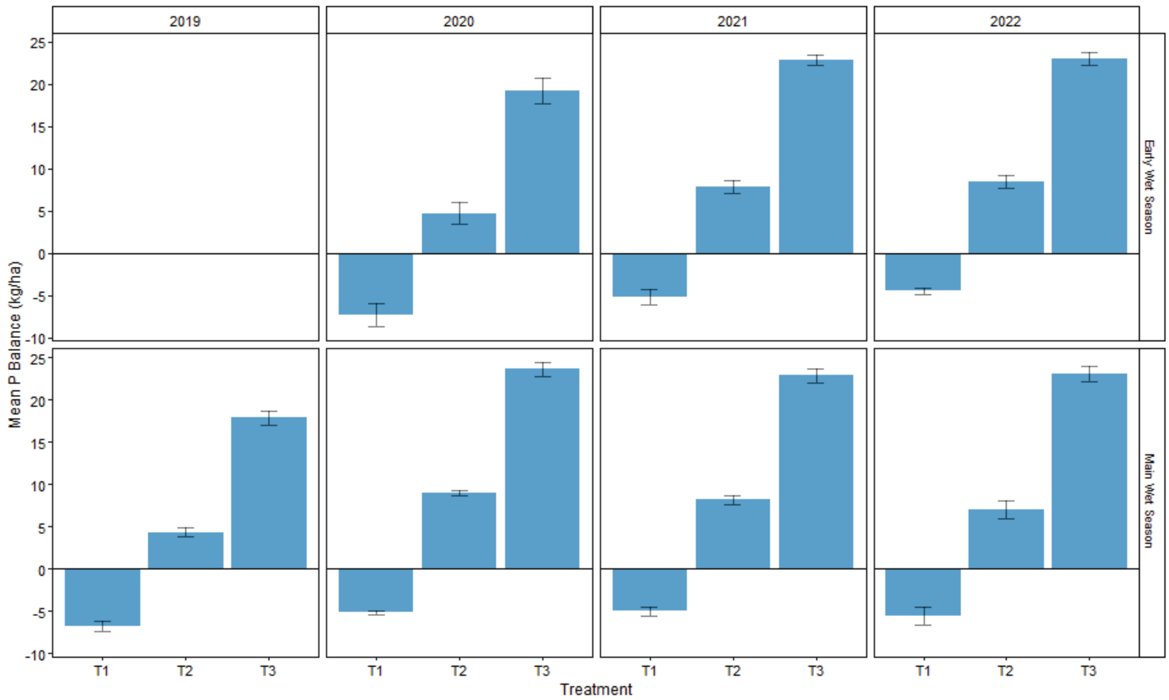

Figure 16. Mean annual P balance (kg P/ha) measured as fertiliser inputs minus removal in peanut kernels in T1, T2 and T3. In 2019, there was no EWS trials.

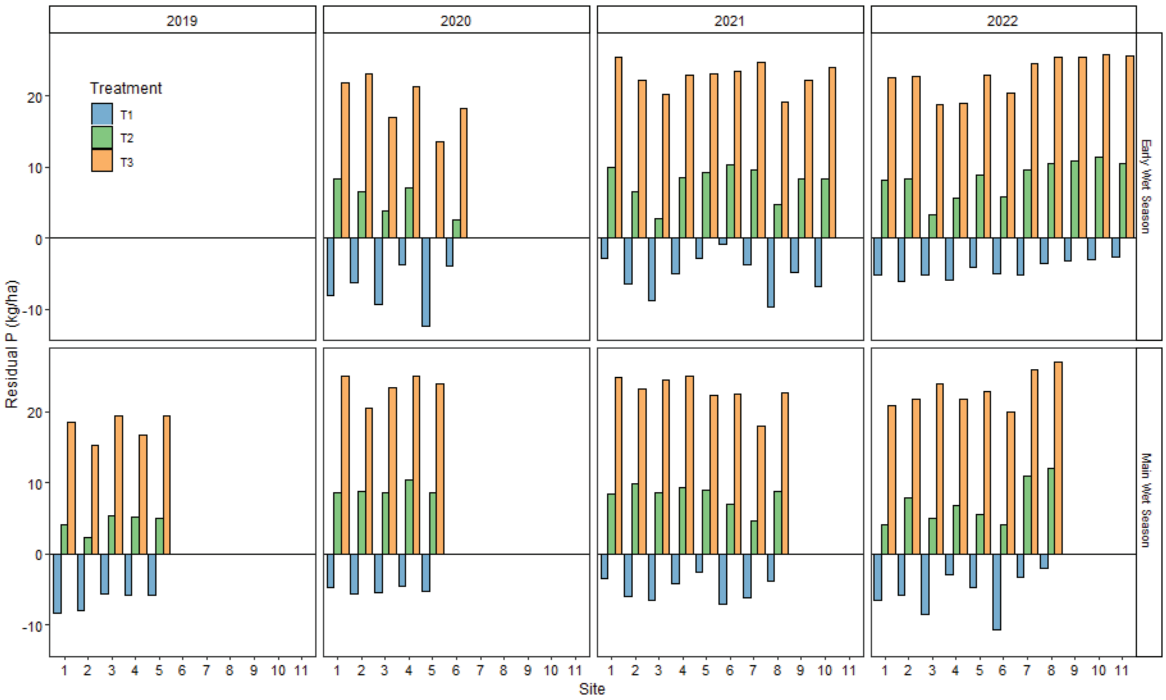

Figure 17. Site-specific P balance assumed to be residual in soil (Kg P/ha) for 2019-2022. Each set of three bars represents three treatments at one site. These sites were different each year and season. In 2019, there was no EWS trials. Dambae District sites were added in 2022 and in EWS were sites 9, 10 and 11, in MWS were sites 7 and 8.

Replicated Trials

There were significant kernel yield differences between sites (Figure 18). Treatment differences in yields were not significant at each of the four sites due to high variability, inconsistency and unpredictability of response, irrespective of soil test P and K values (Table 10 and Table 11).

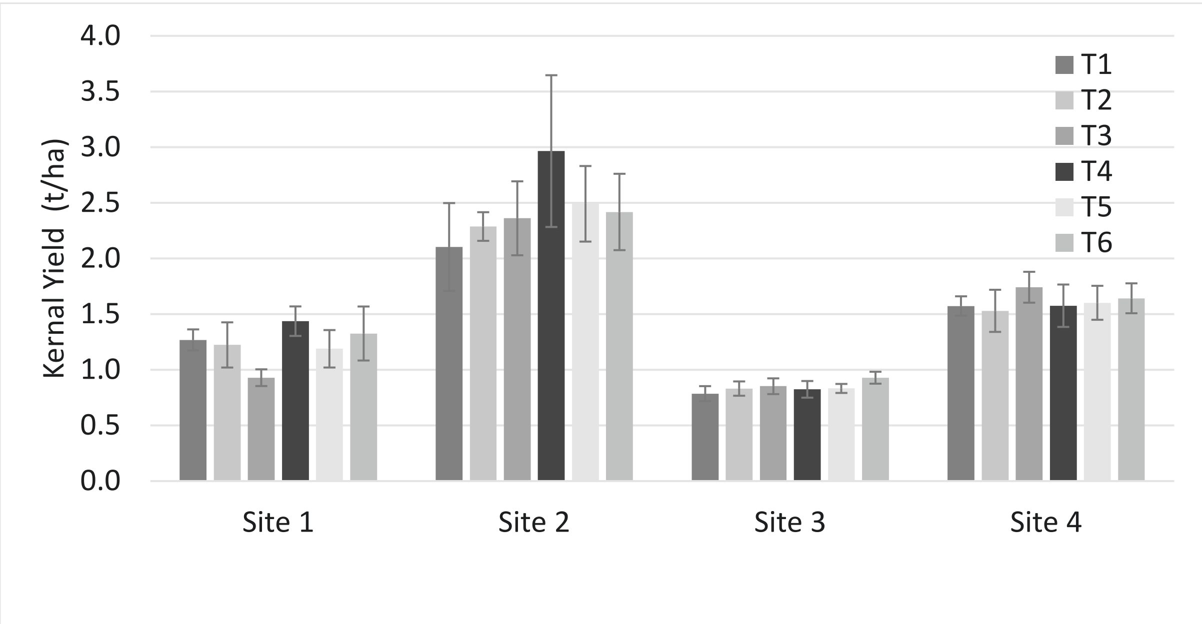

Figure 18. Kernel yields according to treatments and sites. Sites 1 (sand) and 2 (sandy loam) were in Aoral District and 3 (clay loam) and 4 (gravelly clay loam) were in Dambae.

Although these large, replicated field trials proved hard to implement and manage and resulted in non-significant treatment differences, we can make these observations:

Marginal crop response to P at three rates of K (Table 10)

- 50 % of the responses to P were negative
- 50 % of the responses to P were positive

Although soil P test values appear adequate (>40 ppm P), responses were variable, inconsistent and not predictable by soil P.

Marginal crop response to K at two rates of P (Table 11

- 31 % of the responses to K were negative
- 69 % of the responses to K were positive
- Responses were variable, inconsistent and not predictable by soil K that ranged from deficient (<50 ppm) to sufficient (>100 ppm)

Overall response to P and K rates compared with the control (T1) (Table 12)

- 16 % of responses to P and K fertilisers were negative
- 80 % of responses to P and K fertilisers were positive response
- Except for site1, all sites benefited from P and K additions.

In these formal replicated trials, initial soil test values did not predict response to K and P fertilisers. Yield responses were variable and inconsistent but mostly positive.

Simplified on-farm “satellite trials” comparing common farmer’s practice (little or usually no fertiliser used) with a “recommended” fertiliser package on many farms across many years is a more appropriate way to evaluate the benefits of fertilisers. Using the approach of single replicates across multiple farms can allow for a greater number of sites to be included as replicates. This provides a greater range of starting soil test nutrient values and allows for redundancy in replicates if sites are lost due to environmental, management or other issues.

Table 10. Marginal crop response to P at three rates of K

	Site 1	Site 2	Site 3	Site 4
Starting soil Osen P ppm (0-20 cm)	65	58	48	119
Treatments for P response calculation	Kernel yield response (kg/ha)			
T2-T1 (15P minus 0P at 0K)	-0.05	0.18	0.05	-0.04
T5-T3 (30P minus 15P at 20K)	0.26	0.13	-0.02	-0.14
T6-T4 (30P minus 15P at 40K)	-0.11	-0.55	0.10	0.07

Table 11. Marginal crop response to K at two rates of P

	Site 1	Site 2	Site 3	Site 4
Starting soil K ppm (0-20 cm)	37	105	45	380
Treatments for K response calculation	Kernel yield response (kg/ha)			
T4-T2 (40K minus 0K at 15P)	0.21	0.68	-0.01	0.05
T3-T2 (20K minus 0K at 15P)	-0.29	0.07	0.02	0.21
T4-T3 (40K minus 20K at 15P)	0.51	0.60	-0.03	-0.17
T6-T5 (40K minus 20K at 30P)	0.14	-0.07	0.10	0.04

Table 12. Treatment response compared to using 0P and 0K fertiliser (T1)

	Site 1	Site 2	Site 3	Site 4
	Crop yield response (kg/ha)			
T2 (15P 0K) minus T1	-0.05	0.18	0.05	-0.04
T3 (15P 20K) minus T1	-0.34	0.26	0.07	0.17
T4 (15P 40K) minus T1	0.17	0.86	0.04	0.00
T5 (30P 20K) minus T1	-0.08	0.39	0.05	0.03
T6 (30P 40K) minus T1	0.06	0.32	0.14	0.07

Replicated field experiment

Large formal replicated trials repeated across many sites are ambitious, resource hungry, difficult to maintain and are prone to failure e.g. due to rapid weed infestation in hot humid environments. It is often difficult to control confounding factors that may influence crop yields in these trials. Because of these difficulties, variable responses are common in on-farm development work due to unknown factors affecting yield that were not identified, monitored or managed. These responses are difficult to predict based on soil test values. Here, responses to both P and K fertiliser combinations were variable and inconsistent but mostly positive. Simplified on-farm satellite trials comparing farmer's practice (little or no fertiliser used) with a "recommended" fertiliser package on many farms across many years is likely to be a more appropriate way to evaluate and communicate the benefits of fertilisers for farmer-adoption.

Satellite Experiments

Satellite trials were a simple and effective way to engage participating farmers and their friends test and witness the benefits of fertilisers on their crops. Peanut yields gave a consistently reliable positive response to P and K fertilisers used in T2. The maximum marginal profits and lowest risk of loss were obtained with this lower rate of fertiliser. This rate is sustainable and will halt P and K depletion observed in the farmer's practice, provided that only kernels are removed from the plots and residues are returned.

Recommending T2 initially will ensure a low cost, low risk, high return and sustainable entry point for farmers to adopt fertiliser use in upland crops. It is likely that this strategy would later need to shift to higher rates of fertilisers (T3) to account for likely removals of crop residues e.g. to feed livestock and loss processes e.g. erosion, leaching, fixation etc. Even if the marginal profits of T3 remains 0 after accounting for additional revenues from residues, we would still be operating at maximum profits (this occurs where marginal cost = marginal revenue), albeit at higher risk. These recommendations will continue to be made without recourse to site-specific soil testing as this is unlikely to be available in a reliable and timely manner to support site-specific fertiliser decisions soon.

Colleagues at CARDI suggest that, with knowledge about how to use fertilisers effectively, local farmers are already adopting T2 to improve their livelihood. A few other considerations would accelerate adoption. These include:

- Making fertilizers more affordable and locally accessible to farmers
- Providing access to credit to afford the cost of fertilisers
- Encouraging sustainable nutrient management strategies to minimise and reverse soil fertility decline
- Supporting R&D to maximise the benefits of fertiliser use

Participatory rural appraisal was used to identify specific problems that farmers are facing and to determine impediments to using fertilizers. It also provided an opportunity evaluate the social benefits of fertilizers on family income, access to education and training, food security, nutrition, and gender equity.

In conclusion, by developing capacity among colleagues and farmers to address soil nutrient decline, nutrient deficiencies, low yields and profits, we can provide the evidence that is needed to convince farmers and policymakers to adopt fertilizer use and improve food security and livelihood in Cambodia.

Activity 2.5 Develop site specific management technologies for the soil-landscapes of the study regions.

Development of a Land Capability Assessment Methodology.

A tool is under development to classify on a scale of 1 to 5 the land suitability of common soils in the surveyed areas to grow and sustain different crops. From the information collected on soil constraints, soil nutrient status and management techniques in Activities 2.1 to 2.4 and reports for key soil types in Activity 1.3 a tool was developed to classify the land suitability of common soils in the surveyed area to grow and sustain different crops. A literature review of cropping systems like those of our study area identified rules to classify land characteristics and land qualities in relation to land suitability for upland crops. From these rules, land capability classification of Cambodian upland soils and landscapes was developed for profiles described by the soil survey activities.

The project developed an excel spreadsheet tool to rate a soil profile and its accompanying chemical, physical and terrain data using a comprehensive set of qualities for land suitability classes of 1 (good) to 5 (unsuitable). Common soil types identified in the soil survey were used to develop the tool. Issues of farmer concern, identified in the socio-economic work (obj 4), such as lack of fertiliser and costs, lack of labour, lack of water and land degradation during farming for upland rainfed crops were addressed. To take account of those concerns the tool includes soil qualities related to leaching and PBI, interpretation of PAW and rainfall, erosion, soil carbon and mechanisation. Next steps are to consult local experts (CARD, GDA-DALRM, RUA, other stakeholders) to refine the rules and the tool.

The LCC developed here uses these frameworks to assess capability for growing upland crops. In addition, SCAMP (Moody and Kong, 2008) was also used to assess soil and land attributes and their effect on crop growth. This work complements the work of GDA-DALRM which developed a method to assess LCC at country scale for world reference base classified soil polygons for use in broadscale policy planning. In contrast, this work will allow site specific assessment based in local soil type and soil characteristics. The intention is to produce a simple tool which allows soil and crop data entry after which a recommendation of LCC would be created. The full details of how the tool works to create the recommendation are not required by the end user. These end users are expected to be provincial extension staff, local agronomists, students and researchers. The details of the decisions and rules used in the LCC tool are described here for transparency and to improve confidence in the validity of the method. These rules are flexible and can be updated with user feedback. The tool can be upgraded to modify the rules, add soil attributes and crops.

The LCC developed here does need further testing on a greater number of upland soils and further consultation with local experts (CARD, GDA-DALRM, RUA, other stakeholders) to refine the rules and the tool.

Objective 3: Provide tools and information that enable stakeholders to identify the main soil types, and their constraints to crop production

Activity 3.1 Develop simple tools for in-field soil-landscape assessment.

The decision support framework, SCAMP (Moody and Cong, 2008) was identified as a tool to link the outputs from soil and landscape mapping to site specific soil management guidelines. The SCAMP methodology is a technical document designed for researchers and extension staff with expertise in soil interpretation. The project team identified this document as a resource that may be used in Cambodia in its current form, or a revised form.

Dr Phan Thi Cong led a workshop for the training and evaluation of SCAMP by project staff in October 2019. This was a 3-day workshop, 2 days in seminars/workshop activities and 1 day field training. A request was approved by ACIAR Publications team to translate and print SCAMP into Khmer. SCAMP translation was completed by ACIAR and was proofed by Dr Seng Vang and staff at GDA-DALRM. In 2020/2021, the project identified a need to make SCAMP more accessible and easily utilised by stakeholders in the field.

A small working group participated in the SCAMP workshop – Requirements to disseminate the SCAMP package effectively – Stakeholder groups. In its current form the SCAMP document would be difficult for some stakeholders (farmer groups and Extension and Agriculture Advisors (Agriculture Co-operators)) to navigate. The delivery of the information for some groups would require the material be organised into a different structure; some parts removed with the addition of photos and/or links to video content to assist with the characterisation of soil parameters.

A group of researchers from CARDI and GDA-DALRM met to go through the Level 1 Application to work through how the booklet could be modified.

Specific questions addressed for each attribute were:

- Is this attribute required?
- Is the method described well?
- Do the figures or tables help to describe the method?
- Can some information be removed to simplify the description without loosing the ability to describe the task?
- What should be added (video, picture, diagram)

Options for delivery could be a simplified flip book design which only has Level 1 measurements and interpretations for training farmer groups and Extension and Agriculture Advisors (Agriculture Co-operators). This could also be developed into a web based application. The group also discussed training CARDI, GDA-DALRM, University stakeholders in the current SCAMP Khmer document.

Activity 3.2 Develop a framework for documentation of upland soils as a version of the CASC.

Final draft fact sheets have been prepared for 4 soils, one in Aoral District and three in Dambae District (Attachment 9). These are the start of an upland soil manual for the entire country and it is recommended that fact sheets for other soils are created as the soils are identified in the regional survey program. As an example, the "Aoral Sand" fact sheet describes a sandy soil profile dominant in Aoral District. This soil group is partly catered for by the Prey Khmer soil group in the CASC (White et al., 1997), especially the coarse sandy phase, however there are significant differences in the upland soils of the Aoral and surrounding districts and the creation of a new soil group and phases is recommended. Ultimately these fact sheets can be combined into an upland soils manual as a companion publication to the rice soils manual. This work will also link with the recently published World Reference Base soils of Cambodia publication (DALRM 2022).

Objective 4: Develop knowledge of soil resources and capability for soil resource management

To minimise and abate land degradation will require changes to land management practices including, minimum mechanical soil disturbance, maintaining permanent organic soil cover by crop residues or cover crops, crop species diversification through crop rotation and site specific nutrient management. In Cambodia, considerable effort will be required to change the practices of many of the millions of smallholder farmers who rely on traditional farming systems and that when faced with land degradation issues tend to either "expand their agricultural frontier to new locations" or "wait and hope for the next boom crop" (Kong et al., 2021).

In order to understand smallholder farmers' knowledge, attitudes and practices relating to soils and soil fertility management CUSP sought to understand smallholder farmers' local knowledge of soils and soil fertility processes and their attitudes and practices relating to soil fertility management, in particular fertiliser use. Understanding farmer perspectives is critical for the design of new policies and programs to enable farmers to adopt more sustainable land management practices.

Community Soils Activity

Through the community soils activity the project determined farmers' perspective and understanding of: soil type, soil related constraints, suitable crops for particular soils and soil management practices. This provided a good foundation for understanding farmer perspectives of soils and what this might mean for the development of tools for identification of soils and site specific management practices. A detailed analysis of each village is available in the report 'Community soils baseline activity – Aoral and Dambae Districts'. The key insights from this work were:

- Farmers were able to identify different soil types and used a wide range of terminology to talk about soils including some new terms. Farmers from Aoral and Dambae Districts described 26 local soil types. The names given to the soils combined reference to colour (red, white, black, iron rust), texture (sticky, sandy, gravel) appearance (crocodile poo, monitor lizard poo, termite mound soil) and specific attributes (salty). A range of other descriptions were also provided; for example, participants in Aoral District explained that "when they step on *lbay ksach* / mixed sandy soil there are bubbles and some water in it that looks like *khuor andeng* / catfish brain, it's muddy and a bit white; it's like when we mix cement for construction". In Dambae District, farmers described "*sram daek* / iron rust soil" or "floating soil" which was considered to be "spicy" and the colour of "curry".
- Farmers were able to describe the properties of these soils; this included colour, texture, water holding capacity, fertility and whether the soil required fertiliser. Farmers from Tang Robang, Svay Popeah and Srae Veaeng provided more detailed knowledge perhaps owing to the amount of time they have spent farming their land.

- Farmers seemed to have clear views on what they thought would/wouldn't grow on different soil types.
- Soil fertility specifically was not readily identified as a crop production challenge; water/irrigation was more of a concern. Several people did mention diseases, in most cases specific details were not provided, but these could be nutrient deficiencies.
- Some farmers were interested in growing different crops, but those in Dambae District in particular were already heavily invested in tree crops.
- In Dambae, market information and training appears to be a major gap for farmers in terms of understanding why prices fluctuate and how to decide what to grow as well as strategies for increasing the price of a product (e.g., by storing at selling it later). This is not surprising, in a study on *What Farmer's Want* (Ashby et al., 2009), it was found that farmers want a combination of four skillsets: 1) financial education, 2) sustainable production, 3) innovation and 4) marketing, that together "represent capacity for sustainable entrepreneurship."

Gender and extension analysis

The gender and extension analysis identified and confirmed a number of important insights relevant to the design of any practices, policies and programs to enable farmers to adopt more sustainable land management.

Key findings – access and demand for extension:

- Access to any formal extension is limited, many individuals have participated in a project or trainings, accessed information through social media and television, received advice or ideas from neighbours or input suppliers, but extension support is not widely or routinely available.
- Overall there does not seem to be a culture of seeking advice and many people are satisfied with this situation, but some people said they would like to learn more.
- Individuals that had sought or received advice reported that they couldn't always follow the advice because they lacked capital, labour or technical knowledge to apply it.
- Any extension activities are likely to attract female participants and older individuals because these are the people that are available; aside from not being available younger men are less interested in attending trainings either because the topic is not of interest or because they are doing off-farm work, but some are more willing to participate in practical demonstrations.
- Having clear criteria for inviting participants can ensure more diverse participation of men, women, young, old and individuals beyond 'the usual suspects.'

Key finding – effective extension:

- PDAFF considers the following methods of engaging farmers the most effective, these methods all involve seeing and doing rather than a more traditional classroom approach. The literature supports these claims. Effective methods include study or exchange visits, demonstrating/showing a method working, learning by doing including 'homework' so they can practice what they have learned, peer-to-peer / farmer-to-farmer activities.
- PDAFF indicated that their own funding doesn't often allow them to use these methods and that they are reliant on projects and other organisations for funding these kinds of activities.

Key findings – gender:

- There is a need for gender sensitive design of land management tools/practices and research activities to ensure that any changes in roles and responsibilities does not negatively or disproportionately impact women/men's workloads, roles, responsibilities, risk or autonomy

- Location of the inputs, fields or activities used in trials/trainings/activities/practice can limit or skew participation of women particularly if they are too far away or difficult to access
- Responsibility for different crop management tasks depends on whether it is perceived of as 'heavy' or 'light' – men are generally responsible for heavy work and women light work so this can impact on who is responsible for new activities and their workloads
- Potential health and safety concerns associated with particular crops and their management can influence who will be responsible for the task (e.g., men are more likely to complete tasks that are considered to have a health risk such as applying pesticides)

Soil fertility and fertiliser use study

This study sought to: understand farmer perspectives of soil fertility; explore smallholder understanding of soil fertility; document the extent of fertiliser use; and, investigate the constraints to fertiliser use.

<u>Aoral District</u>

In Aoral District, farmers in general thought that crop yields and soil fertility were declining, the main explanation they had for this was drought and a lack of water. However, some farmers also attributed this to not using fertiliser, erosion, weeds, planting the same crop and not leaving/incorporating crop residues into the soil. Fertile soils were mostly associated with particular soil types, especially black or 'Kandeng' soils; for some particular soil attributes (loose, moist, deep and soft) indicated that a soil was fertile and/or that the soil produced a good yield. The use of fertiliser was considered one of the main ways to make a soil more fertile especially organic fertiliser/manure. Incorporating plant residues was also commonly thought to increase soil fertility. A decline in soil fertility was thought to be due to not implementing these management practices (e.g., applying fertiliser, incorporating crop residues), but was also attributed in some instances to using too much fertiliser. Farmers were not able to identify the cause of a range of crop symptoms (nutrient deficiencies, drought, pests/disease and herbicide damage) presented in photographs, instead largely attributing them to damage from insects or diseases.

The findings suggest that farmers have some knowledge of what management practices can make a soil more or less fertile; but nutrient management was not consistently reported as a key factor for sustaining (or improving) soil fertility and crop yields. That said, nearly all farmers use fertiliser on their rice crop although only a small number of farmers used fertiliser on their upland crops.

The farmers surveyed reported three main reasons for not using fertiliser on their upland crops (even though in more than half the cases (64 %) they did use fertiliser on their lowland crops):

1) They felt there was no need because the soil is still fertile; for many farmers, the upland areas they were farming had been cleared in the last 5 years.
2) They lacked the funds; payment for fertiliser was also identified as a challenge by input suppliers that said their main concern was that repayments for fertiliser purchased on credit were often late.
3) They had a range of concerns about using fertiliser; the notion that inorganic fertiliser is bad has been reported consistently throughout the project and was reiterated by farmers in this study.

Regardless of whether a farmer was using inorganic fertiliser or not, overwhelmingly, the farmers we spoke to thought inorganic fertiliser was bad for their health and their soil. Farmers expressed concern that inorganic fertilisers contain chemicals, cause people to "get sick" and "make crops less tasty". Further that, inorganic fertiliser makes "soil hard", water repellent, "sticky" and "dry" and "less fertile". The responses from farmers suggest that a major barrier to them using inorganic fertiliser is the perception that it is bad. This seems to be compounded by a lack of knowledge about fertiliser and in some cases a thinking that it is not needed. Affordability was identified as a factor for some farmers, but access to fertiliser doesn't appear to be a major issue; however, this could be because there is little demand.

In order to improve awareness and knowledge of fertilisers, farmers thought that trainings and demonstrations would be useful, particularly delivered by agricultural officers from PDAFF. Individuals from PDAFF also thought this would be valuable along with the development of tools including the use of photographs (e.g., of different fertiliser types) and farmer-to-farmer learning approaches (e.g., study tours and volunteer farmers to implement and showcase technologies). The study findings suggest that the content of this training also needs to include strategies to dispel misconceptions that inorganic fertiliser is inherently bad.

In summary, key findings included that:

- There is work to be done to dispel some of the misconceptions about fertiliser and increase understanding of fertiliser use (e.g., how to use, when to use, how much to apply, what type to use)
- There is work to be done to better understand decision making regarding fertiliser use on lowland versus upland crops including how investments in new (upland) crops and land are perceived by farmers, their annual revenue, the stability of the income and risks from year to year
- Demonstrations/trials and trainings were considered a good approach to developing farmer capacity, but visual tools e.g., photos and short videos and farmer-to-farmer learning are also needed
- Government agricultural officers are considered the most appropriate providers of knowledge
- Affordability of fertilisers is an issue for some farmers, therefore a cost-benefit analysis is an important part of demonstrations and trials
- Access and availability of fertilisers do not seem to be a major issue, but that could be because there is not great demand

<u>Dambae District</u>

In Dambae District, most farmers also thought that crop yields and soil fertility were declining. The main explanations they had for yield decline were related to fertiliser use (not using it, not using enough and using it improperly), soil fertility decline, rainfall and flooding, pests and diseases. Soil fertility decline was also largely attributed to a lack of or limited fertiliser as well as long-term cultivation of the same land and with the same crops. The application of fertiliser was considered the main way to make a soil more fertile. The majority of farmers took steps to preserve soil fertility, including fertilization and tillage. Nearly all the farmers that participated in the study applied fertiliser to their upland crops and considered it a good investment.

Affordability of fertiliser seems to be the main challenge for farmers in Dambae District. At the time of the survey fertiliser prices were increasing globally and input suppliers also identified this as a challenge. In terms of acceptability, although farmers considered inorganic fertilisers to be bad for their health and the soil this did not stop them from applying them. This suggests that farmers thought that the benefits outweighed the potential health risks and that they may not connect soil health with crop performance. Certainly, farmers were not able to identify the cause of a range of crop symptoms (nutrient deficiencies, drought, pests/disease and herbicide damage) presented in photographs, instead largely attributing them to damage from insects or diseases. Access to fertiliser did not seem to be an issue for the farmers that we spoke to.

Although more than half of the farmers that we spoke to had received training or advice regarding fertiliser use, most of the farmers said they would like additional advice in the form of training, field demonstrations or experiments. Provincial agricultural officers likewise indicated that practical activities as well as some theory would be useful. Farmers were interested in learning about applying fertiliser, types of fertiliser that are good for crops, fertiliser that are suitable for the soil type and fertiliser that is not bad for the soil or health. According to the agricultural officers, farmers would benefit from activities that advise farmers about recommended fertiliser rates, growing cover crops, practicing crop rotation, using organic fertiliser, making compost and land preparation techniques.

In summary, key findings included that:

- Fertiliser is widely used by the farmers that we spoke to on their upland crops in Dambae District
- Farmers consider fertiliser to be a good investment and farmers use it even though they harbour concerns that it is bad for their health and the soil
- Affordability of fertilisers is a key constraint and therefore a cost-benefit analysis will continue to be an important part of demonstrations and trials
- Provincial agricultural officers expressed the view that practices for improving soil health and managing soil fertility other than inorganic fertiliser should be promoted; there is an opportunity to further raise awareness of recommended fertiliser rates among farmers
- Demonstrations/trials and trainings were considered a good approach to improving farmer knowledge of fertiliser
- Government agricultural officers are considered the most appropriate providers of knowledge
- Access and availability of fertilisers do not seem to be a major issue

In conclusion, these findings highlight the need for extension activities that demonstrate effective ways to manage Cambodian upland soils that build on local understanding of soils while addressing knowledge and awareness gaps.

8 Impacts

8.1 Scientific impacts – now and in 5 years

Rapid Soil Assessment

The MIR and ISE facilities are now being used routinely to service the R&D needs of projects. In the next 5 years, we anticipate that the validity of the MIR calibration will be broadened from current project area to Cambodia more widely. With the MIR at CARDI, near-infrared spectrometer (NIR) with CIRAD and interest for an MIR facility to be adopted at GDA-DALRM a larger number of projects will have access to rapid and cost-effective soil data for natural resource assessment and management.

The MIR analysis techniques were utilised for the analysis of samples from the land degradation study, satellite trials, experiment plots as well as in collaboration with other projects and research collaborators. This analysis has become routine for project samples.

As part of Cross Project (SLAM 2018/127) soil samples were collected from other projects with a wider geographic range from those collected in CUSP. These were processed with the MIR to determine if the addition of more samples from greater geographic diversity would improve the calibration for pH of MIR samples. In addition this study included analysis which compared the calibration for pH using CARDI analysis and an analysis of the pH results from CARDI laboratory with different water sources (deionised vs distilled) used in the laboratory.

Through a collaboration with CIRAD and GDA-DALRM the project accessed soils from the archive of GDA-DALRM for MIR analysis. The spectra collected were then analysed using the CUSP calibration model. This information will be used to determine how well the current calibration fits soils collected from other locations in Cambodia. The team from CIRAD also analysed the calibration set of archive soil samples from CUSP using NIR and will use these samples for development of a NIR calibration for total organic carbon.

Ms Maria Then (PhD candidate Murdoch University) developed NIR protocols in her PhD study (not CUSP related). Ms Then used the protocols to scan 178 samples from soil profiles samples by laboratory NIR (wavelength range 800nm to 2500 nm) at Murdoch University. The same wet chemistry analysis dataset (n=66) from CSBP (See section 5. Methods) used for the MIR was utilised for calibration of the NIR spectra. Analysis completed calibration for total organic carbon. Further development of the methodology will be completed to reduce the noise in the spectra, the TOC calibration will be validated and then additional parameters will be estimated from the NIR spectra. This activity was expanded to scan the 178 samples with the portable ASD NIR equipment and the spectra will also be analysed to determine which soil attributes can be estimated by this methodology and if ca also completed. The CUSP has identified that handheld NIR devices might be a valid way to collect rapid soil analysis in the field in Cambodia. Initial NIR analysis using the laboratory based NIR is the first step to determine the validity of this.

Soil Survey and Soil Classification

The soil survey of Dambae District has confirmed the soil and landscape units of previous work in the region of Kampong Cham Province. It has also identified 2 additional soil types. The project has identified 4 new soils which will are considered as additions to the soils described in the CASC. The new soil profile types will necessitate a revision of the CASC or the development of an Upland Soils Guide.

The project has confirmed the WRB group of Nitisols (strongly structured at depth, developed on basalt) through chemical analysis (>=4 % dithionite-extract Fe and >=0.2 % Oxalate-extract Fe (then ratio ox:dith>=0.05)). These soils are a valuable and productive soil in Cambodia, and of economic importance. It is likely that they cover enough area in Cambodia to be significant. This better defines the Cambodian soils designated as Labansiek in the CASC to be split to those that are classed as non-petroferric, Nitisols, and those that are petroferric likely Ferralsols. More soils need chemical analysis to confirm distribution of these soils. These soil group was included as a note in the GDA-DALRM publication "The World Reference Base (WRB) Classification of Cambodian Soils" (DALRM 2022).

8.2 Capacity impacts – now and in 5 years

A major impact of CUSP has been capacity development of researchers, farmers and other stakeholders. Key knowledge and skills have been developed in the areas of soil survey and classification, rapid soil analysis using MIR and ISEs and farmer fertiliser use practice and profitability. Participating researchers have also developed understanding in the areas of gender-sensitive research and research management and planning. Individual research capacity has also been developed through the involvement of students.

Soil survey and classification
Training in soil survey and classification occurred throughout the project with individuals from CARDI, RUA, GDA-DALRM and NUBB. This included through on-the-job training as part of the project soil survey and classification activities, subsequent application of soil survey and classification skills for aligned ACIAR projects (e.g., ACIAR Cross Project between SMCN/2016/237 and SMCN/2014/088 (Assessment of soil pH and lime requirement in Cambodia) and CSE 2015/044 in Battambang Province) and formal training events.

The workshop on Soil Survey and Classification was attended by 12 participants and covered the principles of soil survey, how to describe a soil profile and the landscape around the soil profile, and an overview of the World Reference Base for soil classification. The CUSP project used the soil survey codes books and recording sheets developed by the project in the training and distributed the relevant soil survey and WRB guidelines from FAO to participants. The participants will be able to use the techniques and tools developed by the project in their future requirements for soil survey and classification. GDA-DALRM have already reported translating the training PowerPoint presentations, documents on the World Reference Base and soil profile data entry sheet into Khmer and using them in further training of GDA-DALRM staff.

Rapid soil analysis using MIR and ISE
The project upgraded the equipment in the CARDI Soil and Water Laboratory. This included the purchase and replacement of new equipment and recommissioning of existing equipment (see Table 13). Equipment was also recommissioned at RUA. The upgrade of equipment was accompanied by formal training, on-the-job training and ongoing mentoring.

Table 13. CUSP upgrades to CARDI and RUA soil and water laboratories

Equipment	CUSP Upgrade
MIR	Purchased
Orion meter for ISE, K, N, pH	Purchased / Replaced
Orion meter for pH, EC	Purchased / Replaced
Electrodes N, K, pH, EC, NO_{3+}, NH_{4-}	Purchased / Replaced
Jenway Flame Photometer	Recommissioned (CARDI)
Spectrolab S20 Flame Photometer	Recommissioned (RUA)

Through the commissioning of the ISE equipment and the subsequent training program in the equipment use and methodology, CUSP has exposed the staff in the laboratory to new analysis techniques. The equipment has been extensively during the project to analyse soil samples collected during soil survey, from experiment sites and sourced by the project from other stakeholders. The laboratory is continuing to analyse the soil samples.

Through the re-commissioning of CARDI's Jenway Flame Photometer and RUA's Spectrolab S20 Flame Photometer, including training, CARDI and RUA now have the capacity to analyse soils and plants, calibrate and troubleshoot any problems with the equipment. This method of soil analysis complements the rapid ISE methods by providing capacity for conventional analysis for soil and plant tissue potassium in CARDI and RUA.

Beyond the life of this project, this equipment strengthens the capacity of CARDI to use its facility for rapid soil analysis using MIR and ISEs in ongoing research and development. It enables staff to work confidently and in a safe manner to: prepare soil specimens for MIR and ISE measurements, measure soil attributes using MIR and ISE, calculate and report soil test values.

Farmer fertiliser use practice and profitability
The community soils activity and satellite trials have raised researchers' understanding of farmers' local soils knowledge, including their understanding of soil fertility and fertiliser use. This new knowledge is important as it enables researchers to make locally appropriate recommendations, design future research and development activities that recognise local understanding. For example, the satellite trial activities of the project have raised farmer awareness and understanding that fertiliser is necessary to maintain soil fertility, improve crop yield and generate higher income and profit. Through the trial process the types of fertilisers have been modified to what is available locally and amounts modified based on what farmers can afford. The CARDI Agronomy and Farming Systems team have observed that farmers associated with the project have continued to grow peanuts and now apply fertilisers to their fields.

Research management and planning
In year 1 the project instituted a methodology of using facilitated workshops to design and implement project activities. In year 2, the project continued this methodology to plan upcoming activities. We have continued to use a multi-disciplinary team approach in the planning and implementation of our activities throughout the project, this has allowed the team members to have a broader view of the issues that may lead to success or failure of an activity and development research management and planning capability.

Research capability
In addition to specific skills and knowledge developed through the project, CUSP also has a legacy of developing individual capacity to conduct research through the involvement of students. This includes four BSC theses and two MSC (one yet to be completed). Project team member Miss Te Kim Sokheng has also been awarded a John Allright Fellowship to complete her PhD research on Managing potassium nutrition for upland soils of Cambodia commencing in 2024.

8.3 Community impacts – now and in 5 years

Rapid soil analysis techniques allow evidence based advice to lift productivity and profits in a sustainable way that preserves the soil. As the soil management techniques, tools and capacity developed through this project continue to be strengthened we anticipate rural communities will benefit from improved local extension advice and planning.

The community soils activity detailed local soils knowledge; accounting for this knowledge in future tools and resources has the potential to improve the relevance and uptake of appropriate soil management practices among smallholders in the Cambodian uplands.

8.3.1 Economic impacts

The main economic impacts have been through investment in rapid soil analysis techniques and the cost-benefit analysis of fertiliser use.

The MIR facility cost $35,000 and its calibration cost $15,000. The technique has been used to analyse 1333 samples so far. Conventional analysis of these samples would have cost more than $200 K. The cost savings repaid for the facility and enables ongoing access to the facility and data for other projects.

Investment in the ISE equipment, support equipment and consumables for 1000 samples for pH, nitrate, ammonium and potassium analysis cost $8700. This investment allowed the backlog of samples waiting analysis to be cleared within a few months. We estimate that the investment repaid for itself within a year and will continue to provide benefits to CARDI and researcher's utilising the Soil and Water Laboratory into the future.

Satellite trials on peanut production compared the return on investment of no fertiliser (farmer practice) with an investment in fertiliser. The trials found that with an investment of less than 50 $USD in fertiliser farmers could generate profit of 30 to 60 % (depending on season) higher than farmer practice with no fertilizer application. The potential economic impact of this finding is far reaching as with relatively small investments farmers can considerably increase their profits.

8.3.2 Social impacts

During farmer field days in both seasons, the majority of farmers preferred the application of a single rate of fertilizer as it would be economically efficient, while its yields were competitive compared to the double fertilizer rate. The introduction of peanut crop in the target areas could draw farmers' interest in this particular crop production as it is easy to grow and provide better yield and income. Within the 3-year demonstration, the number of farmers adopting/growing peanut in the communities is gradually increasing. Participant farmers expressed their awareness of soil fertility enrichment and yield improvement via growing peanut with minimal fertilizer application. Moreover, peanut is considered a ground cover crop that could minimize the detrimental impacts of soil erosion in upland or sloping areas during the rainy season with tolerance to flash flooding as well as drought. Some farmers also applied combined N, P and K fertilizers in a small quantity in their peanut farms, but in different rates from the project recommendation.

8.3.3 Environmental impacts

The MIR technique is simple and once calibrated, does not used any chemicals at all. One piece of equipment does several analysis (Table 9).

There are no environmental impacts to report. The CARDI study of nutrient decline and land degradation will report on changes in soil properties after different durations of land clearing in Aoral District. The study of RUA in land use change and the analysis of soil characteristics under contrasting land uses (fallow, forest, tree crops, upland crops) will provide another dataset documenting the changing landscape and soil characteristics within Aoral District. This will inform the focus of future investigations that will concentrate on improving soil nutrition, reducing soil erosion and defining sustainable farming systems (land use, crop sequence and frequency) in these landscapes. The studies will provide a protocol that can be implemented in other locations that have been under recent clearing pressure in upland locations.

8.4 Communication and dissemination activities

The project used a number of methods to engage with stakeholders to disseminate project outputs many of which have been detailed in Sections 5 to 8. These included seminars, workshops, training activities and discussion papers. For these events stakeholders invited, depending on the activity, were CARDI, RUA, GDA-DALRM, CIRAD and NUBB. For all satellites trial activities there were associated farmer field days where the information on yields, economic benefits and crop management activities were presented and discussed. Further communication of project activities was through CUSP updates a newsletter published 3 times in 2018, 2019 and 2021. Conference attendance allowed communication of project scientific achievements to be disseminated to local and international audiences. Table 14, provides the details of a number of the activities completed by the project.

Table 14. Communication and dissemination activities

Newsletters	CUSP Update Newsletters (2018, 2019, 2021)
Field days	Farmer field days at satellite trial locations (from MWS 2019 to MWS 2022)
	Training course - Technology Packages for Peanut Cultivation and Sustainable Soil Fertility Management for Smallholder Farmers in Cambodian Uplands (2023)
Discussion papers	Soil Manual of Cambodia. Discussion Paper (2019)
	Proposed new soil work, Cambodia. Discussion Paper. (2019)
Journal & Book Chapter	Bell RW, Seng V, Vance WH, Philp JNM, Hin S, Touch V, Denton MD. (2022) Managing Sands of the Lower Mekong Basin to Limit Land Degradation: A Review of Properties and Limitations for Crop and Forage Production. *Soil Systems*, **6** 58.
	Hin S, Bell RW, Newsome D, Vance W, Seng V. (2023) Origin and Properties of Deep Sands of Southeastern Cambodia: Some Preliminary Findings. In: Hartemink, A.E., Huang, J. (eds) Sandy Soils. Progress in Soil Science. Springer, Cham.
Conference presentations	Boyd B, Lim S, Vance W. (2022) Cambodian smallholder farmers' soils knowledge and practices: Implications for land management capacity. TropAg. 31 Oct - 2 Nov 2022, Brisbane Australia.
	Galloway P, Bell R, Wong M, Lim V, Schoknecht N, Hin S, Vance W. (2023) Landscape evolution and soil distribution in geologically dynamic central-eastern Cambodia Soil Science Australia Conference, 25-30 June 2023, Darwin Northern Territory
	Hin S, Bell, W, Newsone, D, Vance, W, Seng, V. (2023) Origin and Properties of Deep Sands of South-Eastern Cambodia. Global Conference Sandy Soils. 31st May to 4th June 2023, Madison, Wisconsin, USA.
	Holmes K, Galloway P, Schoknecht N, Vance W, Bell R. (2023) Geographic framework to support agricultural land management in Cambodia. Soil Science Australia Conference, 25-30 June 2023, Darwin Northern Territory
	Lim V, Sun C, Srom S, Touch V, Hin S, Vance W, Wong M, Bell R. (2023) The variable effect of K and P application on peanut yield in upland soils in Cambodia. Soil Science Australia Conference, 25-30 June 2023, Darwin Northern Territory
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Stakeholder workshop	Hin S. (2019) Soil survey activities in Aoral District, Kampong Speu Province. National soil information and land suitability evaluation system for Cambodia workshop. 5 March 2019, Phnom Penh Cambodia.
	Hin S. (2022) Soil Database – Development of soil database for central storage of Cambodian soil data. Presented at the workshop on Advances in Soil Survey and Soil Classification in Cambodia. Soil surveyor practitioners joint meeting. 31 March 2022, Phnom Penh.
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	Vance W. (2022) SCAMP – What is it and how can it be used to improve knowledge of soils in Cambodia? ONLINE Presented at the workshop on Advances in Soil Survey and Soil Classification in Cambodia. Soil surveyor practitioners joint meeting. 31 March 2022, Phnom Penh
Lectures/seminars	Bell R. (2023) Soil Constraints and Management in Cambodia. CUSP Lecture. 15th November 2023, CARDI Phnom Penh.
	Hin S. (2021) Cambodian Soil Database - Introduction. June 29 2021, Online CUSP seminar.
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9 Conclusions and recommendations

The CUSP implemented a range of activities designed to improve soil knowledge and management in Cambodia. For example, the project assessed current knowledge of soil characteristics and soil constraints to crop production of farmer groups and implemented a program to demonstrate crop management techniques to reduce the yield gap. For soil surveyors and researchers, capacity building activities strengthened knowledge in soil survey and identifying soil constraints to crop production. Access to information was seen as a key requirement to improving knowledge, and to this end the project maintained and updated the CSD, facilitated dialogues between soil survey experts for the development of harmonised methods, data storage and access. At the same time the coverage of soil survey activities was extended by GDA-DALRM with investments form other donors.

Despite these improvements the project identified a number of key gaps. The project identified a need for a data audit of the current soil profile data held within different institutions as the first step to advancing the CSD to become a tool that houses all Cambodian soil survey information. In both the previous and newly surveyed Cambodian uplands there is a need to make distinctions between soils in upland areas and those previously described in the CASC, which was predominantly on lowland soils used for rice production (White et al., 1997). Interrogating the new data will provide information to identify main soils of the uplands as inputs into an upland soils manual following an agronomic classification system that Cambodian stakeholders are familiar with. In addition, newly identified main upland soils can be characterised for constraints to crop growth and land degradation risks to identify sustainable soil and land management practices.

The CUSP also identified a critical need for further activities to strengthen farmers' soil knowledge and capability to manage their soils. In the CUSP smallholder farmers demonstrated they have good knowledge of local soil types and a detailed language for describing their soils. However, there was limited understanding of soil fertility processes and the connection between crop symptoms and nutrient deficiencies. The CUSP implemented a program of engagement with farmers through satellite trials designed to demonstrate crop management techniques and provide a diagnostic of soil fertility. Satellite trials compare farmer practice to one or two of the 'new' management techniques across multiple sites. From these demonstrations farmers were able to connect fertiliser use (NPK), and rates to improved plant growth and yield. They were also able to consider economic analysis and other risk factors when considering their final preference, which was for the lower recommend rate. The satellite trials were found to be an effective method of engaging with farmers for the research activities, but a sustainable and scalable approach is needed to build capability for managing upland soil resources more broadly.

The ISE and MIR rapid soil analysis techniques were utilised for the analysis of samples from the land degradation study, satellite trials, experiment plots as well as in collaboration with other projects and research collaborators. A simple MIR equipment the size of a shoe box and costing ~Au$ 60 K calibrated can save the need to invest in separate equipment, methods, chemical and laboratory support needed to measure CEC, exchangeable Ca, Clay %, TOC, exchangeable Mg, Sand and ECEC simultaneously and accurately. This technology is particularly suited to development settings where it is hard to run a conventional lab due to numerous infrastructure, logistical and supply problems. This analysis has become routine for project samples and has been expanded to other research projects and collaborations with CARDI. The calibration provides good estimates of the TOC, sand %, clay % and parameters related to CEC. Other parameters are estimated with lower levels of accuracy. It is important that users of MIR estimates understand what they will use the data for and what level of error they should accept to determine whether an MIR estimate is worthwhile. Initial calibrations were made in 2020 using the soil samples from the project sites. These calibrations were updated as more conventional soil analysis became available and ongoing work should investigate the benefits of including more soil samples in the calibration that cover a larger representation of the different physiographic regions in Cambodia.

In summary, specific recommendations include:

- Extending the validity of the MIR calibrations for soil characterisation across Cambodia.
- Improving the framework used to develop the maps of Agricultural Land Management Zones and Systems for Cambodia describing the soil distribution in a landscape context. Next steps to improve the framework should include: consultation with stakeholder groups, inclusion of improved soil and environmental rasters as inputs, use of other classification approaches along with ground truthing.
- Ongoing investment in capacity building and technical support in soil survey, soil and landscape mapping, soil analysis, soil and crop management.
- Conducting an audit of the wealth of soil information which has been collected by a number of agencies, both within and outside of Cambodia. The audit should consider: what is available, where is it held, in what format etc. with the aim of harmonising all the available information, storing it in a national soil information system, and making it readily available to those who need it.
- Interrogating the new Cambodian uplands survey data to make distinctions between soils in upland areas and those previously described in the CASC, which was predominantly on lowland soils used for rice production (White et al., 1997). This will provide information to identify main soils of the uplands as inputs into an upland soils manual following an agronomic classification system that Cambodian stakeholders are familiar with. In addition, newly identified main upland soils can be characterised for constraints to crop growth and land degradation risks to identify sustainable soil and land management practices.
- Continuation of the Cambodian Soils Practitioners Stakeholder Group. This stakeholder group is important to support development of a government-led soil information system and development of a Cambodian soil strategy.
- Development of strategies to increase farmer understanding of fertiliser use (e.g., how to use, when to use, how much to apply, what type to use) to dispel some of the misconceptions about fertilise use.
- Ongoing research to understand farmer decision making regarding fertiliser use on lowland versus upland crops including how investments in new (upland) crops and land are perceived by farmers, their annual revenue, the stability of the income and risks from year to year.
- Development of visual tools for developing farmer soil and land management capacity e.g., photos and short videos in addition to tested strategies such as farmer-to-farmer learning, demonstrations and satellite trials.

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11 Appendixes

11.1 Appendix 1: List of abbreviations and acronyms

AFACI	Asian Food & Agriculture Cooperation Initiative
ASP	Asian Soil Partnership
CamSIS	Cambodian Soils Information System
CARDI	Cambodian Agricultural Research and Development Institute
CASC	Cambodian Agronomic Soil Classification
CEC	cation exchange capacity
CIRAD	Centre for International Development
CSA	Community Soils Activities
CSD	Cambodian Soil Database
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CUSP	Cambodian Upland Soils Project
DAP	Diammonium phosphate
DEM	Digital elevation model
DPIRD	Department of Primary Industries and Rural Development
DPTA	diethylene-triamine-penta-acetic acid
ECEC	Effective CEC
EWS	Early wet season
FAO	Food and Agriculture Organization of the United Nations
FAO TCP	Food and Agriculture Organization of the United Nations Technical Co-operation Programme
FCC	Fertility Capability Classification
GDA-DALRM	General Directorate of Agriculture - Department of Agricultural Land Resources Management
GSP	Global Soil Partnership
IPNI	International Plant Nutrition Institute
ISE	Ion selective electrode
LCC	Land capability classification
LULCC	Land Use and Land Cover Change
MIR	Mid-infrared spectrometer
MOP	Muriate of Potash
MrVBF	Multi-resolution valley bottom flatness
MWS	Main wet season
NIR	Near-infrared spectrometer
NUBB	National University of Battambang
ODC	Open Development Cambodia
PDAFF	Provincial Department of Agriculture, Forestry and Fisheries
r^2	Coefficient of determination
RGC	Royal Government of Cambodia
RMSECV	The root mean square error of cross validation
RPD	The residual predictive deviation

RUA	Royal university of Agriculture
SCAMP	Soil Constraints and Management Package
SRTM	Shuttle Radar Topography Mission
TOC	Total organic carbon
TSP	Triple superphosphate
WRB	World Reference Base