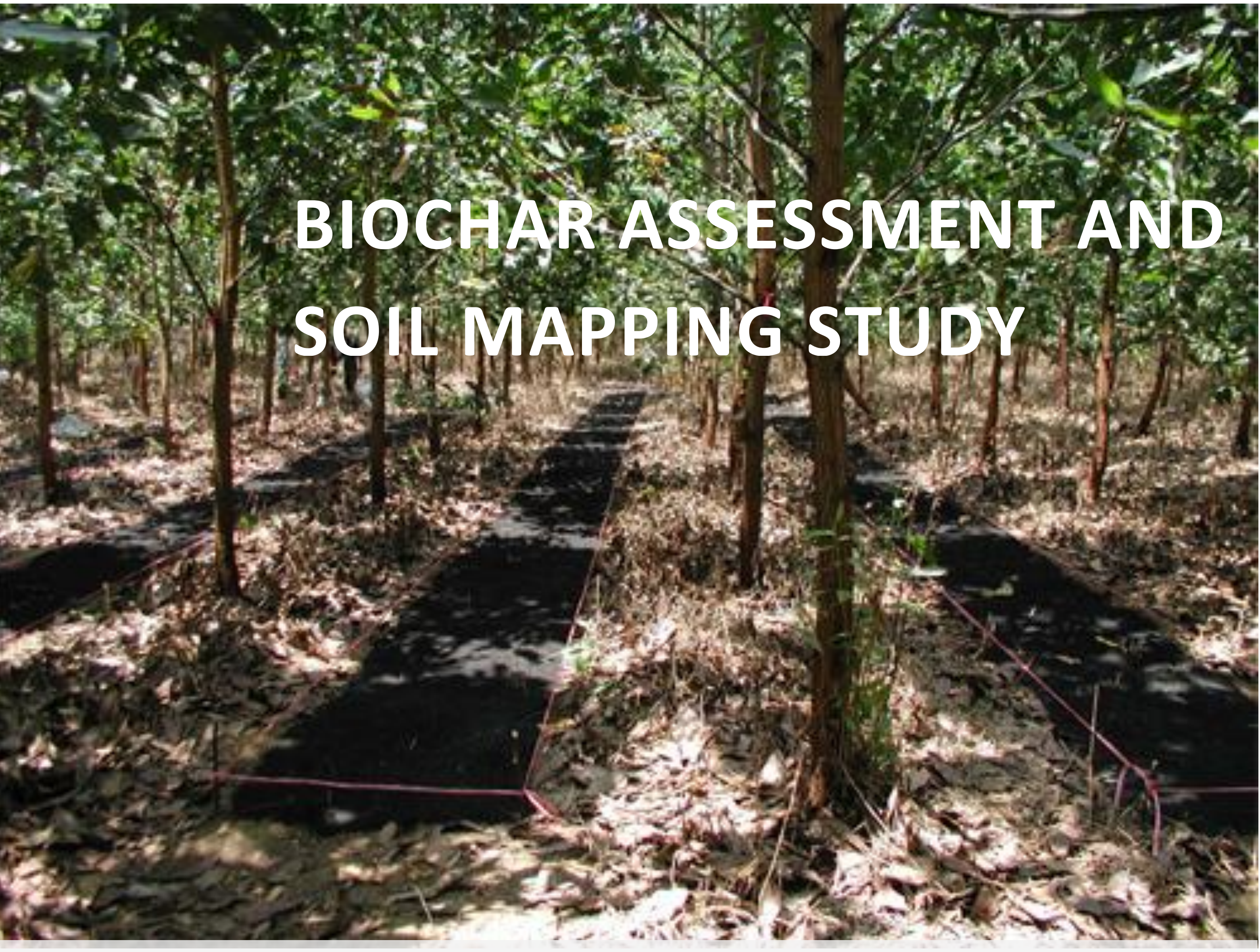
TA8163-REG: IMPLEMENTING THE GREATER MEKONG SUB-REGION CORE AGRICULTURE SUPPORT PROGRAM (Phase 2)

BIOCHAR ASSESSMENT AND SOIL MAPPING STUDY



Biochar Assessment Final Report:
Soils Mapping and Identification of Potential Biochar 'Hotspots' and Pilot Sites in the GMS

Prepared by: ICEM

Prepared for: Asian Development Bank

Citation: ICEM. 2016. *TA8163-REG Biochar Assessment Final Report: Soils Mapping and Identification of Potential Biochar 'Hotspots' and Pilot Sites in the GMS.* Prepared for the Asian Development Bank.

More information: www.icem.com.au | info@icem.com.au
ICEM - International Centre for Environmental Management
6A Lane 49, To Ngoc Van,
Tay Ho, HANOI,
Socialist Republic of Viet Nam

Team: Project Team: Balwant Singh (Team Leader / Biochar Assessment and Soil Specialist), Nguyen Cong Vinh (Assistant Biochar Assessment and Soil Specialist), Mai Ky Vinh (GIS and Soil Mapping Specialist).

TABLE OF CONTENTS

LIST OF FIGURES

MAIN REPORT

APPENDICES

LIST OF TABLES

MAIN REPORT

APPENDICES

1 EXECUTIVE SUMMARY

Biochar is the carbon rich product produced when biomass such as such as wood, manure or leaves, is heated with little or no available oxygen. The production and application of biochar into the soils offer multiple potential benefits:

- Store organic carbon in the soil on a millennia scale thus providing climate change mitigation benefits;
- Significant soil improvements, such as releasing nutrient elements, reducing nutrient leaching and gaseous losses, reducing soil acidity, increasing water holding capacity, and improving the soil fauna or soil biological function.

Biochar production also provides:

- An efficient and renewable energy source;
- A sustainable solution for the management of green wastes;
- Economic benefits by creating new opportunities for local and regional businesses, increase government revenue, and create employment for the local people;
- Social benefits through local community involvement and generate better public perception for biochar use for sustainable agricultural production (on-site biochar production using smaller units).

This biochar assessment project aims to evaluate the potential application of biochar technology in the Greater Mekong Sub-region (GMS). The project included all GMS countries, i.e. Cambodia, Lao PDR, Myanmar, Thailand, Viet Nam and Yunnan Province and Guangxi Zhuang Autonomous Region of the People's Republic of China (PRC).

The key objectives of the project are:

- Develop a spatial representation of the diversity of soil types with biochar feedstock or biomass supply in the GMS; and
- Produce a biochar assessment report identifying potential suitable areas for biochar applications (or biochar hotspots) based on the biomass availability, competing demands for biomass and potential benefits.

The key results and outcomes of the project are briefly described in the following sections.

Soils in the GMS

- The soil data quality in the GMS region is varied and different soil classification systems have been used in the GMS countries. We have used the available data to produce the GMS soil map that is based on the FAO-UNSECO classification system (1988, 1997).
- Acrisols, Ferralsols and Leptosols[1] cover nearly 65% of the area in the GMS. The majority of these soils have physical and/or chemical limitations in terms of their use for crop

[1]Acrisols – strongly weathered acid soils which mostly occur on old land surfaces with hilly and undulating topography; Ferralsols – Red and yellow tropical soils of humd tropics with high contents of iron and aluminium oxides; Leptosols – thin soils with coarse fragments and continuous rock very close to the surface, and common in mountainous regions,

production. The important soil constraints include shallowness and the presence of stones and rocks, inherent low fertility, acidic pH and low availability of phosphorus.

- About 25% of the remaining soils are mostly Cambisols, Fluvisols, Gleysols and Luvisols[2]. These are the key agricultural soils of the region. The inherent fertility of these soils varies from low to moderate in most cases. Some soils from the Fluvisols and Gleysols groups may have moderate to high fertility.
- There are significant areas (over 3.34 million ha) of acid sulfate soils (Thionic Fluvisols and Thionic Gleysols), which have extreme acidity and thus present severe actual or potential limitations to cropping.
- In the GMS, there is over 2.84 million ha of sandy soils (Arenosols) and these soils hold little water and have very low inherent capacity to supply and retain essential plant nutrients.
- The soil data should be updated and a revised soil map should be produced for the GMS. The revised map should be based on the World Reference Base (WRB) system, which has been officially recommended by the International Union of Soil Sciences and is being adopted worldwide (IUSS Working Group WRB, 2014). A unified and consistent soil map of the GMS will be an important resource for monitoring soil parameters, future planning and other environmental applications in the region.

Land suitability for biochar application

- The benefits of biochar application to soil, in terms of crop productivity, can be maximised by selecting the right soils for biochar addition.
- For the GMS region, biochar suitability of soils was determined based on soil properties, i.e. pH, percent base saturation, texture and soil depth.
- Soil properties, slope steepness and land use information were used to rank agricultural land into biochar suitability classes. Three biochar suitability classes of agricultural soils, i.e. low, medium and high suitability, were created and a biochar suitability map with these classes was produced for the GMS.

Availability of agricultural and animal waste for biochar production

- More than 104 million tonnes per annum of agricultural residues (excluding forestry waste and waste from agro-processing) can be sustainably removed from agricultural land for biochar production. The agricultural residues are predominantly based on rice production with the contribution of waste from rice cropping varied from 51 – 84% of the total available waste in the GMS countries.
- Animal wastes are enriched with essential plant nutrients and could be useful feedstock alone or additive to crop residues for biochar production. Based on the total number of livestocks and poultry animals in the GMS countries, it is estimated that approximately 294 million tonnes of dry animal waste is generated annually.
- Due to the scattered presence of both agricultural residues and animal wastes, the major challenge is in the collection of these wastes for biochar production.

[2]Cambisols – young soils where horizon differentiation has begun; Fluvisols – young soils formed in revier sediments, Gleysols – soil saturated with groundwater to develop reducing conditions; and Luvisols – fertile soils with higher clay content in a subsoil

- There is significant competition from other users for both waste materials in the GMS, for example, biogas and bioenergy production and other uses (e.g. mushroom production). Detailed economic and environmental analysis comparing various uses should be undertaken for selected areas in the GMS.

Potential 'Hotspots' for Biochar Application in the GMS

- Based on the biochar application suitability of the agricultural land, potential biomass availability and ADB economic corridors, two to four biochar hotspots (agricultural land areas with high suitability for biochar application) have been identified in each of the six GMS countries.
- These sites are located close to the ADB transport corridors and significant amount of crop residues and animal wastes are potentially available in the selected areas.
- The identified hotspots are: Tay Ninh, Vinh Phuc, Binh Thuan and Binh Dinh provinces in Viet Nam; Svay Rieng and Kâmpóng Chhnang provinces in Cambodia; Vientiane and Savannakhet provinces in Lao PDR; Rayong, Kalasin, Nakhon Pathom and Nakhon Ratchaima provinces in Thailand; Nay Pyi Taw Council and Shwe Bo district in Myanmar, and Luliang County in Qujing district in Yunnan Province and Yongning, Gangbei and Xingbin districts in Guangxi authonomous region in the PRC.

Assessment of agricultural waste for biochar production and other competing uses and practices

- Rice husk is perhaps the single most important agricultural waste that could be used as a feedstock for biochar production.
- Approximately 1.8 million tonnes of rice husk can be available for biochar production at the identified hotspots in the GMS. The conversion of rice husk into biochar has a potential to reduce over 1 million tonnes of CO_2 (~ 2.0% of the CO_2 emission from the whole agricultural soils in the GMS) in the atmosphere. Indirectly biochar application can reduce nitrous oxide (N_2O) emission from agricultural soils.
- Additionally, the rice husk biochar can reduce the consumption of P and K fertilizers by 20 and 100% (based on the recent fertilizer consumption data), respectively.
- The potential of rice husk biochar to reduce the N fertlizers is only 4%; however, this can be significantly increased (up to 20%) if biochar is produced by mixing animal manures with rice husk.
- Significant amounts of rice straw is burned in open fields, which has serious consequences for the local and regional air quality as high levels of particulate and gaseous toxic compounds are released in the atmosphere. Black carbon is now considered a potent climate driver that absorbs sunlight in the atmosphere and contributes to increased temperature.
- An assessment of the economic viability and carbon abatement potential of straw for biochar production via pyrolysis process with that of bioenergy production by straw briquetting and straw gasification showed the net present value of all three options were negative or unprofitable.
- The inclusion of local and national subsidies for avoided straw burning and bioelectricity programme had significant effects on straw briquetting and straw gasification with both these options becoming profitable. However, the outcome for biochar production via pyrolysis process remained negative or unprofitable.

- Biochar production via pyrolysis process option will break even when biochar is priced at \$206 Mg^{-1} (metric ton or 1000 kg), if there are no subsidies in place.
- The total CO_2-e abatement potential of biochar can be more effective than bioenergy production by straw briquetting and straw gasification options if indirect contributions (such as reduced nitrous oxide (N_2O) emission and improved fertiliser use efficiency) of biochar are considered in the modelling.

Other recommendations

- Demonstration trials should be set up at farmers' fields in the identified hotspot areas of the GMS.
- These trials should be used for demonstration and training purposes, and for optimising the biochar applications for rice and other crops.
- In co-ordination with the relevant national agenicies, workshops and training programs should be organised to educate farmers for biochar production and about its potential economic and environmental benefits.
- In the GMS women are the majority farmers or producers; sustainable agriculture development using biochar in crop production will assist in womens empowerment and creating gender equality in the region.
- To increase the nutrient supply capacity of biochars, it is suggested to mix animal wastes with rice straw and other crop residues for producing biochar, which will increase the agronomic value of biochar.
- Smaller biochar production units may be more suitable for areas where biomass availability is limited or scattered.
- Incentive should be given for developing local institutional arrangements for the collection of crop residues and animal wastes.
- The production of biochar for soil application will require some financial incentives from the local and national governments in the initial stages to make it ecomically sustainable.
- Incentives for the collection of straw and other agricultural and animal wastes for biochar production should be given, particularly in remote areas and small landholders who have limited resources to purchase inorganic fertilisers.
- Additionally, subsidised equipment and energy should be considered for biochar production in the hotspot areas identified in the study.
- Biochar application should be encouraged for high value crops (e.g. horticultural crops) for increased financial benefits and developing sustainable production systems.
- Use of biochar in growth media (e.g. plant propagation nurseries) and environmental applications (e.g. for restoration and remediation of industrial and contamianted soils) should be explored.
- Animal wastes are known to contain relatively high concentrations of essential plant nutrients and therefore biochar produced from animal wastes or mixtures of agricultural residues and animal waste should be considered. Such biochars may serve as a useful source of nutrients in organic farming systems.
- Mangrove (e.g. *Rhizophora apiculate, Sonneratia alba, Avicennia alba*) vegetation should be considered for sustainable biochar production.
- A regulatory framework should be created for quality control and to permit the use of various waste materials as a biochar feedstock, biochar production methods, and

classification of biochars in the GMS. These measures will increase consumer confidence in the uptake of biochar technology.

- Research and analytical capabilities for biochar and soil analyses in the GMS and particularly in Cambodia, PDR Lao and Myanmar are lacking and this needs to be addressed immediately through training staff and creating required analytical laboratory facilities.
- Long-term field experiments (perhaps at experimental farms of national agenices) comparing biochars with traditional fertliser treatments should be established for monitoring agronomic and environmental benefits of biochar with the existing farming systems.

2 INTRODUCTION TO THE PROJECT AND THE PURPOSE OF IDENTIFYING POTENTIAL HOTSPOTS FOR BIOCHAR APPLICATION

The Greater Mekong Sub-region (GMS) is a natural economic area bound together by the Mekong River; it covers approximately 2.6 million km^2 and has a combined population of around 326 million[3]. The GMS is comprised of Cambodia, Lao People's Democratic Republic (Lao PDR), Myanmar, Thailand, Viet Nam, Yunnan Province of the People's Republic of China (PRC) and Guangxi Zhuang Autonomous Region in the PRC. Agriculture is a priority sector because nearly 70% of the population in the GMS lives in rural areas in 2009 and are mostly working in the agricultural sector (ADB, 2012).

The Core Agriculture Support Program (CASP) Phase II (2011-2015) proposes strategic directions to address emerging challenges to agricultural development in the GMS, particularly in relation to expanded cross-border trade in food and agricultural products and agribusiness investment (ADB, 2011). The program creates initiatives that require a greater commitment to harmonising national agricultural development strategies in the region. Numerous factors impact the GMS agriculture sector and some key ones include: (i) accelerated globalisation and trade liberalisation, (ii) climate change, (iii) degradation of the agricultural resource base, and (iv) investments in transport infrastructure that facilitate cross-border trade and economic growth.

The CASP Phase II adopted a vision for the GMS to be the leading producer of safe food, using climate friendly agricultural practices and is integrated into global markets through regional economic corridors. The foundation of the strategy includes agricultural research and technology that emphasises *climate friendly agricultural development*, private sector involvement to ensure *sustainability*, and institutional mechanisms to enhance regional cooperation with incentives to achieve the vision. The motivation is to ensure not only achieving food and economic security in rural areas but also providing environmental services, clean water, and mechanisms for carbon (C) sequestration.

This project is one of the steps in achieving the goals of CASP Phase II. Biochar provides an innovative solution for GMS gender-responsive and climate-friendly agriculture. Biochar is the C rich product produced when biomass, such as wood, manure or leaves, is heated with little or no available oxygen.[4] It is added to soils to improve soil functions and to reduce greenhouse gas emissions from biomass. However, many of the benefits of biochar applications are dependent on soil and biochar properties. Also, large quantities of biomass may be required to produce biochar for soil application. The project addresses these issues with the following key objectives:

i) Develop a spatial representation of the diversity of soil types and soil properties of selected areas in the GMS;
ii) Based on soil type (and properties), determine the level of appropriateness of biochar application for the whole region;
iii) Undertake a biochar potential assessment to identify biochar hotspots and produce technical and economic feasibility assessment for biochar development in these areas.

[3] http://www.adb.org/countries/gms/main
[4] http://www.biochar-international.org/biochar/faqs#question1

The overarching aims are to promote climate friendly agriculture, reduce the use of agricultural chemicals and fertilisers, reduce GHG emissions, alleviate poverty, and draw the attention of policy makers for promotion of biochar in the GMS.

2.1 PROJECT IMPLEMENTATION PLAN

The **project is implemented**[5] **over 14 months between 1 December 2014 and 29 February 2016** in three (3) broad overlapping phases: (1) *identification of 'biochar potential hotspots'* based on soils and biomass information gathered from available data or provided by national agencies, and other factors (e.g. slope, land use, ADB economic corridors); (2) *detailed mapping and verification of hotspots* involving further detailed data gathering on each hotspot and consultations with national agencies; (3) *biochar assessment study for potential biochar study areas/ pilots* involving selection of pilot areas and development of pilot design guidelines/ recommendations taking into account local biochar production and application suitability factors.

The project included three field missions to five GMS countries (although Yunnan and Guangxi of the PRC were included in the project scope, field missions to these areas were not conducted because permission was not granted). The first mission to five GMS countries (Viet Nam, Lao PDR, Cambodia, Myanmar and Thailand) to meet with, introduce the project to and request information (soils, biomass, biochar) from counterpart national agencies (various ministries covering areas such as agriculture, fisheries, rural development, livestock and land management) was carried out in February-March 2015 (during Phase 1). The second mission occurred in June-July 2015 (during Phase 2) and included team review and email consultation with national agencies on the selected hotspots for the purposes of hotspot verification and data collection. This mission coincided with the 12th WGA Annual Meeting on the 25th – 26th June in Bangkok, Thailand. A final third mission occurred in August 2015 when selected hotspot sites were visited in Cambodia, Lao PDR and Myanmar (commencing Phase 3). During these visits consultation occurred with local government and land holders for the purpose of detailed biochar pilot design.

2.2 PROJECT STATUS AND PROGRESS

All phases are now complete. A GMS soils map using the FAO-UNESCO classification system has been developed from the best available GMS soils data (includes data from GMS government agencies, the MRC and the FAO). A GMS potential biochar application suitability map has been produced using soils information and slope. Areas of suitable cropping/ agricultural production systems[6] (identified from GMS land use information) and areas of potential biomass availability (estimated from cropping and livestock production) was then assessed on the potential biochar application suitability map to identify preliminary biochar hotspots. The identified biochar hotspots have been reviewed by national agencies and final hotspots in each country selected in line with national agency objectives and priorities. Team field visits to selected hotspots (third field mission) were conducted during August for the purposes of consultation and data collection for the design of biochar pilots. This report and detailed soils map with biochar compatability in selected areas are the final project outputs. An online interactive GMS soils, land suitability for biochar application and biochar hotspot map was also developed.

---

[5] The project is implemented by the ADB Working Group on Agriculture under TA component (iii) of the CASP.

[6] Forestry was not considered to be a viable system for biochar production and application because it may have adverse impact on forest conservation and the focus is on the utilization of agricultural wastes for biochar production and land application.

3 DISTRIBUTION OF SOIL TYPES IN THE GMS

Biochar is a carbon rich material produced by heating biomass such as wood, manure or leaves with little or no available oxygen. The application of biochar to soil can produce several benefits, such as i) sequester carbon in the soil for hundreds to thousands of years thus providing climate change mitigation benefits; ii) significant soil improvements such as improving water holding capacity, releasing nutrient elements, reducing nutrient leaching, reducing soil acidity, and improving the soil fauna or soil biological function. The improvement in soil properties from biochar addition is largely dependent on soil type (i.e. soil properties).

The soil data from individual GMS countries were converted to the FAO-UNESCO classification system and combined to produce a unified soil map of the GMS. Different classification systems have been used in producing the original soil maps in the GMS countries and as a result of this, there are some inconsistencies in the unified GMS soil map that was produced using the FAO soil classification system. The inconsistencies and errors have largely resulted due to the lack of available soil profile data in some of the GMS countries. In some cases, the national agencies have wrongly classified the local soil types into the FAO classification system. Such errors in the soil classification are most evident in the border areas between the GMS countries when a particular soil type in a country changes into another soil type across the border. Detailed soil, elevation and soil properties maps and related data for individual countries in the GMS are given in Appendix 1.

The distribution of soils and slope classes in the GMS are presented in Figures 1 and 2. Brief description of Soil Groups and Soil Units is given in Appendix 2. Both the soil types and slope classes formed the basis to identify potential agricultural land that could benefit from biochar application to soil in the GMS. In the following section features of soil types present in the GMS are discussed.

3.1 ACRISOLS

Acrisols are the most widespread soils in the GMS. These soils occupy over 91 million ha, representing over 32% of the area in the GMS countries region (Figure 1; Table 1). Acrisols occur over a wide range of elevation varying from nearly level to steeply dissected or mountainous. These soils are more common in high rainfall areas where annual rainfall exceeds 1500 mm and there is no marked dry season. These soils form on acid to moderately basic parent materials, mostly on residuals of sedimentary, igneous or metamorphic rocks, and on terraces and dissected peneplains of old alluvial deposits (FAO, 1979). These soils are usually very poor in nutrients and highly susceptible to erosion.

Ferric Acrisols mainly occur in Cambodia, PRC, Lao PDR and Viet Nam in more humid parts that are undulating to rolling. Ferric Acrisols are acid soils with low organic matter content, and are low in bases and phosphate. Although these soils are moderately well to well drained in the present state, they have experienced impeded drainage at some stage in their development. Consequently, hard iron concretions or distinct semi-hard nodules have accumulated in the argillic (clay-rich) B horizon. The presence of hard concretions and somewhat cemented or indurated nodules within rooting depth is a limiting factor for plant growth (FAO, 1979). In addition, natural fertility and productivity are low. Gleyic Acrisols are developed on old alluvium and occur on nearly level to rolling lower terraces, and mainly in northeastern Thailand (Figure 2). These highly leached soils are physically and chemically very poor. Similar to Ferric Acrisols, these soils have a low natural fertility, a low organic matter content, low pH, and are low in bases. Humic Acrisols are the typical non-volcanic mountain soils that exist in more humid parts of Lao PDR, Thailand and Viet Nam. They occur mainly on mountain slopes where macrorelief is steeply dissected to mountainous. These soils vary considerably in thickness, and they have a moderate natural fertility due largely to their relatively high organic matter content, but are acid and low in bases. They have good physical characteristics and are mainly well drained, but erosion hazard is great if slopes are exposed. Plinthic Acrisols are not extensive, occurring mainly in Lao PDR. These soils are acidic with low levels of organic matter content and exchangeable bases, and have a low natural fertility. A continuous plinthic horizon occurs within 125 cm of the soil surface, which is compact and relatively impermeable. Due to the presence of plinthic horizon, Plinthic Acrisols have impeded drainage and are physically and chemically poor, and generally not suitable for agriculture. Haplic Acrisols also occur in PRC, Lao PDR, these soils do not have a characteristic ho**rizon or properties as for the other Acrisols described above.**

Table 1: The distribution of different soil types according to the FAO-UNSECO soil classification system in the Greater Mekong Sub-region.

Soil Group	GMS countries						Total area (ha)	Area (%)
	Cambodia	Lao PDR	Myanmar	Thailand	Viet Nam	PR of China		
Acrisols	2,544,421	15,671,108	323,248	15,990,831	19,461,317	37,532,501	91,523,425	36.16
Allisols	-	124,861	-	-	150,603	-	275,464	0.11
Andosols	-	-	92,701	-	110,220	-	202,921	0.08
Anthrosols	1,405,534	-	-	-	-	-	1,405,534	0.56
Arenosols	184,013	25,908	1,293,950	733,016	603,349	-	2,840,236	1.12
Calcisols	-	-	-	281,543	2,536	-	284,079	0.11
Cambisols	-	4,593,947	19,178,525	906,343	-	1,603,186	26,282,001	10.38
Ferralsols	630,852	173,379	24,688,045	12,881	2,687,854	-	28,193,012	11.14
Fluvisols	3,357,619	41,656	5,894,828	244,649	5,186,007	2,828,728	17,553,487	6.94
Gleysols	2,017,682	28,631	4,081,133	4,294,003	221,639	1,990,850	12,633,939	4.99
Histosols	-	-	447,377	76,373	24,775	-	548,525	0.22
Leptosols	4,731,371	560,379	1,656,133	21,007,478	429,945	16,197,818	44,583,124	17.61
Lixisols	-	88.920	-	1,899,038	1,203,719	-	3,191,677	1.26
Luvisols	-	963,239	-	4,792,467	139,470	841,688	6,736,864	2.66
Nitisols	-	-	1,900,391	-	-	-	1,900,391	0.75
Planosols	166,536	-	-	-	-	-	166,536	0.07
Plinthosols	1,894,431	97,306	-	-	-	-	1,991,737	0.79
Podzols	-	-	-	58,390	-	-	58,390	0.02
Regosols	-	-	-	250,496	-	-	250,496	0.10
Solonchaks	-	-	5,472,493	166,368	1,098,311	-	6,737,171	2.66
Solonetz	-	19,467	-	-	-	-	19,467	0.01
Vertisols	629,185	-	432,020	423,196	-	1,168,436	2,652,837	1.05
Residential	-	3,948	-	-	-	-	3,948	0.00
Water	539,012	173,120	-	311,098	510,981	75,587	1,609,798	0.64
Rocks	-	428,260	-	-	1,032,403		1,460,663	0.58
Grand total	18,100,658	22,994,129	65,460,845	51,448,169	32,863,129	62,238,795	253,105,725	100.0

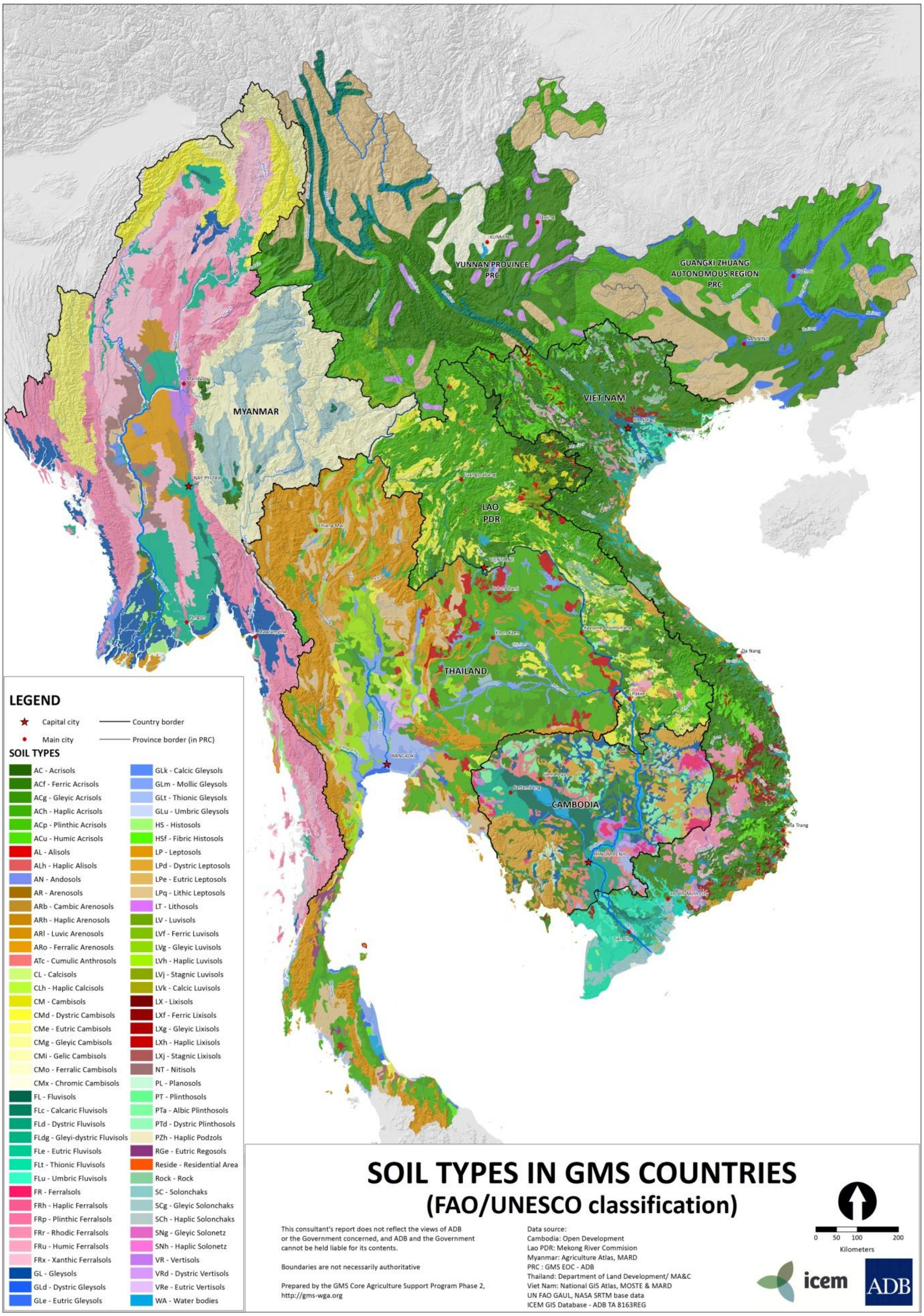


Figure 1: The distribution of soil types according to FAO-UNESCO classification in the Greater Mekong Sub-region.

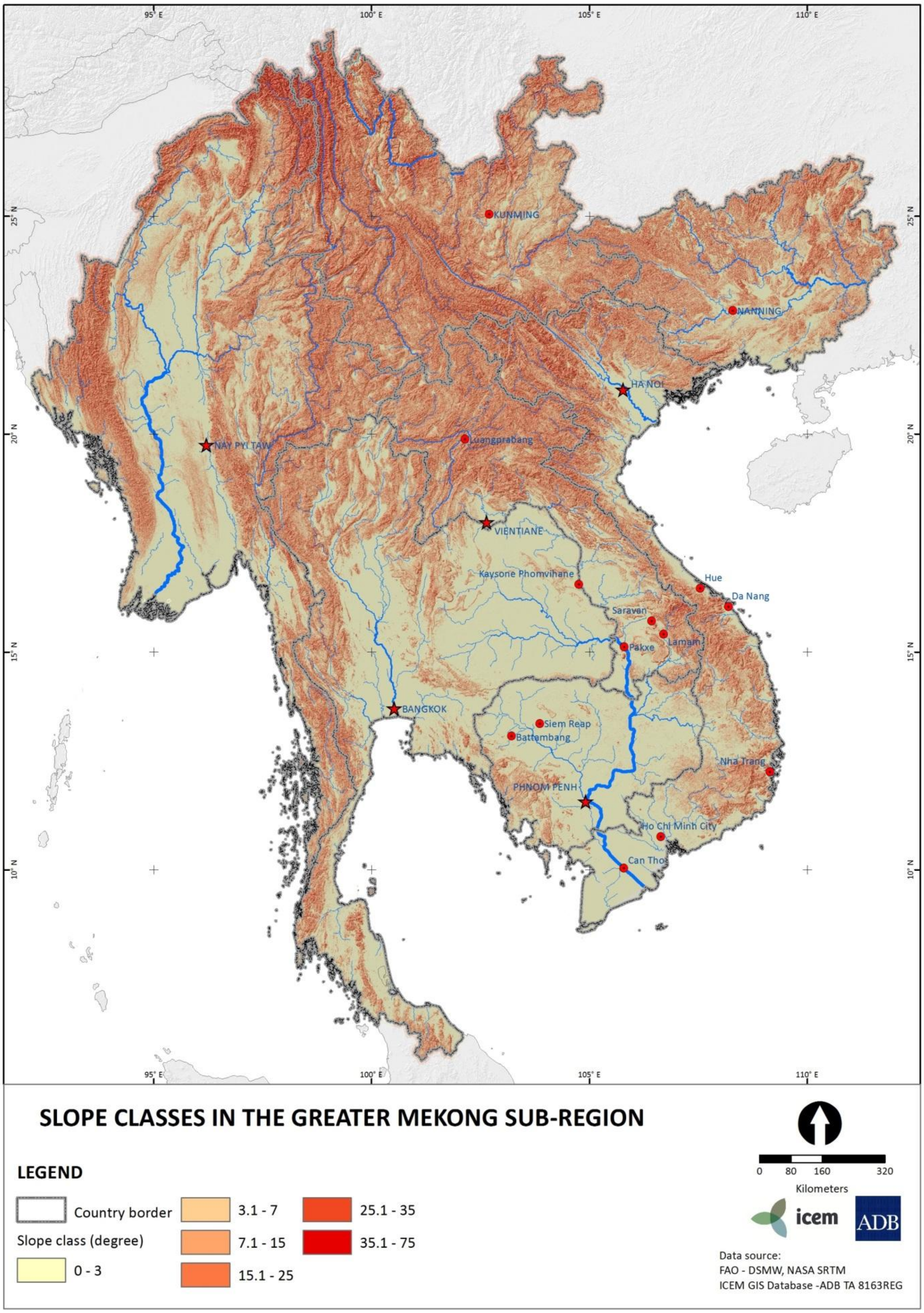


Figure 2: The distribution of slopes in the Greater Mekong Sub-region

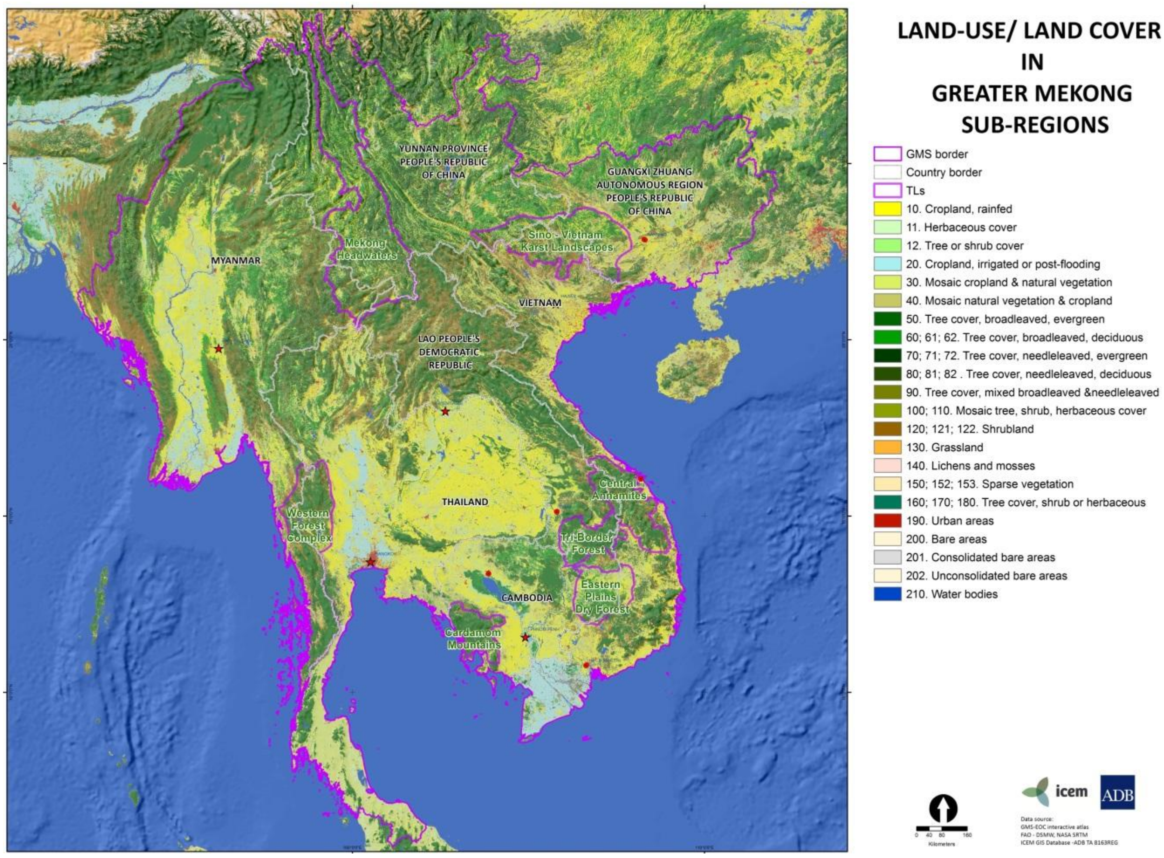


Figure 3: The distribution of land-use in the Greater Mekong Sub-region

3.2 ALISOLS

Alisols are present in Lao PDR and Viet Nam, covering only 0.11% of the land area. Similar to Acrisols, Alisols also have an argic (clay-rich) subsoil horizon and a low base saturation but unlike Acrisols have high-activity clays. These soils are usually derived from the weathering basic rocks. Alisols exist on old land surfaces with hilly and undulating terrain, and many properties and land use are similar to Acrisols. The generally unstable surface soil of cultivated Alisols makes them susceptible to erosion and truncated soils are quite common. Due to the highly acidic pH, toxic levels of aluminium (Al) at shallow depth and poor natural soil fertility are common constraints of these soils.

3.3 ANDOSOLS

Andosols have limited existence in the GMS, covering an area of about 203,000 ha. These soils are derived from glass-rich volcanic ejecta (such as ash, tuff, pumice) under a range of environmental conditions. Andosols usually have poorly ordered minerals, low bulk density and very high phosphate adsorption capacity.

3.4 ANTHROSOLS

Anthrosols have the main characteristics that result from human activities. Cambodia has over 1.4 million ha of these soils surrounding the Tonlé Sap Lake used mainly for paddy growing (Figure 1). Cultivation of wetland rice fields is done to alter the soil structure to reduce water percolation and to allow water-logged condition in soils. These soils exist in the central plains on extremely flat terrain and are used chiefly for paddy growing.

3.5 ARENOSOLS

Arenosols are deep sandy soils and these soils cover about 2.84 million ha (1.12%) of the GMS countries. Cambic-, Haplic-, Luvic- and Ferralic- Arenosols have been identified in the GMS regions. All these soils have common characteristic in being deep, coarse textured and excessively drained soils. Also, Arenosols have strongly acidic pH, are poor in organic matter content and have low levels of exchangeable bases and low CEC. Cambic Arenosols are developed from slightly consolidated Miocene sandstone with a nearly level to rolling macrorelief and the additional characteristics of these soils being the presence of a cambic B horizon immediately below the A horizon. Luvic Arenosols are non-calcic soils that show an increase of ≥ 3% clay within 125 cm of the surface, and lack an albic E horizon with a minimum thickness of 50 cm, and lack Gleyic properties within 100 cm of the surface. Ferralic Arenosols show ferralic properties (presence of Fe rich mottles or nodules) and colouring of the horizon underlying the A horizon. Haplic Arenosols have no diagnostic horizon other than an ochric A horizon, and these soils lack ferralic or Gleyic properties within 100 cm of the surface and are non-calcic. Arenosols are physically and chemically poor and suffer from moisture deficiency owing to excessive drainage and very low supply of plant nutrients. The agricultural potential of these soils is low, and significant inputs are required for cropping.

3.6 CALCISOLS

Calcisols have limited (0.11%) presence in the GMS region and mostly occur in the central part of Thailand. These soils have substantial accumulation of secondary carbonates in soil profile. There is often decreased availability of P and micronutrients due to the high pH and the presence of $CaCO_3$ in Calcisols.

3.7 CAMBISOLS

Cambisols are relatively young soils where horizon differentiation is at initial stages of formation that is evidenced by changes in colour, texture and structure. These soils covers an area of over 26 million ha that makes up about 10.4% of the land area in the GMS (Figure 1). These are deep soils with medium to fine texture; other characteristics are varied for different soil units. Dystric, Eutric, Gleyic, Gelic and Ferralic sub-units of Cambisols have been identified in the GMS countries. Dystric- and Eutric- Cambisols are found in Myanmar, Thailand and Lao PDR. Dystric Cambisols have slightly acid to acid pH, and low content of organic matter and bases. The natural fertility of these soils is low. The exposed soils on sloping terrain are subject to severe erosion unless properly terraced. They occur on steeply dissected to mountainous terrain and acid to intermediate parent rocks. Eutric Cambisols have slightly acid to neutral pH, medium texture, and good physical properties. Eutric Cambisols are developed from basic to intermediate parent materials of volcanic origin and usually found on mid-slopes of volcanoes. These soils are more fertile than Dystric Cambisols due to their higher organic matter content and moderate supply of bases. Gleyic Cambisols are poorly to somewhat poorly drained with slightly acid to neutral pH and a moderate supply of bases. These soils are developed on relatively recent alluvial deposits derived from intermediate to basic parent materials. Gleyic Cambisols occupy broad, slightly dissected low continental river terraces. The physical and chemical properties of these soils are highly favourable for the sustained cultivation of a wide range of crops. The main limitation is occasional flooding. Gelic Cambisols have permafrost within 200 cm of the surface. These soils exist in the mountainous terrain in the north of the Myanmar. Chromic Cambisols have an ochric (paler or lighter coloured) A horizon and a base saturation o f 50% or more at least between 20 cm and 50 cm from the surface. Ferralic Cambisols are strongly acidic, low in bases, and have good physical properties due to their relatively high organic matter content. The main limitations to permanent agriculture are low natural fertility and susceptibility to water erosion.

3.8 FERRALSOLS

Ferralsols are deeply weathered yellow or red soils and their clay fraction is dominated by sesquioxides and kaolinite. These soils cover an area of about 28.2 million ha (11.1%) and occur in all of the GMS countries. Ferralsols exist on undulating to steeply dissected or mountainous terrain, with elevations ranging from 100 to over 3000 m (Figure 2). Rhodic Ferralsols are developed on old basalt plateaus (in Viet Nam and Cambodia) with an undulating to rolling macro-relief. These soils are slightly to strongly acidic, have moderate organic matter content and percent base saturation and CEC are generally low. Rhodic Ferralsols are generally well-structured and their infiltration rate is high. Natural soil fertility of these soils is generally low. Humic Ferralsols are mainly restricted to parts of Viet Nam where these soils occur on rolling and steeply dissected terrain. These soils are strongly acidic with moderate to high organic matter content and low CEC and exchangeable bases. Humic Ferralsols are moderately deep to deep, medium to fine textured and well-drained soils. A petroferric horizon consisting of a more or less continuous layer of indurated material or a layer of hard ironstone concretions occurs within the rooting zone, which may limit plant growth. The combination of limitations within the rooting zone, low soil fertility and high susceptibility to erosion on exposed slopes generally precludes these soils from permanent cultivation. Xanthic Ferralsols are medium textured and well to excessively drained soils with strong to extremely acidic pH. Organic matter content of these soils is medium to low and they are low in bases and have a low CEC. Similar to Humic Ferralsols, the presence of indurated material within rooting depth limits plant growth, the severity of this effect depends on the depth of occurrence and abundance of concretions. Low natural fertility and the presence of a petric layer within rooting depth are the main limitations to permanent cultivation, while steeper members are susceptible to erosion on unprotected slopes. Haplic Ferralsols have limited presence in Lao PDR and Thailand. These soils have a ferralic B horizon but don't have the characteristics to qualify for Xanthic, Rhodic and Humic Ferralsols.

3.9 FLUVISOLS

Fluvisols are young soils that have developed in fluvial deposits. They exist in all five countries, occupying approximately 6.95% of the area (Figure 1). Dystric Fluvisols are developed on recent fluviatile, marine and lacustrine deposits and occupy positions on river levees, present flood plains, deltas and lake shores where alluvium is derived from predominantly acid parent rocks. These soils are medium to fine textured, and poorly to very poorly drained, although better-drained soils occur on levees. Soil pH is slightly to strongly acid, low exchangeable base percentage and organic matter content is generally moderate to high. These soils generally occur on flat terrain; however, levees often have an undulating microrelief. Such soils are intensively used for paddy cultivation in areas where flooding is not too deep. Levee soils are traditionally used for settlement sites with home gardens, orchards and banana plantations. Along coasts, soils are periodically inundated by sea water and mangrove vegetation occurs in such areas. Gleyi-dystric Fluvisols are similar to Dystric Fluvisols except they show gleyic properties (i.e. soils are saturated with water for a significant period of time) within 100 cm of the surface. Eutric Fluvisols occur in the alluvial plains of the Chao Phraya, Mekong and Red rivers upstream of the deltas and are dominant in the coastal plains of southern Thailand and Viet Nam. Many features of Eutric Fluvisols are similar to those described for Dystric Fluvisols, however, unlike Dystric Fluvisols, these soils have developed on recent alluvium derived mostly from intermediate to basic parent rocks. Therefore, these soils have slightly acidic to neutral pH, moderate base status and moderate to high organic matter content. A large proportion of Eutric Fluvisols is used for rice production. Better-drained levee soils are generally used for vegetable or horticultural crops. Calcaric Fluvisols are calcareous between 20 cm and 50 cm from the surface. These soils exist in PRC and formed in the fluvial deposits derived from karst that is common in many parts of PRC. Thionic Fluvisols are characterised by the presence of a sulfuric horizon or of sulfidic materials within a depth of 125 cm. These soils exist mainly in the Chao Phraya and Mekong deltas, and to a lesser extent in tidal swamps along the coasts of Viet Nam, Cambodia and Thailand. These soils are developed on brackish water alluvium containing considerable amounts of sulfides, mainly Fe sulfide mineral pyrite. Potential acid sulfate soils occur where the alluvium remains totally reduced or inundated. However, active acid sulfate soils develop in areas after drainage and aeration of originally waterlogged and reduced alluvium that contained sulfides. The oxidation of pyrite and other sulfides produces sulfuric acid and create highly acidic conditions in soils. The availability of Al^{3+} ions and other trace metals increases to toxic levels for plant roots and micro-organisms. Natural vegetation in active sulfate soils consists mainly of Avicennia and Rhizophora mangroves, and Melaleuca leucadendron (FAO, 1979). The agricultural potential of Thionic Fluvisols is generally very low. Umbric Fluvisols mainly occur in Viet Nam; these soils have an umbric horizon, which is a thick, dark coloured surface horizon that is rich in organic matter with base saturation less than 50%.

3.10 GLEYSOLS

Gleysols are formed from unconsolidated materials and show gleyic properties within 50 cm of the surface. These soils are saturated with groundwater for long enough periods to develop reducing conditions or gleyic properties. Gleysols have been identified in all five countries of the GMS and cover an area of approximately 12.63 million ha (5%). Dystric, Eutric, Calcic, Molic, Thionic and Umbric sub-units have been identified, and the area for each of the sub-units is shown in Figure 1. Dystric Gleysols are developed on relatively recent marine and riverine alluvium and occupy positions on raised coastal flats and low river terraces. Dystric Gleysols are strongly leached, fine-textured kaolinitic clay soils with poor to very poor drainage. Soil reaction is strongly to slightly acid, and they have a low to moderate organic matter content and are low in exchangeable bases. They are waterlogged and inundated during the rainy season, but dry out to some depth during the dry season. Poor drainage and regular waterlogging generally preclude the use of these soils for the cultivation of dryland crops or tree crops. These soils have low natural fertility, and in northeastern Thailand potential or actual salinity is a limiting factor in dry years. In addition, Al toxicity in strongly acid soils may depress crop yields. Eutric Gleysols occur in parts of PRC, Lao PDR and Thailand. They occupy raised coastal flats and low river terraces, but, unlike Dystric Gleysols, are developed on more recent alluvium derived from more basic parent material. Eutric Gleysols are mainly fine textured, although medium and coarse-textured soils. Soil reaction is generally slightly acid to neutral, organic matter content is moderate to low, and they have a moderate supply of bases and a moderate to high CEC. Consequently, these soils are fairly fertile. They are poorly to very poorly drained, being waterlogged and inundated during the rainy season, but dry out to some depth during dry periods. Their agricultural potential depends on the degree of water control feasible. They have been largely cleared of the original mixed swamp forest and are intensively used for continuously irrigated rice, or rice in rotation with vegetables, pulses, tobacco and occasionally sugarcane (Figure 3). Both Mollic Geysols and Umbric Gleysols have a dark coloured organic rich horizon and bases saturation is ≥ 50% and less than 50%, respectively. Calcic Gleysols have a calcic horizon within 125 cm of the surface; these soils have been identified in Myanmar only. Thionic

Gleysols are the soils that have a sulfuric or sulfidic horizon within 125 cm from the surface; extreme acidity is a major constraint in the use of these soils if they are drained.

3.11 HISTOSOLS

Histosols are the soils formed in organic soil materials. These soils are typically formed under waterlogged conditions typical of peat bogs, moors, and swamps. Most of these soils occur in Myanmar (0.22%). They have developed over sub-recent coastal swamps with a flat to slightly depressed environment where conditions are favourable for the accumulation of organic matter and plant debris. These soils have numerous physical and chemical constraints for agriculture use.

3.12 LEPTOSOLS

Leptosols are thin soils (less than 10 cm) over continuous rocks. These soils are widespread in all the GMS countries covering over 44.5 million ha (17.6%). Leptosols occur in mountaineous regions with medium to high altitude with strongly dissected topography. Dystric, Lithic and Eutric sub-units have been recognized in the GMS. There is little agricultural potential for these soils, best to keep them as forest land.

3.13 LIXISOLS

Lixisols have greater clay content in the subsoil than in the topsoil, as a result of clay migration from pedogenic processes. The clays in these soils have low-activity (CEC < 24 $cmol_c\ kg^{-1}$ clay) and a high base saturation (≥ 50%) through the B horizon to a depth of 125 cm. Lixisols exist mainly in Thailand and Viet Nam, covering 1.26% of the area in the GMS. Ferric, Gleyic, Haplic and Stagnic sub-units of Lixisols have been identified in the region. Lixisols have higher percent base saturation and therefore are less dispersive and somewhat stronger structure than normally found in Acrisols; however, slaking and caking of the surface soil are still serious problems. Lixisols generally have better physical and chemical properties than Ferralsols or Acrisols; they retain more moisture and have higher pH than Ferralsols or Acrisols. Lixisols are strongly weathered soils with low levels of available nutrients and low nutrient reserves. Areas with Lixisols that are still under natural savannah or open woodland vegetation are widely used for low volume grazing. It is important to preserve the surface soil due to its relatively high organic matter content. Degraded surface soils have low aggregate stability and are prone to slaking and/or erosion if exposed to the direct impact of raindrops.

3.14 LUVISOLS

The dominant characteristics of Luvisols are a marked textural differentiation within the soil profile, with the surface horizon being depleted of clay and with accumulation of clay (argic horizon) in the subsurface; and the clays are high-activity (CEC ≥ 24 $cmol_c\ kg^{-1}$ clay) and a high base saturation (≥ 50%) through the B horizon to a depth of 125 cm. Luvisols covers about 6.7 million ha land and are largely present in Thailand (~4.8 million ha). Ferric, Gleyic, Haplic, Stagnic and Calcic sub-units of Luvisols have been identified in the GMS. Ferric Luvisols are present in PRC, Viet Nam and northern Lao PDR. These soils are developed from weathering products of limestone plateaus, and have a rolling to steeply dissected macrorelief. The presence of a layer of hard Fe concretions within rooting depth also limits plant growth, and they are susceptible to erosion on unprotected slopes. These soils are fine textured and well drained. Soil reaction is slightly acid to neutral. Organic matter content is moderate, and the CEC and content of bases are low. They are high in Al oxides and have severe deficiencies of P, K, Ca and Mg. The potential for agricultural development is rather low. The natural vegetation is mixed moist deciduous forest, and land use is restricted to a form of shifting cultivation practised by mountain people. Gleyic Luvisols are developed on old terrace alluvium in inter-mountain basins in northern Thailand and Lao PDR. These are fine textured and poorly to somewhat poorly drained with slightly acid to mildly alkaline. Organic matter content is generally low, while base status and CEC are moderate to high. Physical and chemical properties are generally good. These soils are generally fertile; however, agricultural potential of these soils is largely dependent on the availability of irrigation water during the pronounced dry season. Calcic Luvisols are found in a small area in Thailand. These soils are mildly alkaline, moderately deep to deep, fine-to-medium-textured and well-drained soils. Organic matter content is moderate, and base status and CEC are high. They are found on gently sloping coastal terraces and are developed from weathering products of limestone. The eluvial horizons of Stagnic Luvisols are depleted to the extent that an unfavorable platy structure is formed with pseudo-gley or stagnic properties. Haplic Luvisols don't have characteristic features of all other sub units of Luvisols, except the characteristic features of argillic B horizon with high CEC and base saturation as described earlier.

3.15 NITISOLS

Nitisols are deep, well-drained and red tropical soils with diffuse horizon boundaries and a subsurface horizon with more than 30% clay. The soil structure of these soils is moderate to strong angular blocky that easily break into characteristic shiny, polyhedric (`nutty') elements. These soils are strongly to slightly acidic with medium to high organic matter content and base status and CEC are generally low. Despite their strongly weathered characteristic, Nitisols are far more productive than most other red tropical soils. They are developed on a wide variety of highly weathered rocks and sediments and have a nearly level to hilly macrorelief. Nitisols exist only in Myanmar covering 0.75% of the GMS area.

3.16 PLANOSOLS

Planosols have limited presence (< 0.1% area) in the GMS and they occur only in Cambodia (Figure 1). These soils have an E horizon (bleached, light-coloured horizon) and show signs of periodic water stagnation. The bleached horizon abruptly overlies dense, slowly permeable subsoil with significantly more clay than the surface horizon. Planosols occur predominantly in flat lands but can also be found in the lower stretches of slopes, in a strip intermediate between upland and lowland areas. The surface soil is usually acidic and low CEC. Surface horizons of Planosols have weak and unstable structure. Surface of sandy soils becomes hard when dry, and silty soils become hard as concrete in the dry season and convert to heavy mud when they become waterlogged in the wet season. The poor structure stability of the surface soil, the compactness of the subsoil and the abrupt transition from topsoil to subsoil all impair the rooting of crops.

3.17 PLINTHOSOLS

Plinthosols are soils having 25% or more plinthite by volume (FAO, 1997). Plinthite is a Fe rich, and humus-poor mixture of kaolinitic clay with quartz and other constituents that change irreversibly to a layer or to irregular aggregates on exposure to repeated wetting and drying. By definition the plinthite horizon should be 15 cm thick within 50 cm of the soil surface or within a depth of 125 cm when underlying a bleached horizon or a horizon which shows stagnic properties within 50 cm of the surface or Gleyic properties within 100 cm of the surface. These soils cover about 0.8% of the area in GMS and mostly exist in Cambodia. The presence of an indurated horizon in these soils presents a major challenge as it restricts water movement and root penetration.

3.18 PODZOLS

Podzols have the presence of a spodic B horizon that is brown or black humus combined with Fe or Al or both. These soils have been only identified in Peninsular Thailand and cover about 58, 400 ha. These are sandy soils that are highly acidic, high Al-levels, low chemical fertility and unfavourable physical properties.

3.19 REGOSOLS

Regosols are weakly developed soils that do not have any diagnostic horizon other than an ochric or umbric surface horizon. Eutric Regosols occur over 250,500 ha on recent beach and dune deposits have a nearly level to rolling macrorelief in Thailand. Regosols have slightly acidic pH, low organic matter content and base status is moderate. These soils are coarse textured, deep and excessively drained. Due to their limited capacity to hold and supply nutrients and water, Regosols have limited agricultural potential.

3.20 SOLONCHAKS

Solonchaks have a high concentration of soluble salts (salic properties) in the soil profile. These soils exist over approximately 6.7 million ha in Thailand, Myanmar and Viet Nam. Solonchaks in waterlogged black swamps are Gleyic Solonchaks sub unit; without their salic properties these soils would have been Gleysols. Due to the presence of high salt contents, Solonchaks have limited potential for cultivation except for salt-tolerant crops.

3.21 SOLONETZ

Solonetz accommodates soils with a natric B horizon, which is a dense, strongly structured, clay rich horizon that has a high proportion of adsorbed sodium ions. These soils occur only in Lao PDR, covering approximately 19,500 ha. Solonetz are generally associated with flat lands deposits that contain a high proportion of sodium ions. Excessive sodium ions in these soils either cause directly toxicity to crop plants or indirectly affect plant growth through poor structure.

3.22 VERTISOLS

Vertisols are clay rich soils (≥ 30% clay) that develop at least 1 cm wide cracks from soil surface downwards on drying. Additionally, structural aggregates have slickensides at some depth between 25 and 100 cm from the surface, with or without gilgai. Vertisols exist in PRC, Cambodia, Myanmar and Thailand, covering an area of nearly 2.65 million ha. Vertisols are developed from a variety of parent materials including old clay terrace alluvium, old basic volcanic rocks and limestone-clay sediments. Vertisols occur on level to gently undulating terrain and a distinctive gilgai microrelief is common. These soils are generally fertile with high CEC and changeable bases. The major constraint is their adverse physical properties and poor workability, Vertisols are imperfectly to poorly drained during the rainy season and dry out rapidly and crack deeply in the dry season. Vertisols are adaptable to a wide variety of annual or perennial crops.

Summary of the GMS Soils

The soils in the GMS countries exist in 21 out of the total 29 major soil group according to the FAO soil classification (FAO, 1988). Four soil groups, i.e. Acrisols, Ferralsols and Leptosols cover about 64.9% of the land area in the GMS. Acrisols are the most predominant soil in the region, covering more than 36% of the area. The majority of the steeply sloping, lithic, stony and petric sub units of

Acrisols have severe physical limitations for cropping. These constraints together with their inherent low fertility mean that most these soils are under native forests.

Leptosols cover approximately 17.6% of the total area in the GMS. Due to the shallowness and the presence of stones and rock outcrops in these soils, they are generally not suitable for cropping. Ferralsols also cover approximately 11.1% of the total land area in the GMS. These have acidic soil pH and low natural fertility, particularly the availability of phosphorus is a major problem in these soils. The soils of the Plinthic sub unit of Ferralsols may have physical limitations to plant growth in the rooting zone due the presence of hard layer.

Cambisols, Lixisols, Luvisols and Nitosols together occupy approximately 15% of the total land area and these soils have low to moderate natural fertility, and are considered to have moderate to high agricultural potential with suitable management practices. Fluvisols, Gleysols and Vertisols, make approximately 13% of the total area, and these are the main paddy-growing soils of the region. Thionic Fluvisols and Thionic Gleysols covers about 3.3 million ha land area and these soils have severe actual or potential limitations to sustained cultivation due to the extreme soil acidity present in these soils.

About 1.1% of the area is covered by Arenosols in the five GMS countries. Most of these soils very low inherent capacity to supply and retain nutrients and water due to their sandy texture and they are not considered suitable for sustained cultivation.

4 LAND SUITABILITY FOR BIOCHAR APPLICATION IN THE GMS

4.1 GENERAL INTRODUCTION

The beneficial effects of biochar for long term C storage are well demonstrated and relatively straight forward to predict. However, the agronomic responses of biochar application to soil are not easy to predict and they depend on the properties of both soils and biochars, and environmental conditions. Recent reviews and meta-analysis showed both negative and positive effects of biochar on crop productivity (Glaser et al., 2002; Jeffery et al., 2013). The uncertainty over the likely effects of biochar application to soil on crop yield has been considered as a common hindrance to the adoption of biochar technology across the wider community in Australia and elsewhere (Singh et al., 2014). The mixed results reported in the literature are partly due to the wide range of experimental conditions tested including soil types, climate conditions, crop system, nutrient availability, and the type, rate and chemical characteristics of the biochar (Chan et al., 2007, 2008; Smider and Singh, 2014).

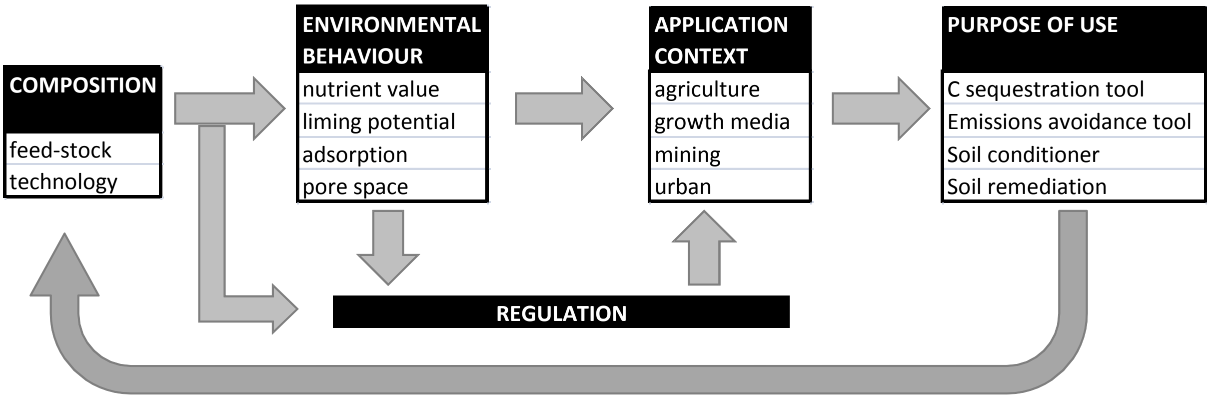


Figure 4: Interrelationships between biochar composition, behaviour and application in the environment (Singh et al., 2014).

Singh et al. (2014) suggested that for land application the properties of biochar can be carefully selected to maximise the benefits appropriate for a particular soil (Figure 4). Some researchers have suggested the characterisation of individual biochar for soil application to optimise benefits and to minimise ecotoxicological risks (Novak et al., 2009; Singh et al. 2010; Kloss et al., 2012).

Meta-analyses and results from different studies suggest that biochars are usually effective in enhancing plant growth in acidic soils as compared to alkaline soils (Atkinson et al., 2010; Jeffery et al., 2011; Biederman and Harpole, 2012; Crane-Droesch et al., 2013). Most biochars have alkaline pH (Singh et al., 2010; Krull et al., 2012) and offer some degree of acid neutralising capacity. Therefore it may be expected that application of biochars to acidic soils can increase the soil pH and reduce the availability of toxic elements (e.g. Al and Mn), which may produce an indirect positive effect on crop productivity. In general, biochars produced from manure, greenhouse waste and grasses are more enriched with plant nutrients compared to wood biochars (Atkinson et al., 2010; Jeffery et al., 2011; Biederman and Harpole, 2012; Crane-Droesch et al., 2013; Singh et al., 2010; Slavich et al., 2013;

Smider and Singh, 2014), however, the C sequestration potential of these biochars is much lower than the biochars made from woody biomass.

The classification and certification systems developed by the International Biochar Initiative (http://www.biochar-international.org/characterizationstandard) and The European Biochar Foundation (http://www.european-biochar.org/en) are useful and could be adopted in the GMS countries in guiding through the complex properties of biochar produced from different feedstocks for particular soil applications (IBI, 2012; EBC, 2012). The GMS countries should consider a common regulatory framework for the quality control of biochars for their application to agricultural soils, and centralised facilities should be created for biochar characterization in the region.

4.2 SOIL PROPERTIES

For the GMS region we have devised a scheme to evaluate the potential of biochar technology that is based on the soil type, slope characteristic and land use. We used the soil map of the GMS (Figure 1) and ranked all soils that exist in the GMS based on their properties expected of the defined soil groups and soil units (FAO, 1988). Soil properties that were considered in determining the biochar suitability ranking included pH, percent base saturation, cation exchange capacity, texture, soil depth and drainage. The listed properties were considered in defining criteria because – (i) the spatial information for these properties is readily available in the FAO-UNSECO soil classification system, and (ii) the importance of these properties in relation to positive agronomic response from biochar application to soils. The meta-analyses of a number of field and glasshouse exepriments show that biochars are more effective in increasing plant growth in acidic soils than in the alkaline soils (Atkinson et al., 2010; Jeffery et al., 2011; Biederman and Harpole, 2012; Crane-Droesch et al., 2013). Most biochars have alkaline pH (Singh et al., 2010; Krull et al., 2012) and offer some degree of acid neutralising capacity. Jindo et al. (2014) reported pH value of 8.99 and 9.82 for rice husk and rice straw biochar, respectively; based on the available feedstocks rice husk and straw biochars are most relevant to the GMS region. Also, most biochars contain some salts or minerals of base cations and the dissolution of such salts will release base cations in soils. It has been observed that oxygen containing functional groups, especially carboxylic and phenolic functional groups, form on aged black carbon which in turn provide sites for increased negative charge (Cheng and Lehmann, 2009; Cheng et al., 2006; Cheng et al., 2008). Therefore in long-term biochar has the potential to increase the cation exchange capacity of soils, which may be significant in sandy soils.

Each soil group was given a whole number ranking between 1 and 5, and each soil unit was given a ranking between 1.0 and 1.5. The soil ranking was then calculated using the soil group as the base number and the soil unit as the exponential function of the base number. For example, Acrisols were given a ranking of 5 (highest in terms of biochar suitability) and Ferric Acrisols were given an additional numerical value of 1.5, so the biochar suitability class for the Ferric Acrisols = $5^{1.5}$ = 11.18.

The calculated ranking data for the soils in the GMS are presented in Appendix 4 and biochar suitability map based on soil properties is presented in Figure 5.

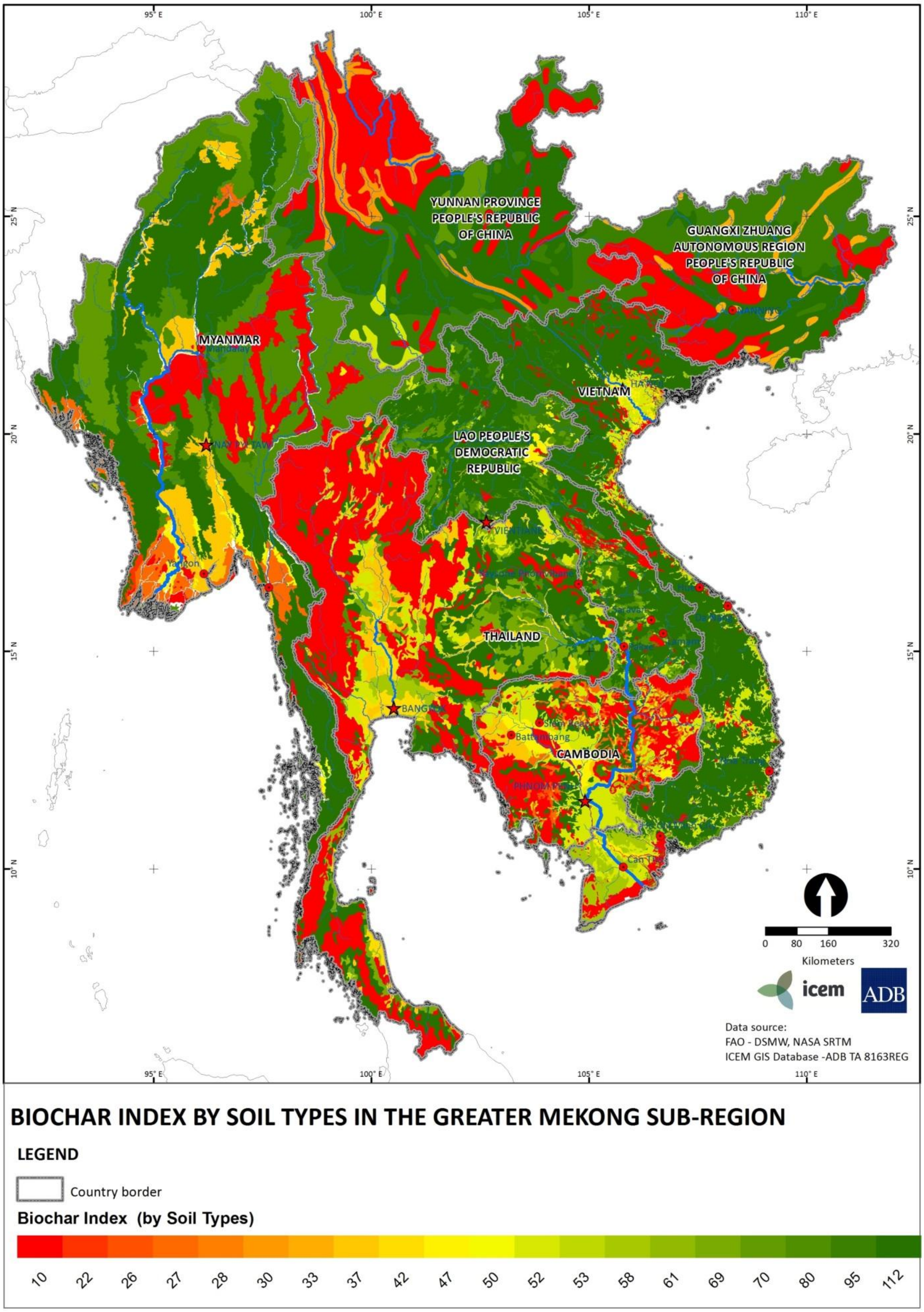


Figure 5: Biochar suitability in the GMS based on the soil types. The areas in the red are not suitable and in the yellow and green are suitable to highly suitable.

4.3 SLOPE CLASSES

Slope steepness has been considered an integral part of soil erosion and this parameter has been used in various prediction equations. For biochar suitability of soils in the GMS, we also used slope as one of the main determinant characteristics because biochar will be washed away if the slope is too steep (Figure 2). There is a prevalence of steep slope in the GMS and hence it is important to consider this parameter in the application of biochar to soils in the region. Erosion prediction equations use one of two independent variables; either percent of the slope or sine of the slope angle (Liu et al., 1994). The erosion prediction equations use linear, power, or polynomial functional forms. Most of the equations were developed using data collected on slopes up to approximately 25% slope; however, some of the equations have been validated using data collected on slopes steeper than 25% degree slope.

We used the equation proposed by Musgrave (1947) that uses percent slope to predict soil loss; the equation is written as:

$$\text{Soil loss} = (S/0.9)^{1.35} \qquad \text{where S is percent slope.}$$

As evident from the above equation, soil loss increases with increasing slope steepness or percent slope. Soil loss was computed based on slope percent of the GMS and for biochar suitability purpose, we inversed the calculated values of soil loss so that soils with steepest slopes are least suitable for biochar application and conversely the soils with minimal slopes are most suitable for biochar application. Lastly, the inversed values were normalised to keep the maximum value similar to the numerical values obtained for the most suitable soil that was 11.18. Example calculations for a range of slope values are presented in the Appendix 5. Biochar suitability map of the GMS based on the slope percent is given in Figure 6.

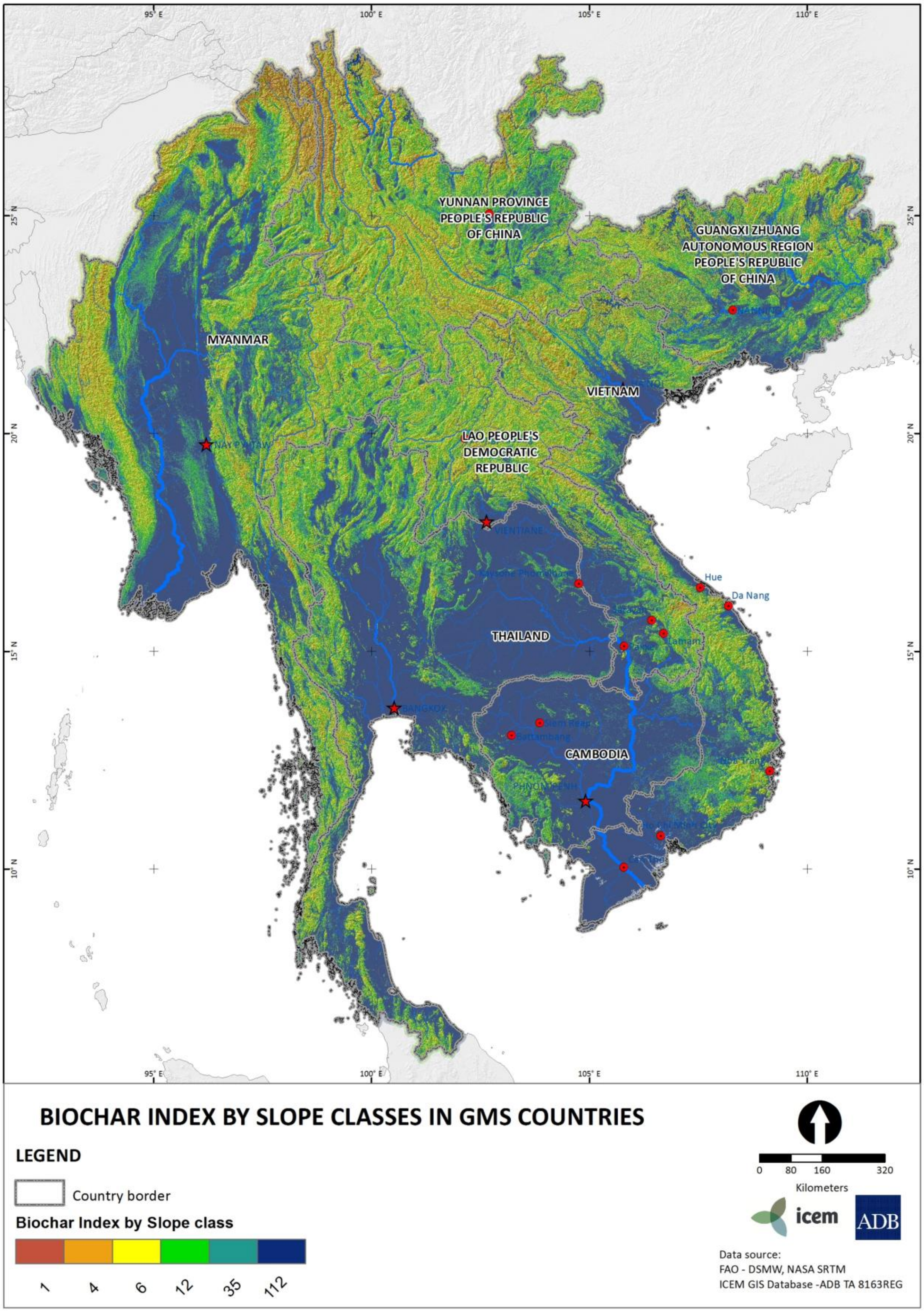


Figure 6: Biochar suitability in the GMS based on the slope classes. The areas in the red and gold are not suitable, in yellow-green may be suitable, and in the green and blue are suitable to highly suitable.

Soil and slope based biochar suitability classes were then combined to develop biochar suitability classes for land application in the GMS. A map with combined soil and slope suitability classes for the GMS is presented in Figure 7. To obtain this map, values from the two datasets were multiplied and the combined map was created with five categories or classes. The five categories were – (i) highly suitable, (ii) suitable, (iii) may be suitable, (iv) may not be suitable, and (v) unsuitable.

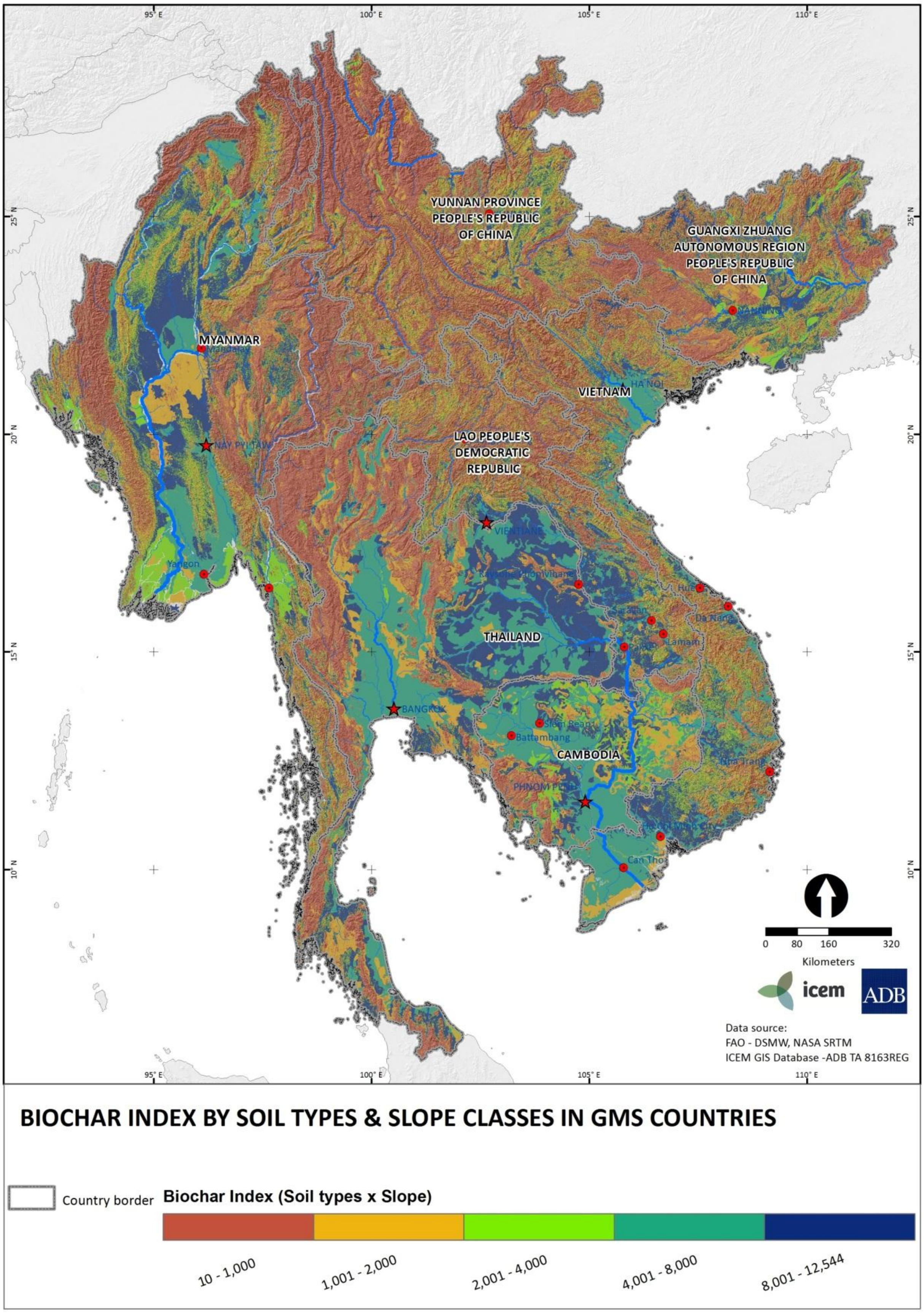


Figure 7: Biochar suitability in the GMS countries based on the combined soil and slope classes. The five suitability classes are (i) highly suitable (blue), (ii) suitable (green), (iii) may be suitable (lime), (iv) may not be suitable (gold), and (v) unsuitable (red).

4.4 LAND USE

From the GMS land use map, we isolated the areas that are potentially suitable for agriculture, it included four different categories as defined in the original land use map in Figure 3. The four categories selected for the purpose were– (i) crop land, rainfed, (ii) Cropland, irrigated or post-flooding, (iii) Mosaic cropland (> 50%) /natural vegetation (<50%); and (iv) Mosaic natural vegetation (>50%)/Cropland (<50%).

The areas of top three suitable land classes (i.e highly suitable, suitable, and may be suitable) derived from soil and slope parameters were isolated and are presented in (Appendix 6). Similarly the area under the four land uses outlined above was isolated; the area in purple in Appendix 7 is considered as the land currently under agriculture use or may be potentially used for agriculture in the GMS. The biochar suitability class map (Appendix 6) was superimposed on the land use data (Appendix 7) to obtain the map presented in A-Figure 33. The map in Figure 8 presents the agricultural land area classified into three biochar suitability classes i.e. land with low, medium and high suitability class for biochar application.

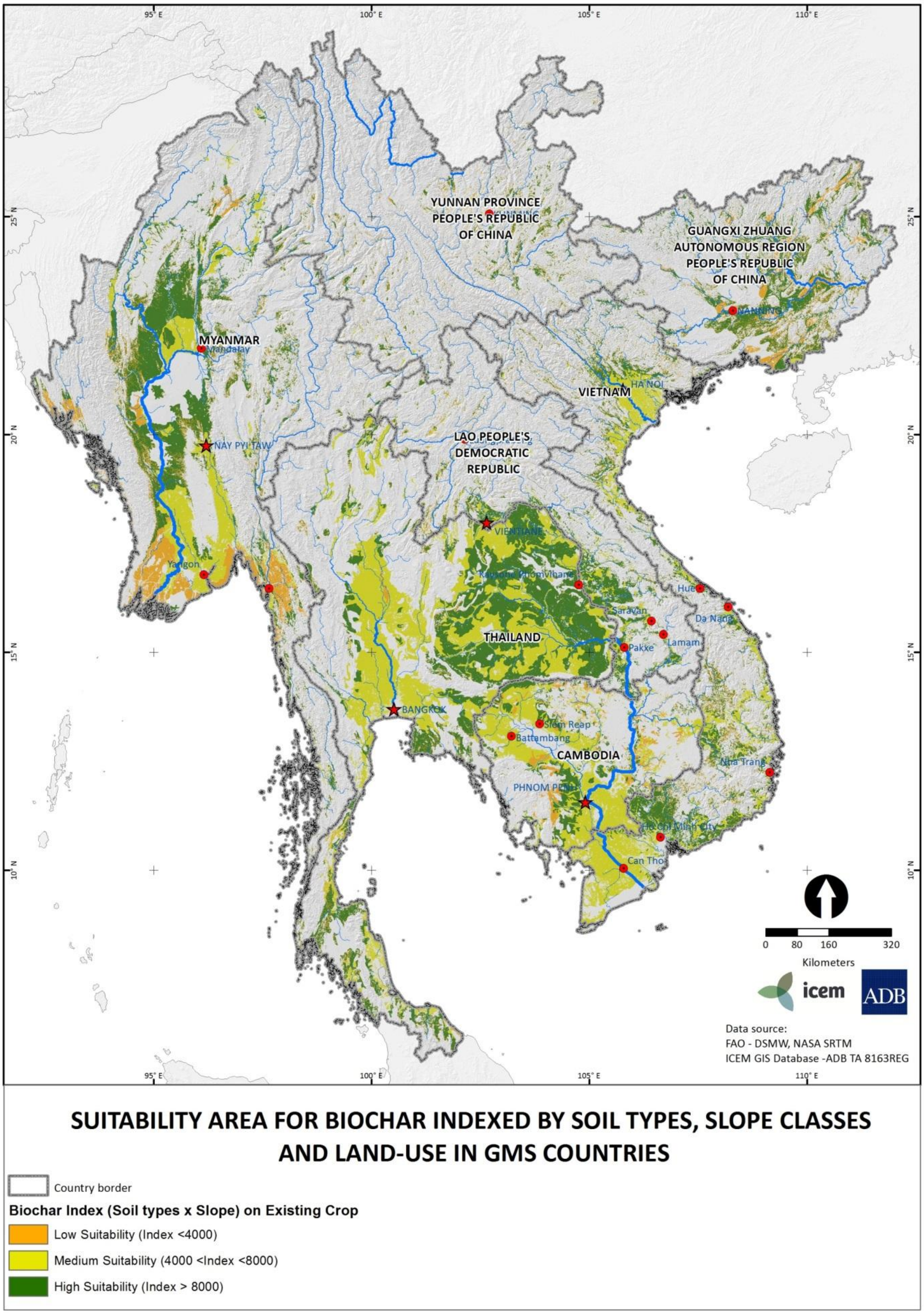


Figure 8: Biochar application suitability area based on soil and slope classes superimposed on the land that is used for agriculture or potentially suitable for agriculture in the GMS. The areas in the orange are least suitable, in the lime yellow have medium suitability and green are most suitable

5 AGRICULTURAL WASTE[7]

5.1 CROP RESIDUES

In the GMS, about 27% of the land area is used for agriculture and another 48% of the land area is forested (FAO, 2015). The share of agriculture land in the total land area of the six countries varies widely. Thailand (42.8%) has the maximum share of land under agricultural use, whereas Lao PDR has the least share of agricultural land (10.7%). Cambodia, Myanmar, Viet Nam and PR China have 32.6, 19.3, 35.0 and 20.9%, respectively of the area under agricultural cropping.

Table 2: Share of agricultural crops (%) of the total agricultural area in Greater Mekong Subregion countries, 2013 (Source: FAOSTAT; China Agriculture Yearbook 2013).

Crop	Cambodia	Lao PDR	Myanmar	Thailand	Viet Nam	PRC*
Rice	53.9	35.6	59.6	56.6	72.9	24.2
Maize	3.6	8.9	3.7	5.2	10.8	15.7
Cassava	6.1	1.8	0.4	6.3	5.0	6.8
Sugarcane	0.5	0.9	1.2	6.0	2.9	11.2
Beans	1.1	0.1	21.4	0.7	1.5	5.6
Sasame	0.6	0.5	12.6	0.3	0.4	0.1
Total agricultural area (000, ha)	5,755	2,469	12,593	21,860	10,842	66,522

*PRC included Yunnan Province and Guangxi Zhuang Autonomous Region.

The amount of agricultural residues is directly related to crop production, and depends on yield and cultivated area. The common feature to all GMS countries is the overwhelming predominance of rice growing. On an average, paddy rice accounts for over 83% of the total cereal production in these countries; the proportion of paddy is very high (over 90%) in Cambodia and Lao PDR, and minimum (about 63%) in PRC. Maize, cassava, sugarcane, bean and sesame are other common crops in the GMS region. In PRC, wheat and soybean are grown over 11.5% of the agricultural land. All these crops generate an abundant amount of residues that could be potentially used for biochar production.

The amount of agricultural waste that can be available for biochar production was calculated based on the residue to seed ratios available in the literature (Scarlat et al., 2010; Landell et al., 2013). Rice, maize, cassava, sugarcane, beans and sesame crops were considered in these calculations. The estimates for agricultural wastes are based on grain yield or total yield in the case of sugarcane, moisture content of seed and crop residues, and sustainable removal rates of wastes from land (Jölli and Giljum, 2005; Scarlat et al., 2010; Landell et al., 2013). Firstly, the grain data were corrected for moisture content based on 20 percent moisture in rice and 15 percent in rest of the grain crops. Then conversion factor of 1.76 for rice, 1.0 for maize, 1.4 for beans and oilseed crops, 0.4 for cassava and 0.1 for sugarcane was used for obtaining straw or residues from the grain or total yield data of the crops. The straw and residues were also corrected for moisture contents based on 25 percent moisture in rice straw, 30 percent in maize straw and 40 percent in oilseed and other crops. No moisture correction was made for cassava considering the conservative factor used for estimating the waste from the total yield.

[7] Agricultural wastes include crop residues and animal wastes. We define crop residues as any plant material left in an agricultural field after harvesting, including leaves, stalks, stubble. Animal wastes consist of animal excretea without bedding materials and/or animal drugs, collected from poultry, ruminants or other animals.

Crop residue removal or collection rate is likely to be varied in different areas depending on a combination of factors, including the availability of equipment (Glassner et al., 1998; Wilhelm et al., 2004; Graham et al., 2007), type of crop (Summers et al., 2003), crop yield (Van der Sluis et al., 2007), environmental requirements and water shortage (Patterson et al., 1995). Estimates on the collection of crop residues sustainably from the agricultural land vary between 30 and 60 percent of the total residues (Glassner et al., 1998; Kadam and McMillan, 2003; Katterer et al., 2004; Panoutsou and Labalette, 2006; USDA-NRCS, 2006; Christou et al., 2007; Van der Sluis et al., 2007). In an assessment study of the availability of agricultural crop residues in the European Union, Scarlat et al. (2010) used the sustainable removal rates of 40 percent for wheat, rye, barley and oats and 50 percent for maize, rice, rapeseed and sunflower. We have used the sustainable removal rate of 50 percent for all crops in our estimates of agricultural residue estimation in the GMS countries.

Significant amounts of crop residues are generated from agricultural crop production and partially remain in the field after harvest. More than 104 million tonnes of crop residues can be potentially available in the GMS for biochar production and this waste is largely based on rice production (Table 3). The availability of residues depends on the amount that can be removed from land to maintain land fertility and on their competitive use for agricultural for other applications. In the GMS, the contribution of waste from rice cropping varied between 51 and 84 percent of the total crop residues; the maximum rice based waste was available in Viet Nam and the minimum proportion is found in Thailand. The other noteworthy crop residues were from maize, cassava and sugarcane.

There are economic and environmental concerns associated with the removal of crop residues from agricultural land (Scarlat et al., 2010). Agricultural crop residues play an important role in maintaining or improving soil characteristics; they provide surface cover for the top soil, prevent soil erosion, maintain or increase soil organic matter, maintain essential plant nutrients in soil and improve water retention (Nelson, 2002). Conversely, the removal of crop residues might decrease soil organic matter, reduce nutrient buffer and supply, and can increase soil erosion (Johnson et al., 2006; USDA-NRCS, 2006).

Table 3: Potential amount (tonnes per annum) of crop residues potentially available from different agricultural crops in Greater Mekong Subregion countries.

Crop	Cambodia	Lao PDR	Myanmar	Thailand	Viet Nam	PRC	Total
Rice	4,957,920	1,803,120	15,188,976	19,041,053	23,252,746	9,433,248	64,243,815
Maize	303,361	376,338	556,325	1,656,810	1,698,720	3,110,839	4,591,554
Cassava	1,360,000	190,400	107,100	5,138,760	1,658,806	421,260	8,455,066
Sugarcane	30,000	59,000	482,500	5,004,800	1,006,554	4,936,745	6,582,854
Beans	33,915	1964	1,651,125	46,856	75,408	684,101	1,809,268
Sesame	9,282	4998	317,730	18,564	11,861	232,91	362,435
Total	6,694,478	2,435,819	18,303,756	30,906,844	27,704,096	18,609,483	104,654,475

The effect of biomass removal depends on several factors such as, crop rotation, tillage, fertilisation, soil characteristics (e.g. soil type, soil fertility, soil organic matter, soil C, moisture, topography and slope, risk of erosion) (Walsh et al., 2000; Kadam and McMillan, 2003), climate conditions (wind, temperature, rainfall intensity and patterns), and harvesting equipment (Nelson, 2002; Wilhelm et al., 2004; Ericsson and Nilsson, 2006; Graham et al., 2007). A proportion of the crop residues may be removed from land without affecting soil degradation and depletion of organic matter and without reducing soil fertility (Ericsson and Nilsson, 2006). Appropriate crop residue removal rates should be based on the minimum level of crop residue that must be kept on land to maintain the soil quality, soil organic matter and reduce the risk of erosion (Patterson et al., 1995; Johnson et al., 2006).

The removal of nutrients from land with crop residues can be compensated by conservation tillage, adequate crop rotation and the addition of manure, digestate from biogas plants or biochar application. Biomass removal from land and associated nutrients-removal might require additional fertilisation to compensate the loss of nutrients with crop residues. The environmental and economic costs associated with fertiliser application must also be considered (USDA-NRCS, 2006).

5.2 ANIMAL WASTES

In addition to the crop residues, animal waste could be a useful and significant feedstock for biochar production in the GMS. Additionally, the biochars produced from animal wastes are enriched with plant nutrients or essential elements compared to the biochars produced from crop residues (Singh et al., 2010; Peng et al., 2011; Jindo et al., 2014). The number of animals and poultry birds in each of the GMS countries is given in Table 4. Among the large animals, pigs, cattle, buffaloes and goats are present in significant numbers, whereas chickens are most abundant among poultry in all of the GMS countries (Table 4).

Table 4: Livestocks and poultry numbers in Greater Mekong Subregion countries, 2013 (Source: FAOSTAT; China Agriculture Yearbook 2013).

Animal	Cambodia	Lao PDR	Myanmar	Thailand	Viet Nam	PRC
Cattle	2,900,000	1,700,000	14,350,000	5,147,521	5,156,727	7,928,000
Buffaloes	676,000	1,180,000	3,250,000	1,288,812	2,559,539	4,080,000
Sheep	-	-	862,000	42,040	-	974,000
Goat	-	450,000	3,930,000	420,354	1,345,421	10,197,000
Pigs	2,150,000	2,800,000	10,530,000	7,923,654	26,261,400	57,664,000
Poultry (×1000)	21,300	33,450	206,103	293,242	314,755	1030,000

Based on the number of domesticated animals and poultry, dry matter waste was estimated for each of the GMS, and the values are presented in Table 5. The amount of dry matter animal waste generated for the animals was calculated based on the factors: cattle= 2.0 kg dry residue head^{-1} day^{-1}; buffalo = 3.0 kg dry residue head^{-1} day^{-1}; pig= 0.6 kg dry residue head^{-1} day^{-1}; sheep and goats = 0.65 kg dry residue head^{-1} day^{-1}; and chicken = 0.325 kg dry residue head^{-1} day^{-1}. The total waste potentially available for biochar production from animal stream is larger than the crop residues because we used a sustainable option for crop waste estimation according to which 50 percent of the crop residues should be retained in the field. The retention of certain levels of residues is important to maintain sustainable levels of organic C, soil cover and general soil quality. It is estimated that approximately 294 million tonnes of dry animal waste is generated annually in the GMS countries; and this amount could be even greater if the bedding material with liquid waste is considered in the waste estimates. The major challenge, however, is the scattered presence of the animals in the region that make it difficult to collect the available waste for biochar production.

Table 5: Dry matter waste (tonnes per annum) potentially available from livestocks and poultry animals in Greater Mekong Subregion countries, 2013.

Animal	Cambodia	Lao PDR	Myanmar	Thailand	Viet Nam	PRC	Total
Cattle	2,117,000	1,241,000	10,475,500	3,757,690	3,764,411	5,787,440	27,143,041
Buffaloes	740,220	1,292,100	3,558,750	1,411,249	2,802,695	4,467,600	14,272,614
Sheep	-	-	204,510	9,974	-	231,082	445,565
Goat	-	106,763	932,393	99,729	319,201	2,419,238	3,877,323
Pigs	470,850	613,200	2,306,070	1,735,280	5,751,247	12,628,416	23,505,063
Poultry	2,526,713	3,968,006	24,448,968	34,785,832	37,337,833	122,183,750	225,251,103
Total	5,854,783	7,221,069	41,926,190	41,799,755	49,975,387	147,717,526	294,494,709

5.3 COMPETITION FROM OTHER USERS FOR ANIMAL AND CROP RESIDUES

In addition to the scattered presence of wastes, there is significant competition from other users for both animal wastes and crop residues in the GMS. Cambodia, Lao PDR, Myanmar, and Viet Nam have some programs for biogas production for household consumption and other uses. Both Cambodia (http://nbp.org.kh/) and Viet Nam (http://www.snv.org/project/national-biogas-programme-vietnam) have a national bio-digester program with support from Government of the Netherlands and other agencies.

In Lao PDR there is an active private sector initiative for rural electrification based on biofuels, spearheaded jointly by the Lao PDR Institute for Renewable Energy and Sunlabob (Briones and Ahmed, 2008). The program is targeted to develop technology using jatropha (*Jatropha curcas*), identified as suitable for planting in the country's vast wastelands (ADB, 2008).

Biofuel development strategy in Thailand is focused on using local agricultural resources to meet the domestic energy needs. The main feedstocks for ethanol production in Thailand are sugarcane (molasses) and cassava. Many developed and developing countries are increasingly utilizing biomass for renewable energy production. For example, biomass is expected to contribute to around two-thirds of the renewable energy share in 2020 according to European Commission projections (Scralat et al., 2010). Therefore, the use of biomass for bioenergy production is expected to increase in the GMS and this will mean the availability of agricultural and animal wastes for biochar production may be limited.

In addition to the use of crop residues for incorporating into soil and for biofuel production, other competitive uses of agricultural residues include animal feed and bedding, mushroom cultivation, surface mulching in horticulture and industrial uses (Powlson, 2007). Straw is often incorporated in soil to protect against soil erosion, as fertiliser, and soil structure improver. Straw is often used as bedding for pigs and poultry and even as fodder for large animals. Maize stover could be a potential feed for cattle or buffaloes. Straw can also be used for making pulp or as insulating material for buildings.

6 POTENTIAL HOTSPOTS FOR BIOCHAR TECHNOLOGY APPLICATION IN THE GMS

Based on the land suitability criteria and availability of crop residues, two to four potential sites were proposed in the interim report and this information was also communicated with the national agencies for each of the GMS countries. These hotpots were chosen based on their location in the medium-high suitability areas in the biochar suitability area map (Figure 8), and the availability of biomass. From the initially proposed sites, two to four most desired areas or biochar hotpots (provincial and district boundaries) have been finalised in each of the six GMS countries (Figure 9). The proposed hotspots are located on the ADB economic corridors and have been identified in consultation with participating national agencies. The identified hotspots have the desired soil types that are likely to provide economic benefits to farmers from biochar application. The locations of these hotspots are outlined with pink boundaries in Figure 9 and a brief justification for each of the sites is given in the following section. Land use data for the hotspot district or province in the GMS chosen for biochar pilot studies are given in Table 6. Detailed data for the hotspots sites in the two PRC provinces were not available. Similar to the national data presented in the earlier section, paddy rice remains the dominant crop in all chosen areas in the GMS with one exception.

Table 6: Land use (ha) for major agricultural crops in the selected areas (hotspots) of the Greater Mekong Sub-region countries.

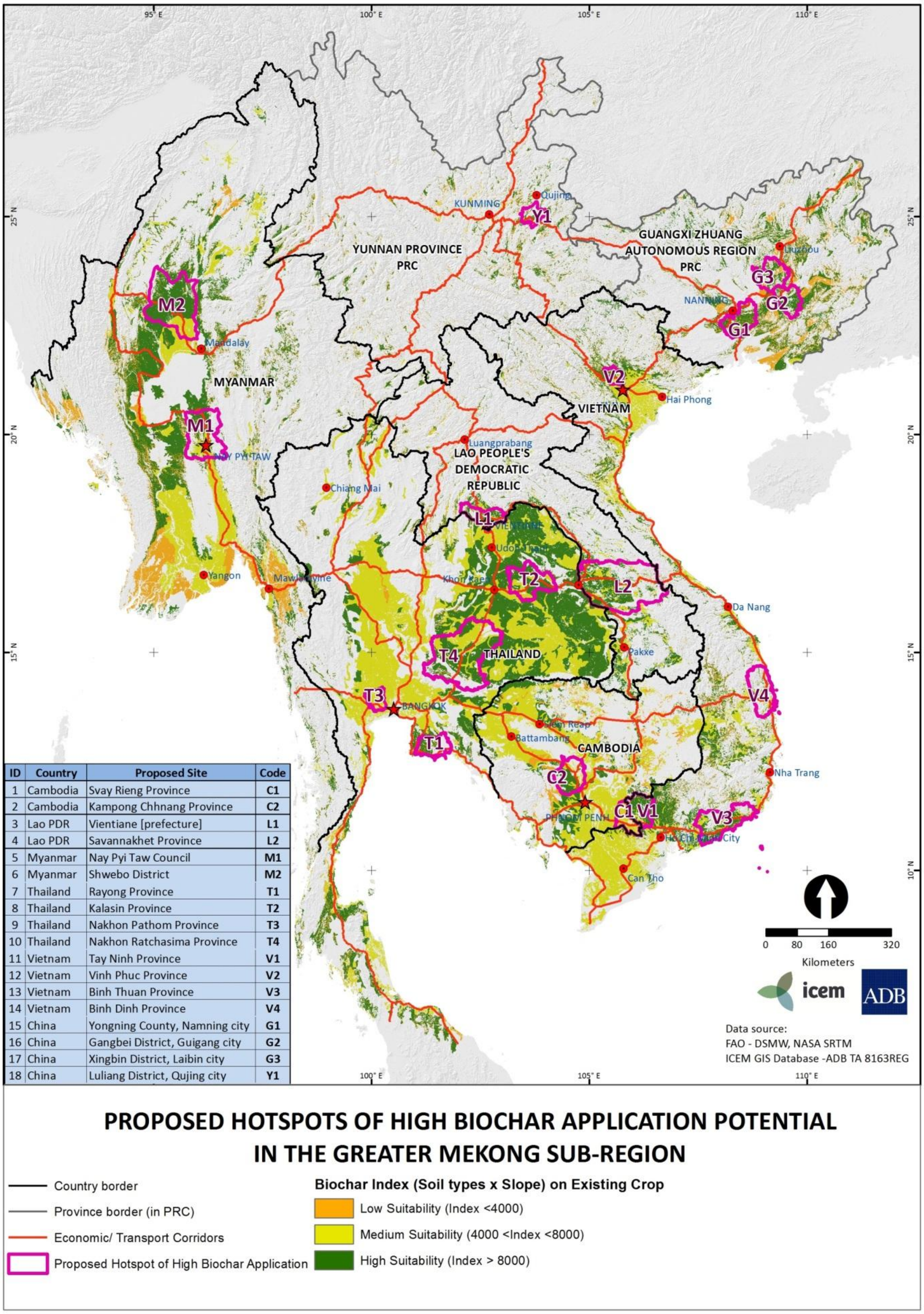
Country	Province/District	Rice	Maize	Sugar Cane	Cassava	Peanut	Total Area
Viet Nam	Tay Ninh (V1)	155,300	5,200	-	45,400	9,400	215,300
	Vinh Phuc (V2)	59,400	13,700	-	-	3,300	76,400
	Binh Thuan (V3)	113,200	19,700	2,900	32,800	5,600	174,200
	Binh Dinh (V4)	111,200	8,300	2,800	13,600	9,000	144,900
Cambodia	Svay Rieng (C1)	183,418	32	710	32,831		
	Kâmpóng Chhnang (C2)	129,024	2608	570	765		
Lao PDR	Vientiane (L1)	52, 031	6,590	145	5,120	1,495	13,350
	Savannakhet (L2)	173,117	3,700	11,850	8,605	1,205	198,477
Thailand	Rayong (T1)	3,969	-	301	6,973	-	11,243
	Kalasin (T2)	277,431	20	58,931	32,433	-	368,815
	Nakhon Pathom (T3)	102,754	-	12,181	-	-	22,935
-	Nakhon Ratchasima (T4)	557,928	103,854	95,351	25,396	-	782,529
Myanmar	Nay Pwi Taw (M1)	154,349	7,589	-	-	1,402	163,340
	Shwebo (M2)	337,397	244			30,811	368,452

The amount of crop residues potentially available from different crops in the chosen areas is given in Appendix 9, which shows a huge potential for the available feedstock (over 6.5 million t per annum excluding PRC) for biochar production. In addition to the crop residue wastes, there is potentially over 6.5 million t per annum (excluding PRC) of animal waste in the selected areas, which could be potentially used for biochar production along with the crop residues (Appendix 9). Rice husk alone, which is perhaps the most important and readily available feedstock for biochar production, is available in large quantities in the identified areas of the GMS region, we estimate approximately 1.8 million tonnes of rice husk may be available for biochar production in the selected areas.

Table 7: Livestocks and poultry animals in the selected areas (hotspots) of the Greater Mekong Sub-region countries.

Country	Province/District	Cattle	Buffaloes	Pigs	Sheep and goats	Poultry	**Total**
Viet Nam	Tay Ninh (V1)	110,7	27,200	212,700	-	3,439,000	3,678,900
	Vinh Phuc (V2)	94,100	21,500	480,100	-	8,434,000	9,029,700
	Binh Thuan (V3)	167,200	8,500	206,100	-	2,591,000	2,972,800
	Binh Dinh (V4)	246,200	21,000	650,400	-	5,928,000	6,845,600
Cambodia	Svay Rieng (C1)	267,388	30,626	114,386	202	2,237,836	2,650,438
	Kâmpóng Chhnang (C2)	211,992	42,693	102,998	709	150,061	508,453
Lao PDR	Vientiane (L1)	149,000	72,000	93,000	22,000	1,508,000	1,844,000
	Savannakhet (L2)	397,000	289,000	269,000	66,000	2,528,000	3,549,000
Thailand	Rayong (T1)	2,436	642	82,131	-	17,422	102,631
	Kalasin (T2)	292	12,966	90,488		43,684	147,430
	Nakhon Pathom (T3)	25,485	382	250,776	-	3,606,780	3,883,423
	Nakhon Ratchasima (T4)	73,639	31,095	366,565		65,849	537,148
Myanmar	Nay Pwi Taw (M1)	243,665	69,837	300,149	16,697	3,913,761	4,544,109
	Shwebo (M2)	710,322	57,647	120,207	246,987	1,279,408	2,414,571

Field excursions were undertaken in Cambodia, Lao PDR and Myanmar to ground truth the selected hotspots areas and after discussion with the local national agencies pilot sites were selected for possible biochar trials in the future. The selected farmers are keen participate in biochar pilot program. The locations and other details of the selected sites are given in the following sections.



ID	Country	Proposed Site	Code
1	Cambodia	Svay Rieng Province	C1
2	Cambodia	Kampong Chhnang Province	C2
3	Lao PDR	Vientiane [prefecture]	L1
4	Lao PDR	Savannakhet Province	L2
5	Myanmar	Nay Pyi Taw Council	M1
6	Myanmar	Shwebo District	M2
7	Thailand	Rayong Province	T1
8	Thailand	Kalasin Province	T2
9	Thailand	Nakhon Pathom Province	T3
10	Thailand	Nakhon Ratchasima Province	T4
11	Vietnam	Tay Ninh Province	V1
12	Vietnam	Vinh Phuc Province	V2
13	Vietnam	Binh Thuan Province	V3
14	Vietnam	Binh Dinh Province	V4
15	China	Yongning County, Namning city	G1
16	China	Gangbei District, Guigang city	G2
17	China	Xingbin District, Laibin city	G3
18	China	Luliang District, Qujing city	Y1

Figure 9: Proposed sites (hotspots) for biochar production for application to agricultural land in the GMS countries. The sites were selected based on medium-high biochar application suitability,

6.1 VIET NAM

6.1.1 V1 - Tay Ninh Province

Tay Ninh is a province that is located in the southeast region of Viet Nam bordering Cambodia. It is an important economic region, with a favourable transportation position being located in the ADB Southern Economic Corridor. The total area of Tay Ninh is 4,028 km² and according to the 2013 census the population is 1,095,600 inhabitants. The province is largely dependent on agriculture and the major land use in the province is for rice production.

Soils in Tay Ninh have been classified under four soil groups and with 12 soil units (Appendix 10 – A-Table 12 and A-Figure 35) according to the Vietnamese soil classification system and three soil groups based on the FAO classification system.

Based on the pH alone, all soils in the province will benefit from biochar application. However, most benefits from biochar application would be expected in degraded gray soils and acid sulfate soils.

6.1.2 V2 - Vinh Phuc Province

Vinh Phuc is located in the Red River Delta on the ADB Eastern Economic Corridor in the transition area between midland mound and hill area. The total land area of Vinh Phuc province is 1,231 km^2, and the total population according to the 2013 census is 1,029,400 inhabitants. About 51 percent of the land area is cultivated for agricultural crops and according 2011 data of the Vinh Phuc Forest Management, the total forest area in the province is 28,313 ha (~22.4%). Degraded gray soil and gray soils that exist over a large area in the province are likely to benefit most from biochar application (Appendix 10 – A-Table 14 and A-Figure 36).

6.1.3 V3 – Binh Thuan Province

Binh Thuan is a coastal central province that is located on the ADB's Eastern Economic Corridor. The Province covers an area of 7,828 km^2, and the total population according to the 2013 census is 1,201,200. Binh Thuan is a major producer of rice in the country. Cashew nuts, maize and rubber are other important crops in this Province.

It is expected that biochar application in most soil types, particularly reddish yellow soils degraded gray soils, sandy soils, red and brownish gray soils in semi-arid regions and yellow red humus soil on mountains ((Appendix 10 – A-Table 15 and A-Figure 37)), will produce some beneficial effects from the liming effect and addition of nutrients. The application of biochar is also likely to increase the nutrient and water holding capacity of the soils in the Province.

6.1.4 V4 – Binh Dinh Province

Bin Dinh Province is situated in the south-central coast region of Vietnam and it is close to the ADB eastern and southern Economic Corridor. It has a vibrant and productive primary sector (agriculture, fishery, forestry) in the region. The total area of Bin Dinh province is 6,025 km² and the population according to the 2013 census is 1, 510,400.

Reddish yellow soils, degraded gray soils and sandy which occupy 83% of the area in the province, will benefit from biochar application ((Appendix 10 – A-Table 17 and A-Figure 38)). Most soils including the most predominant soil (reddish yellow soil) have highly acidic pH with low to medium organic matter content (A-Table 18). Based on the pH alone, all soils in the province will benefit from biochar application. However, most benefits from biochar application would be expected in acid sulfate soils, degraded gray soils and reddish yellow soils.

6.2 CAMBODIA

6.2.1 C1 - Svay Rieng Province

Svay Rieng is among the smaller provinces in Cambodia which is situated on the south-western end bordering Viet Nam. The province has 8 districts, 80 communes and 690 villages. The total population of this Province is about 628,000 and more than 90% of the population is farmers. The total land area of Svay Rieng is 296,640 ha and rice is the main crop in the Province. The total area under rice cultivation in the 2014 was 185,500 ha that included 165,500 ha of wet season rice and 20,000 ha dry season rice. The total rice production in the Province was 504,560 tonnes at an average yield of 2.72 t ha^{-1}. In addition to rice, cassava and sugarcane are the other significant crops in the Province, with an area of 9,120 ha (average yield 55 t ha^{-1}) and 7,250 ha (average yield 18.4 t ha^{-1}), respectively. Rice husk (100,000 t per annum) is perhaps the main feedstock that can be used for producing biochar in the Province and at the chosen hotspot sites. Rice straw is used as animal feed, for mushroom production and in composting animal manures. A significant portion (up to 30 percent) of the straw is burnt in open fields, particularly in lowlands where farmers take multiple cropping in a year.

In Svay Rieng Province the total number of cattle and buffaloes is 269,258 and the number of pigs is 210,153. Additionally, there are about 1,252,000 poultry birds. In the Province there are approximately 2,500 biogas units that use significant amount of cattle manure. Bioslurry from the biogas plants is mixed with water and used for irrigating crops. Wastes from poultry and piggery in the raw forms are generally added to agricultural soils.

Soil fertility potential of main soil types is low to medium and thus will benefit from biochar application. The province also has 6,000-7,000 ha of acid sulfate soils and biochar application to these soils will be beneficial for cropping to increase the pH of highly acidic soils (Appendix 10 – A-Figure 39 and A-Table 19). Approximately 100, 000 t of rice husk can be potentially used for biochar production in the province. Other agricultural wastes are not be available for biochar production, for example sugarcane waste is generally sold or used for another purposes, cassava waste is used for fuel.

The two sites selected for potential biochar trials occur in the region occupied by Prateah Lang soil group which has low soil fertility.

Site 1: Farmer: Solay, Village (phum): Veal, Commune (khum): Chrork Mates, District (srok): Bavet
Farm size: 3 ha; Family members: 5; Animals: 2 buffaloes, 4 pigs, 30 chickens.
Farming system: One rice crop during rainy season.

There may be about 750 kg of rice husk available for biochar production. Animal manure is currently applied directly to land and the waste from pigs is added to fish pond. Biochar can be produced using the double-wall drum system provided by the Department of Agriculture; from the available biomass approximately 375 kg biochar can be produced by the farmer. The rice husk biochar can potentially supply 2.3 kg nitrogen, 1.1 kg phosphorus and 3.2 kg potassium (Prakongkep et al. 2015). Rice husk biochar is alkaline and has potential liming effect which might increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice yield from biochar application the farmer can earn an additional income of about $280 per annum and there may be an additional saving of about $12 per annum from reduced fertiliser application.

Proposed Pilot Site 1 in village Veal of Bavet District.

The farmer at site 1 (village Veal of Bavet District) with the biochar production system supplied by the Department of Agriculture.

Site 2: Farmer: Phen Somearn, Village: Veal, Commune: Chrork Mates, District: Bavet
Farm size: 2 ha; Family members: 3; Animals: 7 buffaloes, 30 chickens and 15 ducks.
Farming system: One rice crop during rainy season.

There may be about 560 kg of rice husk available for biochar production. Animal manure is currently used for biogas production and the residual slurry is applied to fish pond and vegetable crops. Biochar can be produced using the system described above and from the available biomass approximately 280 kg biochar can be produced by the farmer. The rice husk biochar can potentially supply 1.7 kg nitrogen, 0.8 kg phosphorus and 2.4 kg potassium (Prakongkep et al. 2015). Rice husk biochar is alkaline and has potential liming effect in acid soil might increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice yield from biochar application the farmer can earn additional income of about $210 per annu; and there may be an additional saving of about $9 per annum from reduced fertiliser application.

Proposed Pilot Site 2 in village Veal of Bavet District.

Bioslurry waste at proposed Pilot Site 2 in village Veal of Bavet District.

6.2.2 C2 – Kampong Chhnang Province

Kampong Channang is a one of the central provinces of Cambodia and it is located in the basin of Tonle Sap Lake and the Tonle Sap River. The total area of the province 55,210 ha and the population is about 504,000. It has 8 districts, 69 communes and 560 villages.

Rice is the main crop in the Province; in 2014 the total area under rice cultivation was 157,361 ha that included 121,135 ha of wet season rice and 36,226 ha dry season rice. The total rice production in the Province was 511,858 tonnes at an average yield of 3.25 t ha^{-1}. Corn and cassava are the other significant crops in the province with an area of 1,091 ha and 104 ha, respectively. Vegetable and other industry crops, such as sweet potato, mixed vegetables, water melon, peanut and green nut, covers about 6,200 ha. Similar to Svay Rieng Province, rice husk is the main feedstock (over 102,000 t per annum) that can be used for producing biochar in the Province and at the chosen hotspot sites. Rice straw is used as animal feed or left in the field; straw however, is not usually burnt in open fields in this Province.

In Svay Rieng the total number of cattle, buffaloes and pigs is 181,569, 35,093 and 227,352, respectively. The total number of poultry birds (chicken and ducks) is about 1,872,000. There are approximately 1,220 biogas plants in the Province, which uses significant amounts of animal manure. Bioslurry from the biogas plants is mixed with irrigation water and used for irrigating rice and vegetable crops. Manures from poultry and piggeries are added to agricultural soils, generally in the raw form.

The detailed soil map and fertility status of soils in Kampong Chnang Province are given in Appendix 10 – A-Figure 40 and A-Figure 41.

The two sites selected for potential biochar trials occur in the region occupied by Acrisols and Arenosols with low fertility status.

Site 1: Farmer: Ms Kann, Village: Khveat, Commune: Pong Ror, District: Rolea B'ier
Farm size: 2.07 ha Family members: 6; Animals: 5 Cattle, 2 chickens.
Farming system: One rice crop during rainy season.

There may be about 1,400 kg of rice husk available for biochar production. There is little or no animal manure for biochar production. Biochar can be produced using a simple drum and from the available biomass approximately 700 kg biochar can be produced by the farmer. The rice husk biochar can potentially supply 4.2 kg nitrogen, 2.1 kg phosphorus and 6.0 kg potassium. The liming effect of biochar in acid soil is expected to increase the availability of nutrients from its soil application. Based on an estimated 10% increase in rice yield from biochar application the farmer can earn additional income of about $525 per annum; and there may be an additional saving of about $20 per annum from reduced fertiliser application.

Site 1: Rice transplanting on the farm in village Khveat, in Rolea B'ier District.

Site 2: Farmer: Norng Piseth, Village: Trapaing Thum, Commune: Pong Ror, District: Rolea B'ier
Farm size: 1 ha Family members: 8; Animals: 3 bollocks, 2 cows, 50 chickens and 3 ducks.
Farming system: One rice crop during rainy season.

There may be about 600 kg of rice husk available for biochar production. Animal manure is applied directly on land and may not be available for biochar production. Biochar can be produced using a simple drum and from the available biomass approximately 300 kg biochar can be produced by the farmer on an annual basis. The rice husk biochar can potentially supply 1.8 kg nitrogen, 0.9 kg phosphorus and 2.6 kg potassium. The liming effect of biochar in acid soil is expected to increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice yield from biochar application the farmer can earn an additional income of about $225 per annum; and there may be an additional saving of about $10 per annum from reduced fertiliser application.

Site 2: A general view of the paddy field in village Trapaing Thum in Rolea B'ier district.

6.3 LAO PDR

6..3.1 L1 - Vientiane Province

Vientiane is a large province located in the northwest of the country on the ADB Central Economic Corridor. It has a total area of 159,270 ha and the total population is about 783,000. There are 11 districts in the Province.

Rice is the main crop in the Province, with the total area under wet and dry season rice of 53,000 and 11,000 ha in 2015, and total paddy rice production of approximately 290,000 t. In addition to rice, cassava and corn are the other significant crops in the Province with an area of 52,031 ha, 5,120 ha and 6,590 ha, respectively. Rice husk (58,000 t per annum) is the main feedstock for producing biochar in the Province that could be used at the chosen hotspot sites. Rice straw is used as animal feed or left in the field.

In Vientiane province the total number of cattle, buffaloes, goats and pigs is 169,932, 50,499, 18,463 and 102,186, respectively. Additionally, there are about 2.3 million poultry birds. In the province there are biogas plants (exact data not available) that use some of the available animal manure. There are 6-7 piggeries that have more than 200 pigs. Animal waste from large piggeries is used for biogas production and slurry is used for irrigating cassava and palm plantations. Some organic manure is sold to other farmers. Organic manures are added to agricultural soils, generally in the raw form.

Based on the soil pH, texture and organic matter contents of the soils at the chosen sites (Appendix 10 – A-Figures 42-44) it is expected that biochar application to soil will produce beneficial effects on crop productivity.

The two sites selected for potential biochar trials occur in two separate districts and the site details are indicated in maps in A-Figures 42-44. Other details are as follows:

Site 1: Farmer: Mrs Sang Doune, Village: 52 km, District: Phonehong
Farm size: 17 ha; Family members: 7; Animals: 300 pigs, 62 cattle and 300 poultry birds.
Farming system: 6 ha used for paddy rice (one crop during rainy season); 5 ha pasture for cattle, 2 ha fish ponds and 0.08 ha for vegetables. Organic manure used for biogas production for domestic purposes and a part of this is sold to neighbours. About 30 t per annum of organic manure is produced on the farm, which is sold to other farmers.

There may be about 4.7 t of rice husk available for biochar production on an annual basis. Some animal manure is applied on the farm but not available for biochar production. Biochar can be produced using a simple drum system (see photo below) and from the available biomass approximately 2.3 t biochar can be produced by the farmer on an annual basis. The rice husk biochar can potentially supply 14 kg nitrogen, 7 kg phosphorus and 20 kg potassium. The liming effect of biochar in acid soil is expected to increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice yield from biochar application, the farmer can earn additional income of about $1755 per annum; there may be an additional saving of about $70 per annum from reduced fertiliser application. The farmer is already trialling the application of biochar for vegetable production with significant benefits.

General view of the farmer's paddy field (Site#1) at Village 52 km in Phonehong district.

Biochar making equipment at the farmer's field (Site#1, Village: 52 km, District: Phonehong) used for biochar production for vegetable crops.

Biochar application in the field used for vegetable crops (Site #1 in Village: 52 km, District: Phonehong).

Site 2: Farmer: Mr Suvat Ketsutta, Village: Phonhong-Nafai, District: Thoulakhom
Farm size: 14 ha; Family members: 9; Animals: 32 cattle, 30 chickens and 1 pig.
Farming system: 8 ha used for paddy-paddy rotation (i.e. two rice crops grown in a year) and 6 ha pasture for cattle. Organic manure applied on the pasture and rice land and not be available for biochar production.

There may be about 10.2 t of rice husk available for biochar production on an annual basis. Biochar can be produced using a simple drum system and from the available biomass approximately 5.1 t biochar can be produced by the farmer on an annual basis. The rice husk biochar can potentially supply 30 kg nitrogen, 15 kg phosphorus and 43 kg potassium. The liming effect of biochar in acid soil is expected to increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice yield from biochar application, the farmer can earn additional income of about $3840 per annum; there may be an additional saving of about $160 per annum from reduced fertiliser application.

General view of the farmer's paddy field (Site#2) at village Phonhong-Nafai in Thoulakhom district.

6.3.2 L2 - Savannakhet Province

Savannakhet province is located on the ADB East West Economic Corridor and Central Economic Corridor and it is the largest province in Lao PDR. The province covers an area of 21,774 square kilometres and estimated total population of over 950,000. There are 15 districts in the Province.

Rice is the main crop in the Province, with the total area of 211,613 ha and total production of 910,920 tonnes in 2013-14 season. More than 85% of the area is for rice is grown in the wet season. Dry season and upland rice occupy 28,548 ha and 1,748 ha, respectively. Sweet corn, cassava, beans, sugarcane and peanuts are other significant crops in the Province; however the cropped area for each of these crops is less than 5,000 ha. The total area under vegetable crops is about 25,000 ha.

Rice husk (182,000 t per annum) is the main feedstock available in the Province for producing biochar. Rice straw is used as animal feed or left in the field; no reported practice of open burning in the Province.

In Savannakhet Province the total number of cattle, buffaloes, goats and pigs is 416,923, 298,398, 76,925 and 315,950, respectively. Additionally, there are about 3.5 million poultry birds. In the Province there are over 1,000 biogas plants which utilise some of the available animal manure. There are 16 breeding piggeries in the province and the organic manure is either used for biogas production or sold to farmers. Farmers who don't have biogas plants either sell organic manures or add to agricultural soils.

Based on the soil pH, texture and organic matter contents of the soils at the chosen sites (Appendix 10 - A-Figures 45-47) it is expected that biochar application to soil will produce beneficial effects on crop productivity.

The pilot site selected for potential biochar trials is indicated in maps in A-Figures 45-47. Other details are as follows:

Site 1: Farmer: Mr Sisavanh Bungphachan, Village: Pai, District: Champhone.
Farm size: 5.5 ha; Family members: 4; Animals: 9 cattle and 58 poultry birds (40 chicken and 18 ducks).
Farming system: 4 ha used for paddy rice (one crop in a year during rainy season), 1.5 ha for vegetables, banana and pineapple. Organic manure applied to land used for vegetable growing and not available for biochar production.

There may be about 2.4 t of rice husk available for biochar production on annual basis. Biochar can be produced using a simple system (see photo on the next page) and from the available biomass; approximately 1.2 t biochar can be produced by the farmer on annual basis. The rice husk biochar can potentially supply 7.2 kg nitrogen, 3.6 kg phosphorus and 10.2 kg potassium. The liming effect of biochar in acid soil is expected to increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice yield from biochar application, the farmer can earn additional income of about $900 per annum; there may be an additional saving of about $35 from reduced fertiliser application.

General view of the farmer's paddy field at village Pai in Champone district.

A communal biochar and organic fertiliser making facility at village Pai in Champone district.

Simple biochar production equipment used at the communal facility at village Pai in Champone district.

A demonstration of biochar production from rice husk at the communal facility at village Pai in Champone district.

6.4 THAILAND

6.4.1 T1 - Rayong Province

- Approximately 45% of the provincial area has high biochar application suitability (based on the biochar land suitability analysis results).
- It is on the ADB Southern Coast Economic Corridor.
- It is close to to agro-industry sites in peri-urban areas outside Bangkok and there is potential for the availability of commercial wastes for biochar production.

6.4.2 T2 - Kalasin Province

- Approximately 80% of the provincial area has medium-high biochar application suitability.
- It is on the ADB East West Economic Corridor.
- It is close to Khon Kaen city and therefore large potential sources of agro-industry and commercial wastes for feedstock.
- It is on a large floodplain and therefore a large potential source of agricultural waste for feedstock.

6.4.3 T3 – Nakhon Pathom Province

- Approximately 85% of the provincial area has medium biochar application suitability.
- It is on the ADB Southern Economic Corridor and Northsouth Corridor extension.
- It is close to Nakhon Pathom and Bangkok cities and therefore a large potential source of agro-industry and commercial wastes for feedstock.

6.4.4 T4 – Nakhon Ratchasima Province

- Approximately 70% of the provincial area has high biochar application suitability.
- It is on the ADB Central Economic Corridor.
- It is close to Nakhon Ratchasima city and therefore a large potential source of agro-industry and commercial wastes for feedstock.

6.5 MYANMAR

6.5.1 M1 –Nay Pyi Taw Council

Nay Pyi Taw council is an administrative division in central Myanmar which covers an area of 7,057 km2 and the total population is 1,160,242 (**http://www.dop.gov.mm/moip/**). It is situated on the ADB Western Economic Corridor. The Nay Pyi Taw council consists of the city proper and eight surrounding townships. The two hotspots, Le Way and Tat Kone are surrounding townships in the council.

The total cultivated area in the Nyi Pyi Taw Council is 115,935 ha that consists of 67,260 ha of wetland and 44,921 ha of dryland. Paddy is the main crop in Le Way Township and it is the second most important crop in Tat Kone Township after black gram (Table 9). In terms of feedstock for biochar production, rice husk is the only realistic possibility as the residues from legume and other crops used as animal feed. Based on the rice production data, we estimate that in Le Way and Tat Kone townships 8,487 and 19,654 t, respectively of rice husk may be available on annual basis.

There is some possibility for the animal waste use for biochar production considering the large number of domestic animals in the two areas (Table 10).

Table 8: Area under major crops at the three hotspot sites in Myanmar.

Crop	Area (ha)		
	Le Way township	Tat Kone township	Shwe Bo district
Paddy (wet-season)	23,542	9,627	48,117
Paddy dry-season	2,239	501	26,433
Sesame	11,458	1,991	10,643
Green gram	297	22,129	6,260
Black gram	15,102	4,192	1,836
Maize	1,700	1,259	0
Groundnut	2,736	4,722	3,704
Pigeonpea	0	211	2,420
Bean	799	3,932	6,116

Detailed soil analysis data are not available for the area; however, in general Ferralsols have acidic pH, and low to medium soil fertility and benefit most from biochar application (Appendix 10 – A-Figure 48-49.

The two sites selected for potential biochar trials occur in two separate townships in Nay Pyi Taw council and the site locations are indicated in maps in A-Figures 48 and 49. Other details are as follows:

Site 1: Farmer: U Tin Htwe, Village: Kyan Khin Su; Le Wey Township, District: Takhina, Nay Pyi Taw council.
Farm size: 6 ha; Family members: 10; Animals: 3 buffaloes and 15 poultry birds.
Farming system: 5.2 ha used for paddy-pulse production and 0.8 ha used for maize-sesame or pulse production. Organic manure collected and applied on agricultural land, there may be some potential for biochar production.

Among the crop residues only rice husk is available for biochar production. There may be about 4.7 t of rice husk available for biochar production on annual basis. Currently there is no equipment or knowledge about biochar technology in the area. It is possible to use a simple drum system similar to those in use in Lao PDR for making biochar, and from the available biomass approximately 2.3 t biochar can be produced by the farmer on an annual basis. The rice husk biochar can potentially supply 14 kg nitrogen, 7 kg phosphorus and 20 kg potassium. The liming effect of biochar in acid soil is expected to increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice (and pulse) yield from biochar application the farmer can earn additional income of about $1755 per annum; there may be an additional saving of about $70 per annum from reduced fertiliser application.

General view of the farmer's field in village Kyan Khin Su of Le Wey Township in Takhina district, Nay Pyi Taw council.

Site 2: Aung Naing Tum, Village: Kyan Bo; Tat Kone Township, Nay Pyi Taw council.
Farm size: 4 ha; Family members: 4; Animals: 2 bullocks.
Farming system: 2.5 ha used for paddy-green gram production and 2.5 ha used for maize-potato rotation.

Among the crop residues only rice husk is available for biochar production. There may be about 1300 kg of rice husk available for biochar production on an annual basis. Currently there is no equipment or knowledge about biochar technology in the area. It is possible to use a simple drum system similar to those in use it Lao PDR for making biochar, and from the available biomass approximately 650 kg biochar can be produced by the farmer on an annual basis. The rice husk biochar can potentially supply 4 kg nitrogen, 2 kg phosphorus and 5.5 kg potassium. The liming effect of biochar in acid soil is expected to increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice (and pulse) yield from biochar application, the farmer can earn additional income of about $490 per annum; there may be an additional saving of about $20 per annum from reduced fertiliser application.

General view of the field site in village Kyan Bo, Tat Kone Township, Nay Pyi Taw council.

Team members interviewing the farmer in village Kyan Bo, Tat Kone Township, Nay Pyi Taw council.

Table 9: Number of domestic animals at the three hotspot sites in Myanmar.

Animal	Area (ha)		
	Le Way township	Tat Kone township	Shwe Bo district
Buffaloes	17,699	7,162	13,796
Cattle	77,754	20,117	124,205
Sheep/goats	9,931	1,448	28,833
Pig	71,779	52,222	33,680
Poultry	1322,859	709,792	639,847

6.5.2 M2 –Shwe Bo District (Sagaing Division)

The total area of Sagaing Division is about 93,702 km^2 and population is 5,325,347. The hotspot site is close to the Shwe Bo Township which is situated on the ADB Northern Economic Corridor. The total cultivated area in the Shwe Bo district is 664,473 ha, out of which 325,491 ha is wetland and 326,377 ha is dryland. Paddy is the main crop in Shwe Bo district and this area is the main producer of Shwebo Baygya rice, which is a very popular variety of rice. There is abundant amount of rice husk (43,157 tonne per annumin Shwe Bo Township alone) available for biochar production in the area. Additionally, some animal waste can also be used for biochar production considering the large number of domestic animals in the district (Table 10).

The soil map of Sagaing division according to the local classification system is given in A-Figure 50. Eleven different soils have been identified in the Division. Yellow brown forest soils (Xanthic Ferralsols) and Red brown forest soils (Rhodic Ferralsols) are the most predominant soils; these soils are mostly used for forest plantations. Soil at the site chosen for the biochar trial belongs to 'Catena of Savanna soils on Slopes and Compact soils in depressions' soil type. These soils are light textured (sandy loam) with low to medium total nitrogen, phosphorus and potassium. Detailed soil analysis data are not available for the soils in the Division.

One site in Chipa Village was selected for a potential biochar trial and the location of the site is indicated in map in A-Figure 50. Other details are as follows:

Site 1: Farmer: U Nge, Village: Chipa; Shwe Bo Township, District: Shwe Bo, Sagaing Region
Farm size: 2 ha; Family members: 3; Animals: none.
Farming system: All 2 ha used for paddy-green gram production.

Only rice husk is available for biochar production. There may be about 1,600 kg of rice husk available for biochar production on an annual basis. Currently there is no equipment or knowledge about biochar technology in the area. It is possible to use a simple drum system similar to those in us in Lao PDR for making biochar, and from the available biomass approximately 800 kg biochar can be produced by the farmer on an annual basis. The rice husk biochar can potentially supply 4.8 kg nitrogen, 2.4 kg phosphorus and 6.8 kg potassium. The liming effect of biochar in acid soil is expected to increase the availability of nutrients from its soil application. Based on an estimated 25% increase in rice (and pulse) yield from biochar application, the farmer can earn additional income of about $600 per annum; there may be additional saving of about $25 per annum from reduced fertiliser application.

General view of the field site in village Chipa of Shwe Bo Township and District in Sagaing Region.

Team members interviewing the farmer in village Chipa of Shwe Bo Township and District in Sagaing Region

6.6 YUNNAN PROVINCE AND GUANGXI ZHUANG AUTONOMOUS REGION (PRC)

6.6.1 G1 – Yongning District (Nanning Prefecture)

- Approximately 80% of the district area has high biochar application suitability.
- It is close to the ADB Northern and Eastern Economic Corridors.
- It is close to Kunming city and therefore a potential for other biomass wastes for feedstock.

6.6.2 G2 – Gangbei District (Guigang Prefecture)

- Approximately 70% of the district area has high biochar application suitability.
- It is close to the ADB Eastern Economic Corridor.

6.6.3 G3 – Xingbin District (Laibin Prefecture)

- Approximately 35% of the district area has high biochar application suitability.
- It is close to the ADB Eastern Economic Corridor.
- It is close to Wuxuan city and therefore a potential for other biomass wastes for feedstock.

6.6.4 Y1 – Luliang County (Qujing District)

- Approximately 20% of the district area has high biochar application suitability.
- It is close to the ADB Northern Economic Corridor.
- It is close to Luliang city and therefore a potential for other biomass wastes for feedstock.
- It is near the Thanlwin River delta and therefore a large potential source of agricultural waste for feedstock.

7 CRITICAL POINTS

7.1 SOIL AND BIOCHAR

Leptosols cover approximately 17.6% of the total area in the GMS. Due to the shallowness and the presence of stones and rock outcrops in these soils, they are generally not suitable for cropping. Ferralsols also cover approximately 11.1% of the total land area in the GMS. These have acidic soil pH and low natural fertility, particularly the availability of phosphorus is a major problem in these soils. The soils of the Plinthic sub unit of Ferralsols may have physical limitations to plant growth in the rooting zone due the presence of hard layer.

Cambisols, Lixisols, Luvisols and Nitosols together occupy approximately 15% of the total land area and these soils have low to moderate natural fertility, and are considered to have moderate to high agricultural potential with suitable management practices. Fluvisols, Gleysols and Vertisols, make approximately 13% of the total area, and these are the main paddy-growing soils of the region.

About 1.1% of the area is covered by Arenosols in the five GMS countries. Most of these soils very low inherent capacity to supply and retain nutrients and water due to their sandy texture and they are not considered suitable for sustained cultivation.

There is a large proportion of the land area in the GMS that is occupied by acidic and sandy soils (Acrisols, Ferralsols and Leptosols) that could potentially benefit from the liming effect of biochar. Additionally, about 3.3 million ha land area is covered by acid sulfate soils that have severe actual or potential limitations to sustained cultivation due to their extreme soil acidity. Biochar application to acid sulfate soils will produce increased soil pH and improved growing conditions for crops. However, to maximize agronomic benefits of biochar to agricultural soils, it is important to match the soil and biochar properties. In this report land suitability for biochar application has been determined based on the soil types, slope and land use that will allow targeted application of biochar to pmaximise its benefits in the whole GMS.

7.2 BIOMASS AND BIOCHAR

Biochar system analyses in the literature show strong environmental and economic preference for waste biomass (including agricultural waste) as the biochar feedstock rather than wood or other virgin biomass (Roberts et al., 2010; Shackley et al., 2011). In the preceding section, it has been demonstrated that large quantities of crop residues from rice and other crops (about 105 million tonne per annum) and animal wastes (about 294 million tonne per annum) can be potentially available for biochar production in the GMS countries. However, most of the biomass is scattered across the agricultural areas of the GMS and there are logistic issues in the use of these wastes for biochar production, which must be considered carefully.

The main factors that require consideration in the use of agricultural and animal biomass for biochar production include: collection and storage of the wastes, moisture content of the crop residues and animal wastes, seasonality or timing for the waste availability, transportation distance, technology available for biochar production, resources and energy costs, competing users for the biomass and social issues, such as perception and attitudes of farmers in adopting the biochar technology.

Biochar is produced by heating biomass in oxygen deficient environment at high temperatures (350-700° C). Equipment for producing biochar varies from simple primitive campfire methods to specilaised modern bio-refinery. Smaller units, e.g. TLUD - Top Lit Up Draft systems or closed retort drum systems, may be suitable where biomass availability is limited and transportation of the biomass is not possible or expensive. Trailer mounted mobile biochar production units are better suited for a group of farmers; however, these units are more expensive than TLUD or drum systems. These units are also suitable for biochar production from feedstocks that are scattered. The ability of a pyrolysis system to be moved from one location to another could be an important criterion in the selection of biochar production unit.

In modern fixed or stationary methods of biochar production, volatile gasses, hydrocarbons and most of the oxygen and hydrogen in the biomass are burned or driven off and captured, including GHG's. These captured emissions are known as syngas (synthetic gas) and can be used like natural gas. Liquids, called bio-oils, are also captured creating another source of energy, leaving carbon enriched biochar. The heat generated during the pyrolysis process can generate electricity too. The basic process is called pyrolysis. Pyrolysis systems use kilns and retorts and other specialized equipment to contain the baking biomass while excluding oxygen. The reaction vessel is vented, to allow pyrolysis gases to escape. Pyrolysis gases are often called "syngas". The process becomes self-sustaining as the syngas produced is combusted, and heat is released.

In regional or rural areas where suitable farm equipment is available for the collection and transport of agricultural wastes, a fixed biochar production system should be considered because of their energy efficiency, possibility of using syngas in the biochar production and the large capacity for biochar production. Similarly, if large quantities of animal waste are available in concentrated hotspots, fixed units for biochar production should be preferred.

7.3 BIOCHARS AND NUTRIENT SUPPLY

Most soils of the GMS require the application of fertilisers for crop production. The inherent low fertility and continuous removal of nutrients by crops, particularly paddy, have contributed to the low fertility of the soils. Large amounts of nitrogen, phosphorus and potassium fertilisers are applied in the GMS countries (Table 10) to maintain a sustainable level of production of rice and other crops. Biochar production from on-farm wastes for land application offers potential to reduce the dependence on inorganic fertlisers whilst maintaining sustainable agricultural production.

Biochars produced from the most commonly available agricultural residues, such as rice straw and rice husk, may have limited capacity to supply nutrient elements. Jindo et al (2014) reported nitrogen content between 0.37 and 1.22% for rice husk and rice straw biochars produced at 400-600 °C. Similarly, Peng et al. (2011) found very low phosphorus content (0.21-0.28%) in rice straw-derived biochars produced at 400-450°C. Contrary to the rice husk/straw biochars, animal waste biochars are enriched with most nutrient elements (Chan et al., 2008; Singh et al., 2010). It is recommended that to increase the nutrient supply capacity of biochars, it is better to mix animal wastes with rice straw/husk and other agricultural residues for producing biochar with better agronomic value.

In addition to supplying essential plant nutrients, biochars have liming potential which is a useful attribute particularly when applied to acid soils. The amelioration effects of biochar application to acid soils and other indirect agronomic benefits have been demonstrated in many research studies (Slavich et al., 2013; Smider and Singh, 2014).

Table 10: Fertilisers consumption (tonnes) in Greater Mekong Subregion countries, 2012 (Source: FAOSTAT).

Crop	Cambodia	Lao PDR	Myanmar	Thailand	Viet Nam
Nitrogen (N total)	43,905	-	131,769	1,597,572	917,113
Phosphorus (P_2O_5 total)	20,652	-	21,750	500,295	481,576
Potassium (K_2O total)	3,489	-	16,547	439,055	502,435

Based on the energy required for biochar production, it can be argued that animal wastes can be directly applied to agricultural land. However, the conversion of organic waste into biochar has significant long- and short-term beneficial effects, such as change in soil pH (liming effect), stabilising effect on native soil carbon, increase efficiency of fertilizers and decrease losses of nitrogen. During the biochar production, organic carbon and organic nitrogen are stabilised in slow cycling forms (Cross and Sohi, 2011; Singh et al., 2012; Wang et al., 2012a), additionally biochars stabilise native and added soil C (Keith et al., 2011; Slavich et al., 2013) and reduce greenhouse gas emissions from soil (Singh et al., 2010; Van Zwieten et al., 2010). Van Zwieten et al., (2013) showed that poultry litter biochar have less than 50% of the N_2O emissions than raw poultry litter when these were applied to a Ferralsol. The poultry litter biochar also resulted in lower mineralisation of carbon in the soil compared to raw poultry litter, and led to significant increases in plant available phosphorus and soil pH. It should be pointed out that some nitrogen may be lost from animal and other wastes during biochar production; the loss of nitrogen however can be minimised by optimising the temperature used for biochar production.

Approximately 1.8 million tonnes of rice husk per annum is potentially available for biochar production in the identified hotspots areas of the GMS. Based on 50 percent biochar yield, 900, 000 tonnes of biochar can be produced per annum. From the average N, P and K contents in the rice husk biochars (Prakongkep et al., 2013), the rice husk biochar in the hotspot areas of the GMS has the potential to supply approximately 6,390 tonnes of N, 1,800 tonnes of P (4,125 tonnes of P_2O_5) and 8,730 tonnes of K (10,517 tonnes of K_2O) per annum. From the fertilizer consumption data in Table 10, it can be seen that rice husk biochar has potential to reduce the consumption of P and K fertilizers by 20 and 100 percent, respectively. The potential to reduce the N fertlizers is only 4 percent; however, this can be significantly increased if biochar is produced by mixing animal manures with rice husk. In addition to these direct benefits from biochar addition to soil, additional benefits are expected to result from increased availability of nutrients and reduced losses of N after biochar application to soil.

7.4 ASSESSMENT OF AGRICULTURAL WASTE FOR BIOCHAR PRODUCTION AND OTHER COMPETING USES

Rice is the major crop in the GMS and it generates a substantial quantity of straw in the field. Although there is a lack of reliable data for the whole GMS region, limited data suggest 50 percent or more of the residues are burnt in the open field. According to Gadde et al (2009) about 48 percent of rice straw residue is subjected to open-field burning in Thailand. Based on a questionnaire survey, Tipayarom and Oanh (2007) reported that over 90 percent of the rice paddies during the high harvesting season (November-December) are burned in open fields in Thailand. Research in People's Republic of China and Taiwan suggests that between 30 and 40 percent of the straw waste is burned in open fields in these countries (Wu et al., 2001; Lin and Song, 2002; Yu, 2003; Yao et al., 2001;

Chang et al., 2009). There are serious consequences of open-field burning of straw for the local and regional air quality as high levels of particulate, hydrocarbons and toxic compounds are emitted in the atmosphere (Duan et al., 2004; Yan et al., 2006). Also, the burning of rice straw contributes significant amount of greenhouse gas emissions, for examples Gadde et al. (2009) estimated that the burning of rice straw contributed 0.18 percent of the total amount of greenhouse gas emissions in Thailand. There is a serious case to find alternate ways to utilise rice straw and other agricultural residues instead of open-field burning.

In addition to open-field burning, rice straw is being used for various purposes including animal feed, biofuel, organic fertilizer and building material. It is important to evaluate the economic and environmental viability of competiting uses of rice straw (and other crop resideus) in the GMS. There are numerous studies on the carbon abatement potential and life cycle analyses of different biomass materials for ethanol and biochar production in the literature (e.g. Roberts et al., 2010; Sheehan et al, 2003; Spatari et al., 2005; Wu et al., 2006; Kim et al., 2009).

In a recent study, Clare et al. (2014) did a cost-benefit and life-cycle analyses for competiting uses of crop straw in the People's Republic of China including Yunnan Province, which is a part of the GMS. The results from this study will be discussed in relation to the economic viability and carbon abatement potential of straw for biochar production via pyrolysis process ($S_{Biochar}$) with that of bioenergy production by straw briquetting (S_{Briq}) and straw gasification (S_{Gas}). In the absence of any subsidy for bioenergy and biochar production, the net present values (NPV) of $S_{Biochar}$, S_{Briq} and S_{Gas} were negative or unprofitable. Inclusion of local and national subsidies for avoided straw burning and bioelectricity programme had significant effects on the S_{Briq} and S_{Gas} with both these options become profitable. However, the NPV of $S_{Biochar}$ remained negative because relatively lower electricity volume is generated from per unit dry mass of straw via the pyrolysis process.

Clare et al. (2014) identified that NPV of $S_{Biochar}$ is highly dependent on the agronomic value of biochar, which was considered as the most uncertain parameters in the modelling. According to their modelling and if no subsidies are available, the $S_{Biochar}$ will break even when biochar is priced at \$206 Mg^{-1}. In terms of directly-attributable CO_2-equivalent emisions, S_{Briq} was found to be most effective (1.35 Mg CO_2-e per tonne straw (oven dry weight) followed S_{Gas} (1.16 Mg CO_2-e per tonne) and $S_{Biochar}$ (1.06 Mg CO_2-e per tonne). If the long-term (over 100 years) persistence of carbon is considered then $S_{Biochar}$ offers a more permanent reduction in the CO_2 than the other two options. In addition to the direct CO_2-e abatement potential of biochar, indirect contribution to CO_2-e abatement by reduced nitrous oxide (N_2O) emission and improved fertliser efficiency have been considered important from biochar application to soil. When these indirect effects were included in the modelling, the total abatement potential of biochar ($S_{Biochar}$) increased to 1.46 Mg CO_2-e per tonne) which makes $S_{Biochar}$ more effective than S_{Briq} (1.35 Mg CO_2-e per tonne) and S_{Gas} (1.16 Mg CO_2-e per tonne).

Overall, based on the modelling data of Clare et al (2014), it can be concluded that brequetting of straw as local fuel for cooking and heating may be the most efficient use of this resource. Straw briquetting was also given the highest technology readiness level because this technology does not require expensive equipment. The success of the S_{Briq} however, depends on the local sale of briquettes and the continued acceptability of the product for heating because the heat energy of the briquettes is not as fungible as electricity.

Indirect carbon abatement effects of biochar have been considered important. Biochars have significant potential to increased fertilizer use efficiency. Nitrogen and phosphorus from biochar may be slowly available, which could potentially reduce leaching and gaseous losses of nitrogen from soils (Knicker, 2010; Wang et al., 2012a, b). The production of biochar by mixing crop residues with animal waste is an important consideration for making nutrient enriched biochars, which have potential to reduce fertilizer application rates. Also, the application rates for nutrient enriched biochar can be much lower (~1 Mg ha^{-1}) than the amount (10 Mg ha^{-1}) used in various field studies and meta-analysis (Jeffrey et al., 2011). There are reports that biochar-mineral-chemical-composite (mixtures of biochar with clay and fertilisers) are being produced in central China, and application of these mixtures at much lower rates have produced yield increases of up to 40 percent (Joseph et al., 2013). However, the production of such composite mixture is feasible only at large production facilities and requires technical expertise for making such mixtures. Also, comprehensive testing of the agronomic performance of the composite mixtures in comparison to inorganic fertilisers is necessary before making any recommendations.

7.5 RICE HUSK FOR BIOCHAR PRODUCTION

Based on discussions with local government departments and farmers in Cambodia, PDR Lao and Myanmar, rice husk is the most important feedstock for making biochar at the sites identified for pilot studies. Nearly 1.8 million tonnes of rice husk is potentially available for biochar production in the identified hotspots areas of the GMS. Even 50 percent of the rice husk is converted into biochar, there is a potential to reduce over 1 million tonnes of CO_2 in the atmosphere. Obviously, the potential could be much greater if the rice husk available over the whole GMS is considered.

The adoption of biochar technology to begin with will require some financial support from the local and national governments. Incentives for the collection of straw and other agricultural and animal wastes for biochar production should be given. Equipment for small- to medium- scale biochar production facilities should be provided in the hotspots areas identified in the study. Long-term field trials on farmers' fields should be considered by relevant national agencies to monitor and demonstrate agronomic values of biochars produced using different feedstocks.

In addition to feedstock and production strategies, a unified regulatory framework for permitting the use of various waste materials as biochar feedstocks, biochar production methods, and classification of biochars in the GMS should be considered. International Biochar Initiative and European Biochar Foundation have developed documents in this regard which could be adopted or adapted (IBI, 2012; EBC, 2012). Such approaches will build consumer confidence in using biochar for land applications and other uses.

REFERENCES

ADB (Asian Development Bank) (2012) Greater Mekong Subregion Atlas of the Environment. Second edition. Asian Development Bank, Manila, Philippines 2012.

ADB (Asian Development Bank) (2011) Core agriculture support program phase II: 2011-2015. Mandaluyong City, Philippines: Asian Development Bank, 2011.

ADB (Asian Development Bank) (2008). Rural Renewable Energy Initiative in the Greater Mekong Subregion. Manila.

AFES. (1998) 'A Sound Reference Base for Soils' (The «Referentiel pedologique»: text in English). (INRA: Paris, France).

Atkinson, C.J., Fitzgerald, J.D. and Hipps, N.A. (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant and Soil 337, 1-18.

Bell, R.W. and Seng, V. (2004) "Rainfed lowland rice-growing soils of Cambodia, Laos, and North-east Thailand", In: Vang Seng, Eric Craswell, Shu Fukai and Ken Fischer (eds.). Water in Agriculture; Proceedings of a CARDI International Conference on Research on Water in Agricultural Production in Asia for the 21st Century Phnom Penh, Cambodia, 25-28 November 2003. Australian Centre for International Agricultural Research Proceedings No. 116e, pp. 161-173.Canberra (printed version published in 2004).

Bell, R.W., Rerkasem, B., Keerati-Kasikorn, P., Petchawee, S., Hiranburana, N., Ratanarat, S., Pongsakul, P. and Loneragan, J.F. (1990) Mineral nutrition of food legumes in Thailand. Australian Centre for International Agricultural Research Proceedings, Canberra. 52 pp.

Biederman, L.A. and Harpole, W.F. (2012) Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. Global Change Biology-Bioenergy 5, 202-214.

Briones, R. M. and Ahmed, M. (2008). Biofuels and rural renewable energy in the Greater Mekong Subregion: Issues, Challenges, and Opportunities. Journal of Greater Mekong Subregion, 4: 77-96.

CARDI (2009) "CARDI Soil Profile Database (Version 1.0.2)". Database software Pty Ltd, Brian Purdie, Developed by Ted Griffin, Agriculture Western Australia for ACIAR Project LWR/2001/051 Assessing land suitability for crop diversification in Cambodia and Australia. Custodian: CARDI, Phnom Penh, Cambodia.

Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A. and Joseph, S. (2007) Agronomic values of greenwaste biochar as a soil amendment. Australian Journal of Soil Research 45, 629-634.

Chan, Y.K., Van Zwieten, L., Meszaros, I., Downie, A. and Joseph, S. (2008) Using poultry litter biochars as soil amendments. Australian Journal of Soil Research 46, 437-444.

Chang, C.H., Liu, C.C., and Tseng, P. (2009). Emissions Inventory for Rice Straw Open Burning in Taiwan Based on Burned Area Classification and Mapping Using Formosat-2 Satellite Imagery. Aerosol and Air Quality Research, 13: 474–487.

Cheng, C.H. and Lehmann, J. (2009). Ageing of black carbon along a temperature gradient. Chemosphere 75, 1021-1027.

Cheng, C.H., Lehmann, J. and Engelhard, M.H. (2008). Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. Geochimica Et Cosmochimica Acta 72, 1598-1610.

Cheng, C.H., Lehmann, J., Thies, J.E., Burton, S.D. and Engelhard, M.H. (2006). Oxidation of black carbon by biotic and abiotic processes. Organic Geochemistry 37, 1477-1488.

Chiem N.H. (1993) Geo-pedological study of the Mekong delta. Southeast Asian Studies 31, 158-186.

Christou, M., Eleftheriadis, I., Panoutsou, C. and Papamichael, I. (2007). Current Situation and Future Trends in Biomass Fuel Trade in Europe. Country Report of Greece. < http://eubionet2.ohoi.net/GetItem.asp?item=file;4758 > (accessed May 2015).

Clare, A., Barnes, A., McDonagh, J., Shackley, S. (2014a) From rhetoric to reality: farmer perspectives on the economic potential of biochar in China. International Journal of Agricultural Sustainability, 12, 440–458.

Clare, A., Shackley, S., Joseph, S., Hammond, J., Pan, G., Bloom, A. (2014b). Competing uses for China's straw: the economic and carbon abatement potential of biochar. Global Change Biology Bioenergy (2014), doi: 10.1111/gcbb.12220.

Clausen, T.J (2009). Cambodia: preparing the water resources management (sector) project. technical assistance consultant's report. Water Resources Management Sector Development Project ADB TA 4848 CAM.

Clemens, G., Fiedler, S., Cong, N.D., Dung, N.V., Schuler, U. and Stahr, K. (2010) Soil fertility affected by land use history, relief position, and parent material under a tropical climate in NW-Viet Nam. Catena 81, 87-96.

Crane-Droesch, Abiven, S., Jeffery, S. and Torn, M.S. (2013) Heterogeneous global crop yield response to biochar: a meta-regression analysis. Environmental Research Letters 8, 044049. doi:10.1088/1748-9326/8/4/044049

Cross, A. and Sohi, S.P. (2011). The priming potential of biochar products in relation to labile carbon contents and soil organic matter status. Soil Biology and Biochemistry, 43, 2127–2134.

Duan, F., Liu, X., Yu, T., Cachier, H. (2004) Identification and estimate of biomass burning contribution to the urban aerosol organic carbon concentrations in Beijing. Atmospheric Environment, 38, 1275–1282.

Duckworth, J. W., R. E. Salter and Khounboline, K (compilers) (1999) Wildlife in Lao PDR: 1999 Status Report. IUCN -The world conservation union/wildlife conservation society/centre for protected areas and watershed management. Vientiane.

EBC (2012) 'European Biochar Certificate – Guidelines for a Sustainable Production of Biochar.'European Biochar Foundation (EBC), Arbaz, Switzerland. http://www.european-biochar.org/en/download. Version 6 of 1st April 2015, Accessed: 5 June 2015.

EBC (2012) Guidelines for a sustainable production of biochar, European Biochar Certificate. European Biochar Foundation, <www.european-biochar.org> (accessed May 2015 2013).

EMBRAPA (1999) 'Sistema Brasileiro de clasificação de solos'. (Embrapa Produção de Informação: Brasília - Embrapa Solos: Rio de Janeiro).

Ericsson, K. and Nilsson, L.J. (2006). Assessment of the potential biomass supply in Europe using a resource focused approach. Biomass and Bioenergy 30, 1-15.

FAO- UNESCO. (1979) Soil map of the world 1: 5 000 000. Volume IX. Southeast Asia. UNESCO, Paris.

FAO. (1988) FAO/UNESCO Soil map of the World. Revised legend, with corrections and updates. World Soil Resources Report No. 60. FAO, Rome.

FAO. (1997) FAO/UNESCO Soil map of the World. Revised legend, with corrections and updates. World Soil Resources Report No. 60. FAO, Rome. Reprinted with updates as Technical paper 20, ISRIC, Wageningen.

FAO (2015) Drivers Affecting Forest Change in the Greater Mekong Subregion (GMS): An Overview . http://www.fao.org/fileadmin/templates/rap/files/NRE/Forestry_Group/Policy_brief__FPG_-July_2015.pdf

FAO-UNESCO. (1971-1981) Soil map of the world 1:5 000 000. 10 Volumes. UNESCO, Paris.

FAO-UNESCO. (1974) Soil map of the world 1:5 000 000. Volume 1 Legend. UNESCO, Paris.

FAO-UNESCO. (1974) Soil map of the world Volume 1, Legend, FAO Rome Italy, 59 pp.

Funabiki A., Haruyama S., Quy N.V., Hai P.V. and Thai D.H. (2007) Holocene Delta plain development in the Song Hong (Red River) Delta, Viet Nam. Journal of Asian Earth Sciences 30:518-529.

Gadde, B., Menke, C., and Wassmann, R. (2009). Rice straw as a renewable energy source in India, Thailand, and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas mitigation. Biomass and Bioenergy 33, 1532–1546.

Glaser, B., Lehmann, J. and Zech, W. (2002) Ameliorating physical and chemical proper-ties of highly weathered soils in the tropics with charcoal-a review. Biology and Fertility Soils 35, 219-230.

Glassner, D.A., Hettenhaus, J.R. and Schechinger, T.M. (1998). Corn stover collection project. In: US Department of Energy Great Lakes Regional Biomass Energy Program (eds.), Proceedings of BioEnergy'98: Expanding BioEnergy Partnerships. Madison, WI, October 4-8, 1998. Coalition of Great Lakes Governors, Chicago, IL, pp. 1100-1111.

Gong Zitong (eds.) (1994) 'Chinese soil taxonomic classification (First proposal)'. (Institute of Soil Science, Academia Sinica: Nanjing). 93pp.

Graham, R.L., Nelson, R., Sheehan, J., Perlack, R.D. and Wright, L.L. (2007). Current and potential US corn stover supplies. Agronomy Journal 99, 1-11.

Ha, P.Q., Hien, B.H., Hoa, H.T.T., Tu, P.K., Ninh, H.T., Loan, B.T.P., Quynh, V.D. and Dufey, J.E. (2005) "Overview of sandy soils management in Viet Nam", In: Proceedings of "Management of Tropical Sandy Soils for Sustainable Agriculture - A holistic approach for sustainable development of problem soils in the tropics" held on 27th November-2nd December 2005, Khon Kaen, Thailand. pp. 348-352. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand.

Hadden, R.L. (2008) The Geology of Burma (Myanmar): An annotated bibliography of Burma's geology, Geography and Earth Science. Topographic Engineering Center, Engineer Research and Development Center, 7701 Telegraph Road, Alexandria, VA 22315, USA.

Hearn, G., Hunt, T., Aubert J. and Howell, J. (2008) Landslide impacts on the road network of Lao PDR and the feasibility of implementing a slope management programme. A report produced for a study funded by the Department for International development (DFID), UK as part of its South East Asia Community Access Programme (SEACAP), Published in 2008.

He, Z. L., M. K. Zhang, and M. J. Wilson. (2004). Chemical soil constraints to crop production in the red soils area of Southern China. P.103-109 In: The Red Soils of China: Their Nature, Management and Utilization. M J Wilson, Z L He, X E Yang (Eds.), Kluwer Academic Publishers, Dordrecht, Netherlands.

Hoa, N.M., Singh, U. and Samonte, H.P. (1998) Potassium supplying capacity of some lowland rice soils in the Mekong delta. Better Crops International Vol. 12, No. 1, May 1998, pp. 11-15.

Hori H. (2000) The Mekong: Environment and Development United Nations University Press. p. 398.

IBI (2012) IBI Biochar Standards. International Biochar Initiative. Available at: www.biochar-international.org/ (5 June 2015)

IBI (2012) Standardized product definition and product testing guidelines for biochar that is used in soil. International Biochar Initiative. <www.biochar-international.org>, accessed May 2015.

ICEM. (2003) Lao PDR national report on protected areas and development. Review of protected areas and development in the lower Mekong river region, Indooroopilly, Queensland, Australia. 101 pp.

Isbell, R.F. (1996) 'Australian Soil Classification'. (CSIRO Land and Water: Canberra, Australia).

IUSS Working Group WRB. (2014) World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jeffery, S., Verheijen, F.G.A., Bastos, A.C. and Van Der Velde, M, (2013) The way forward in biochars research: targeting trade-offs between the potential wins. GCB Bioenergy doi: 10.1111/gcbb.1207612132.

Jeffery, S., Verheijen, F.G.A., van der Velde, M. and Bastos, A.C. (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis Agriculture, Ecosystems and Environment 144, 175re, E.

Jindo, K, Mizumoto, H., Sawada, Y., Sanchez-Monedero, M. A. and Sonoki, T. (2014). Physical and chemical characterization of biochars derived from different agricultural residues. Biogeosciences, 11, 6613–6621.

Johnson, J.M.F., Allmaras, R.R. and Reicosky, D.C. (2006). Estimating source carbon from crop residues, roots and rhizodeposits using the grain-yield database. Agronomy Journal 98, 622-636.

Jölli, D. and Giljum, S. (2005). Unused biomass extraction in agriculture, forestry and fishery. Number 3, March 2005. Sustainable Europe Research Institute (SERI) Garnisongasse 7/27, 1090 Vienna, Austria.

Joseph S, Graber ER, Chia C, Munroe P, Donne S, Thomas T, Nielsen S, Marjo C, Rutlidge H, Pan GX, Fan X, Taylor P, Rawal A, Hook J (2013). Shifting paradigms on biochar: micro/nanostructures and soluble components are responsible for its plant-growth promoting ability. Carbon Management 4, 323–343. doi:10.4155/cmt.13.23

Kadam, K.L. and McMillan, J.D. (2003). Availability of corn stover as a sustainable feedstock for bioethanol production. Bioresource Technology 88, 17-25.

Katterer, T., Andrén, O. and Persson, J. (2004). The impact of altered management on long-term agricultural soil carbon stocks - a Swedish case study. Nutrient Cycling in Agroecosystems 70, 179-187.

Keith, A., Singh, B., Singh, B.P., (2011). Interactive priming of biochar and labile organic matter mineralization in a smectite-rich soil. Environmental Science and Technology, 45, 9611–9618.

Kim, S., Dale, B., Jenkins, R. (2009). Life cycle assessment of corn grain and corn stover in the United States. *The International Journal of Life Cycle Assessment 14*, 160–174

Kloss, S., Zehetner, F., Dellantonio, A., Hamid, R., Ottner, F., Liedtke, V., Schwanninger, M., Gerzabek, M.H. and Soja, G. (2012) Characterization of slow pyrolysis biochars: Effects of feedstocks and pyrolysis temperature on biochar properties. Journal of Environmental Quality 41, 990-1000.

Knicker, H., (2010). ''Black nitrogen'' – an important fraction in determining the recalcitrance of charcoal. Organic Geochemistry 41, 947–950.

Krull, E.S., Macdonald, L., Singh, B., Singh, B.P., Fang, Y., Cowie, A., Cowie, A., van Zwieten, L., Murphy, D.V., Farrell, M., Kookana, R. and Dandie, C. (2012) From source to sink: a national initiative for biochar research. DAFF, Australia.

Landell, M.G.D., Scarpari, M.S., Xavier, M.A., dos Anjos, I.A., Baptista, A.S., de Aguiar, C.L., da Silva, D.N., Bidoia, M.A.P., Brancaliao, S.R., Bressiani, J.A., de Campos, M.F., Miguel, P.E.M., da Silva, T.N., da Silva, V.H.P., Anjos, L.O.S. and Ogata, B.H. (2013) Residual biomass potential of commercial and pre-commercial sugarcane cultivars. Scientia Agricola, 70, 299–304.

Lin RQ, Song DL (2002) Utilizing status and problems of crop straw on Guangdong province (in Chinese). Soil and Environmental Sciences, 11, 110.

Linquist B. and Sengxua, P. (2001) Nutrient management of rainfed lowland rice in the Lao PDR. Los Banos, Philippines, International Rice Research Institute.

Linquist, B., Sengxua, P., Whitbread, A., Schiller, J. and Lathvilayvong, P. (1998) Evaluating nutrient deficiencies and management strategies for lowland rice in Lao PDR. In: Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. (eds.), Rainfed lowland rice: advances in nutrient management research, Proceedings of the International Workshop on Nutrient Management Research in Rainfed Lowlands, 12-15 October 1998, Ubon Ratchatani, Thailand. Los Baños, Philippines, IRRI, 59-73.

Liu, B.Y., Nearing, M. A. and Risse, L. M. (1994). Slope gradient effects on soil loss for steep slopes. Transactions of the ASAE. 37(6), 1835-1840

Moormann, F.R. and Rojanasoonthon, S. (1968) Soils of Thailand. Soil Survey Report no. 72. Soil Survey Division, Department of Land Development, Thailand.

MRC (2010) State of the Basin Report 2010. Mekong River Commission, Vientiane, Lao PDR.

Mui, N. T. (2006) Viet Nam Country Pasture/Forage Resource Profile. Rome: FAO.

Musgrave, G. W. (1947) The quantitative evaluation of factors in water erosion-A first approximation. Journal of Soil and Water Conservation 2(3), 133-138, 170.

Nelson, R.G. (2002). Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States-rainfall and wind induced soil erosion methodology. Biomass and Bioenergy 22, 349-363.

Nesbitt, H.J. (eds.) (1997) Rice production in Cambodia. Manila (Philippines): International Rice Research Institute. 112 p.

Nguyen, V. B., Bui D.D., Ho Q.D., Bui H.H., Dang T.L., Thai P. and Nguyen V.T. (2002) The basic information of main soil units of Viet Nam. National Institute for Soil and Fertilizer-Department of Science Technology and Product Quality. World Publishing House. Hanoi.

Nguyen, T.S. and Thai, P (1999) Upland soils in Viet Nam: Degradation and rehabilitation. Agriculture Publishing House, Hanoi.

Novak, J.M., Lima, I., Xing, B., Gaskin, J.W., Steiner, C., Das, K.C,, Ahmedna, M., Rehrah, D., Watts, D.W., Busscher, W.J. and Schomberg, H. (2009) Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Annals of Environmental Science 3, 195-206.

Oberthür, T., Ros C. and White, P.F. (2000) Soil map of the main rice growing area of Cambodia. Phnom Penh, Cambodia, Cambodia–IRRI–Australia Project.

Panoutsou, C. and Labalette, F. (2006). Cereals straw for bioenergy and competitive uses. In: European Commission (eds.), Proceedings of the Cereals Straw Resources for Bioenergy in the European Union, Pamplona, Pamplona, 18-19 October 2006. Joint Research Centre, Institute for Environment and Sustainability.

Patterson, P.E., Makus, L., Momont, P. and Robertson, L. (1995). The availability, alternative uses and value of straw in Idaho. Final report of the project BDK251, Idaho Wheat Commission, College of Agriculture, University of Idaho.

Peng, X., Ye, L. L., Wang, C. H., Zhou, H., and Sun, B. (2011) Temperature and duration-depend rice straw-derived biochar: characteristics and its effects on soil properties of an Ultisol in southern China, Soil Tillage Research, 112, 159–166.

Powlson, D. (2007). Using straw for energy - implications for soils and agriculture. In: European Commission (eds.), Proceedings of the Workshop Cereals Straw and Agricultural Residues for Bioenergy in New Member States and Candidate Countries CC, 2-3 October 2007, Novi Sad, Serbia. Joint Research Centre, Institute for Energy, Ispra, Italy.

Prakongkep, N., Gilkes, R.J., Wiriyakitnateekul, W., Duangchan, A. and Darunsontaya, T. (2013). The effects of pyrolysis conditions on the chemical and physical properties of rice husk biochar. International Journal of Material Science, 3, 97-103.

Prakongkep, N., Gilkes, R.J., and Wiriyakitnateekul, W. (2015). Forms and solubility of plant nutrient elements in tropical plant waste biochars. Journal of Plant Nutrition and Soil Science 178, 732–740.

Quang, P.V. (2009). Soil formation and soil moisture dynamics in agriculture fields in the Mekong delta, Viet Nam: Conceptual and numerical models. Licentiate Thesis, Department of Land and Water Resources Engineering, Royal Institute of Technology (KTH), SE-100 44 Stockholm, Sweden.

Roberts, K.G., Gloy, B., Joseph, S., Scott, N.R., Lehmann, J. (2010) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environmental Science & Technology, 44, 827–833.

Roder, W., Schürmann, S., Chittanavanh, P., Sipaseuth, K., and Fernandez, M. (2005) Soil fertility implications for organic rice production in the Lao PDR.

Roder, W. (2001) Slash-and-burn rice systems in the hills of Northern Lao PDR: Description, challenges and opportunities. IRRI, Los Banos.

Scarlat, N., Martinov, M. and Dallemand, J.F. (2010). Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. Waste Management 30, 1889-1897.

Schiller, J.M., B. Linquist, B., Douangsila, K., Inthapanya, P., Douang Boupha, B., Inthavong, S. and Sengxua, P. (2001) "Constraints to rice production systems in Laos", In: Shu Fukai and Jaya Basnayake (eds.). Increased lowland rice production in the Mekong region, ACIAR Proceedings No. 101. (printed version published in 2001).pp. 3-19.

Seng, V., Bell, R.W., Schoknecht, N., Sarith, H., Vance, W. and White, P.F. (2007) Ou Reang Ov: A new soil group for the Cambodian agronomic soil classification. Cambodian Journal of Agriculture 8, 5-12.

Seng, V., Bell, R.W., White, P.F., Schoknecht, N., Hin, S. and Vance, W. (2007) Sandy soils of Cambodia. In: Proceedings of "Management of Tropical Sandy Soils for Sustainable Agriculture - A holistic approach for sustainable development of problem soils in the tropics" conference held on 27th November- 2nd December 2005, Khon Kaen, Thailand. pp. 42-48. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand.

Shackley S, Hammond J, Gaunt J, Ibarrola R (2011) The feasibility and costs of biochar deployment in the UK. Carbon Management, 2, 335–356.

Sheehan, J.; Aden, A.; Paustian, K.; Killian, K.; Brenner, J.; Walsh,M.; Nelson, R. (2003). Energy and environmental aspects of using corn stover for fuel ethanol. Journal of Industrial Ecology 7, 117–146.

Shishov, L.L., Tonkonogov, V.D., Lebedeva, I.I. and Gerasimova, M.I. (eds.). 2001. Russian soil classification system. Moscow, V.V. Dokuchaev Soil Science Institute.

Singh, B., Macdonald, L.M., Kookana, R.S., van Zwieten, L., Butler, G., Joseph, S., Weatherley, A., Kaudal, B.B., Regan, A., Cattle, J., Dijkstra, F., Boersma, M., Kimber, S., Keith, S. and Esfandbod, M. (2014). Opportunities and constraints for biochar technology in Australian agriculture: looking beyond carbon sequestration. Soil Research 52, 739-750.

Singh, B., Singh, B.P. and Cowie, A.L. (2010) Characterisation and evaluation of biochars for their application as a soil amendment. Australian Journal of Soil Research 48, 516-525. doi:10.1071/SR10058.

Singh, B.P., Cowie, A.L. & Smernik, R.J. 2012. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. Environmental Science & Technology, 46, 11770–11778.

Singh, B.P., Hatton, B.J., Singh, B., Cowie, A.L., and Kathuria, A. (2010a) Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. Journal of Environmental Quality 39, 1224–1235.

Slavich, P.G., Sinclair, K., Morris, S.H., Kimber, S.W.L., Downie, A. and Van Zwieten, L. (2013) Contrasting effects of manure and green waste biochars on the properties of an acidic ferralsol and productivity of a subtropical pasture. Plant and Soil 366, 213-227.

Smider, B. and Singh, B. (2014) Agronomic performance of a high ash biochar in two contrasting soils. Agriculture, Ecosystems and Environment 191, 99-107.

Soil Survey Staff. (1960) Soil classification. A comprehensive system- 7th approximation. U.S. Dept of Agri. U. S. Govt. Printing Office, Washington.

Soil Survey Staff. (1991) Soil Survey Manual. Soil conservation service, U.S. Department of Agriculture, Lincoln, Nebraska, USA.

Sophanodora, P. (1995) Forage research in Southern Thailand. In: Mullen, B.F. and Shelton, H.M (eds.). Integration of ruminants into plantation systems in Southeast Asia. ACIAR Proceedings No. 64. pp. 104-108.

Sophanodora, P. (1997) Crop-livestock integration in Southern Thailand: prospects and constraints. In: Stür, W.W. (eds.). Feed Resources for Smallholder Livestock Production in Southeast Asia. Proceedings of regional meeting in Vientiane, Lao PDR. CIAT Working Document No. 156. pp. 77-82.

Spatari, S.; Zhang, Y.; MacLean, H. L. (2005). Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. *Environmental Science & Technology 39*, 9750–9758.

STEA (2000) National environmental action plan 2000. Science Technology and Environment Agency, Vientiane.

Summers, M.D., Jenkins, B.M., Hyde, P.R., Williams, J.F., Mutters, R.G., Scardacci, S.C. and Hair, M.W. (2003). Biomass production and allocation in rice with implications for straw harvesting and utilization. Biomass and Bioenergy 24, 163-173.

Tamura, T., Saito, Y., Sieng, S., Ben, B., Kong, M., Choup, S. and Tsukawaki, S. (2007) Depositional facies and radiocarbon ages of a drill core from the Mekong River lowland near Phnom Penh, Cambodia: Evidence for tidal sedimentation at the time of Holocene maximum flooding. Journal of Asian Earth Sciences 29, 585-592.

Tan, H. (2004). Economic balance of crops and fruits production by K, Mg and S fertilizers application in subtropical red acid soil of Guangxi province, China. Tropics 13, 287-291.

Thuy, D.T. (2013) Evaluating the potential of digitial soil mapping to map soil types in Viet Nam. MSc (Physical Land Resources) Dissertation submitted to Ghent University, Belgium.

Tipayarom, D. and Oanh, N.T.K. (2007). Effects from Open Rice Straw Burning Emission on Air Quality in the Bangkok Metropolitan Region. Science Asia 33, 339-345

Topark-Ngarm, A. and Gutteridge, R.C. (1986) Forages in Thailand. In: Blair, G.J., Ivory, D.A. and Evans, T.R. (eds.). Forages in Southeast Asian and Pacific Agriculture. ACIAR Proceedings No. 12. pp. 96-103.

Tun, T. and Than, M. (1996) Myanmar: country report to the FAO international technical conference in plant genetic resources. Yangon, 1995.

United States Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS) (2006). White Paper Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations. <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053255.pdf> (accessed May 2015).

Van der Sluis, E., Shane, R. and Stearns, L. (2007). Local biomass feedstocks availability for fuelling ethanol production. Biofuels, Food and Feed Tradeoffs, Biofuels, Food and Feed Tradeoffs Conference, April 12-13, 2007, St. Louis, Missouri.

Van Zwieten L, Kimber S, Morris S, Downie AE, Berger E, Rust J, et al. (2010) Influence of biochars on flux of N_2O and CO_2 from ferrosol. Australian Journal of Soil Research, 48, 555–568.

L. Van Zwieten, Kimber, S.W.L., Morris, S.G., Singh, B.P., Grace, P.R., Scheer, C., Rust, J., Downie, A.E., Cowie, A.L. (2013). Pyrolysing poultry litter reduces N_2O and CO_2 fluxes. Science of the Total Environment, 465, 279–287.

Vinh, N.C. (2005) Coastal sandy soils and constraints for crops in Binh Thuan province, southern central Viet Nam. In: Proceedings of "Management of tropical sandy soils for sustainable agriculture - A holistic approach for sustainable development of problem soils in the tropics" held on 27th November- 2nd December 2005, Khon Kaen, Thailand. pp. 60-66. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand.

VSSS, Viet Nam Society of Soil Science (2000) Soils of Viet Nam. Agricultural Publishing House, Hanoi.

Walsh, M.E., Perlack, R.L., Turhollow, A., de la Torre Ugarte, D., Becker, D.A., Graham, R.L., Slinsky, S.E. and Ray, D.E. (2000). Biomass feedstock availability in the US: 1999 State Level Analysis. Oak Ridge National Laboratory, Oak Ridge, TN.

Wang, T., Arbestain, M.C., Hedley, M., and Bishop, P. (2012a). Chemical and bioassay characterisation of nitrogen availability in biochar produced from dairy manure and biosolids. Organic Geochemistry, 51, 45–54.

Wang, T., Arbestain, M.C., Hedley, M., and Bishop, P. (2012b). Predicting phosphorus bioavailability from high-ash biochars. Plant and Soil, 357,173–187.

Wezel, A., Luibrand, A. and Thanh, L.Q. (2002) Temporal changes of resource use, soil fertility and economic situation in upland northwest Viet Nam. Land Degradation and Development 13, 33-44.

White, P.F., Oberthür, T. and Pheav, S. (1997) "Soil and Rice", In: Nesbitt, H.J. (eds.). Rice Production in Cambodia (Manila: International Rice Research Institute) pp. 21-29.

Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B. and Linden, D.R. (2004). Crop and soil productivity response to corn residue removal: a literature review. Agronomy Journal 96, 1-17.

Workman, D.R. (1972) Geology of Laos, Cambodia, South Viet Nam and the Eastern part of Thailand. A Review. London, Institute of Geological Sciences.

Workman, D.R. (1977) Geology of Laos, Cambodia, South Viet Nam and the eastern part of Thailand. Overseas Geology and Mineral Resources. Number 50, Institute of Geological Sciences. HMSO. London.

Wu, L., Chen, J., Zhu, X.D., Xu, Y.P., Feng, B., Yang, L. (2001). Straw-burning in rural areas of China: caused and controlling strategy (in Chinese). China Population, Resources and Environment, 11, 110–112.

Wu, M.; Wang, M.; Huo, H. (2006). *Fuel-cycle assessment of selected bioethanol production pathways in the United States*; Center for Transportation Research, Energy Systems Division, Argonne National Laboratory: Chicago, IL.

Xie, J. and Du, C. 1991. "Proceeding of the international symposium on the role of sulphur, magnesium and micronutrients in balanced plant nutrition" Pp. 262-272, In Soil magnesium status and prospects of magnesium requirements in South China.

Yan, X., Ohara, T., Akimoto, H. (2006). Bottom-up estimate of biomass burning in mainland China. Atmospheric Environment, 40, 5262–5273.

Yao, Z., Wang, S.H., Jiang, X.H. (2001). The current situation and approach of return straw to field in suburb of Shanghai (in Chinese). Agro-Environment and Development, 3, 40–41.

Yu, Z, (2003). The developing trend of resources treatment of crop stalk in Fuzhou city (in Chinese). Fujian Environment, 20, 31–32.

Zhang, Z., Tan, H. & Zhou, Q. 1998. "The soil potassium situation and the research of balanced fertilization in Guangxi" China Agriculture Press, China.

APPENDIX 1: NATIONAL LEVEL SOILS CLASSIFICATION DATA FOR THE GMS

In this section spatial distribution of soil types in each of the GMS countries has been reviewed. The soil data for individual GMS countries were then combined to produce a unified soil map of the GMS using the FAO-UNESCO classification system. The distribution of soils (and their properties) forms basis to identify potential agricultural land in the GMS that could benefit from biochar application to soil.

Soil Classification

Soil classification is a way of grouping soils of similar properties that serves as a communication tool amongst researchers and such information is useful for the management of soils. Soil classification and soil maps have been useful tools for soil evaluation, land management, land use planning and agriculture planning and production. Worldwide a number of classification systems have been developed and are in practice, for example, USA (Soil Survey Staff, 1960), People's Republic of China (Gong Zitong 1994), Australia (Isbell 1996), Russia (Shishov et al., 2001), France (AFES, 1998) and Brazil (EMBRAPA 1999). Although diverse approaches have been used in various soil classification systems, most schemes use a hierarchical structure, where individual soils with similar properties are collected in small groups.

With increasing problems of land degradation, disparity of production potentials of land and increasing interdependence of countries for their supplies of food and agricultural products, the international community has recognised the need for harmonised soil information in the early 1980s. In 1998, the International Society of Soil Sciences (ISSS, since 2002 the International Union of Soil Sciences, IUSS) adopted the World Reference Base (WRB) as its officially recommended terminology to name and classify soils. The WRB is based on the legend (FAO-UNESCO, 1974) and the revised legend (FAO, 1988) of the soil map of the world (FAO-UNESCO, 1971-1981). The WRB has gone through changes since its inception and the current (third) version was published in 2014 (IUSS Working Group WRB, 2014). The WRB uses two levels of categorical detail for soil, the First Level has 32 Reference Soil Groups (RSGs) and the Second Level consists of a set of principal and supplementary qualifiers along with the name of the RSG. In this report, we have presented the soil map of the GMS based on the FAO-UNESCO classification system because of the lack of detailed data to convert to the soil information to the WRB classification system.

1. VIET NAM

1.1 General introduction

The Socialist Republic of Viet Nam is located on the eastern part of the Indochinese peninsula. It extends 1,650 km from north to south at longitudes 8° 02' - 23° 23' north; its latitudes cover 102° 08' - 109° 28' east, the narrowest point in the central part of Viet Nam covering a mere 50 km (Nguyen et al., 2002). The total land area of Viet Nam is approximately 331,000 km^2, out of which hills and mountains constitute about 66% of the country. The population of Viet Nam is about 90 million and it is the most populous country in the GMS.

Viet Nam lies in the tropical belt lying between the Equator and the Tropic of Cancer. The climate in the northern part of Viet Nam is tropical monsoonal with four seasons including spring, summer, autumn and winter. The rainy season in the north extends from mid-April to mid-October. The mean annual rainfall in Hanoi city is 1720 mm and in the mountains, annual rainfall exceeds 4000 mm[8]. Average temperatures fluctuate considerably in the Red River delta region, with temperatures in Hanoi as low as 5°C in the dry season and about 30°C during the rainy season. The southern and central regions have a tropical climate with dry and rainy seasons. The rainy season in the south extends from early May to November, with an average annual rainfall of about 2000 mm in lowland regions. The tropical south has tropical temperatures, with Ho Chi Minh City temperatures varying from 18-33°C throughout the year. Temperatures in the Central Highlands are relatively cooler, with the annual average temperature between 17-20°C.

1.2 Physiography

Viet Nam can be divided into four physiographic regions: the Red River delta in the north, the Annamese Cordillera, a mountain system extending from north to south through west-central covering nearly the entire length of the country, the Mekong River Delta in the south, and relatively narrow coastal plain in the east that lies between the two deltas. The geology of the mountain region is complex consists predominantly of limestones, sandstones, granites, and gneisses in the north and in the south an exposed, folded crystalline basement overlain in several places by basaltic lava flows[9]. The extremely rugged mountains and tropical forest cover about two-thirds of Viet Nam (A-Figure 1). The Red River delta in the north and the Mekong River delta in the south are considered the two "rice bowls" of the country and make up the most heavily populated portion of the country.

There are four distinctive mountain zones in Viet Nam – (i) Northeastern, (ii) Northwestern, (iii) North Truong Son and (iv) South Truong Son. Each of these zones has its own unique features.[10] (A-Figures 1 and 2).

The Northeastern zone (Viet Bac) extends from the Red River valley to the Gulf of Tokin and has tropical forest characteristics. The highest mountain peak in the zone reaches 2,341 m above sea level. The Northwestern mountain range extends from the Sino-Vietnamese border in the north to the western region in Thanh Hoa, Nghe An and Ha Tinh provinces on the central coast. This magnificent mountain region has a temperate climate throughout the year and is nationally known for its resort town of Sapa in Lao Cai Province, which is perched 1500 m above sea level. This zone is also famous for the historical site of Dien Bien Phu and the Fansipan Mountain that is situated 3,143 m above sea level. The North Truong Son Range is the third mountain zone, it a long low mountain range extending from the western part of Thanh Hoa province to the Quang Nam-Da Nang Mountains. The South Truong Son mountain range runs from north to south of the country and is situated in the western side of Viet Nam. Behind these huge mountains a vast expanse of red soil, known locally as Tay Nguyen (the Central Highlands), exists. The central highlands are home to many unique plants and animals not found elsewhere in south-east Asia or in many other parts of the world.

The Red River delta (also known as the northern delta) is formed by alluvium deposits of Red River and the Thai Binh River. The entire region of the Red River delta is no more than 3 m above sea level

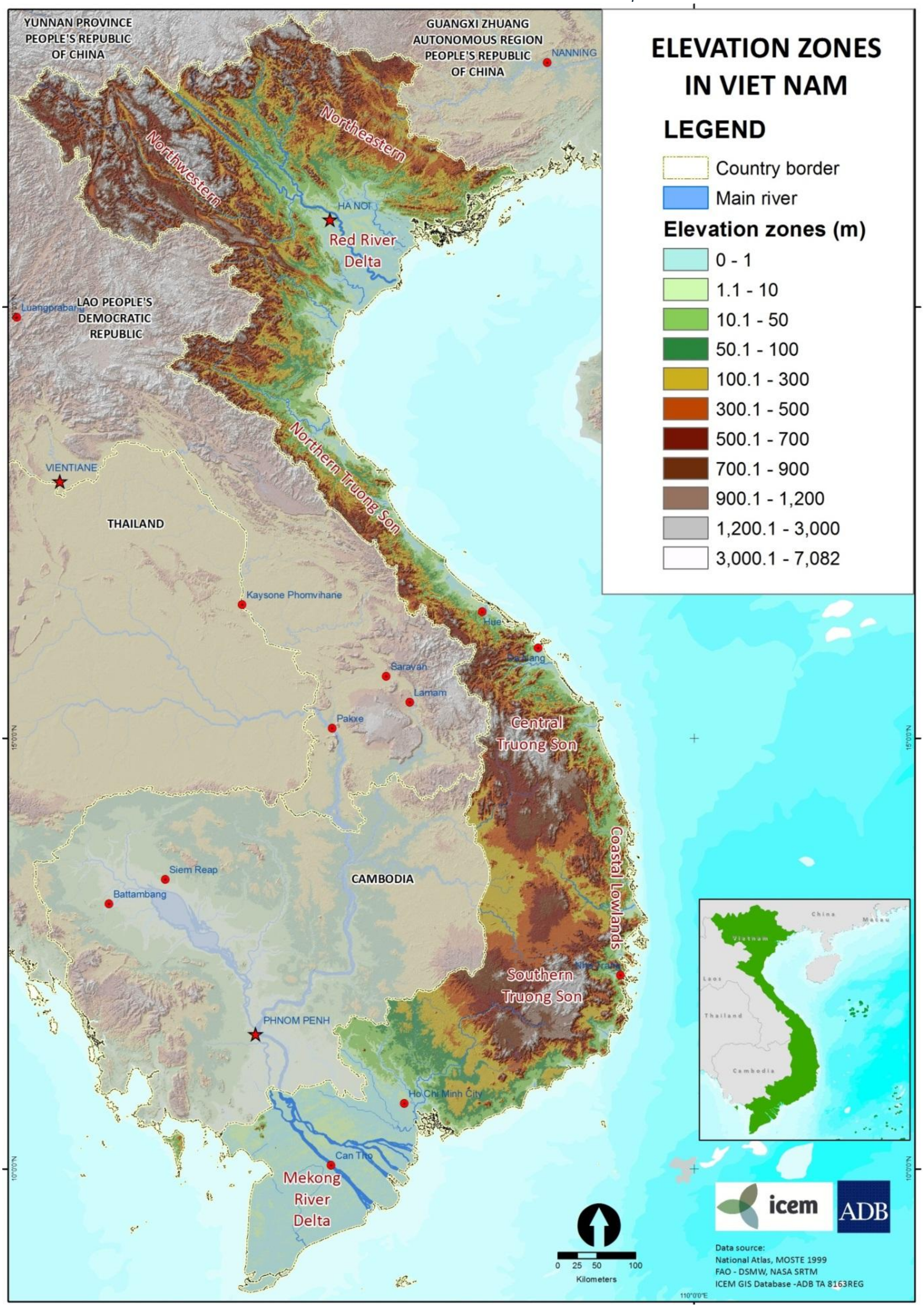
[8] http://www.encyclopedia.com/topic/Vietnam.aspx
[9] http://www.britannica.com/EBchecked/topic/26171/Annamese-Cordillera
[10] http://www.vietnamemb.se/en/index.php?option=com_content&view=article&id=68&Itemid=62

(mostly ≤ 1 m)[11] and covers an area[12] of 15,000 km^2. This region was once an inlet of the Gulf of Tonkin, it has been filled in by the enormous alluvial deposits of the rivers over a period of millennia, and it advances one hundred meters into the gulf annually. An extensive system of dikes and canals has been built in this region for irrigating rice and to contain the Red River. The soils of the Red River delta are variable between fertile to soils lacking in soluble bases.

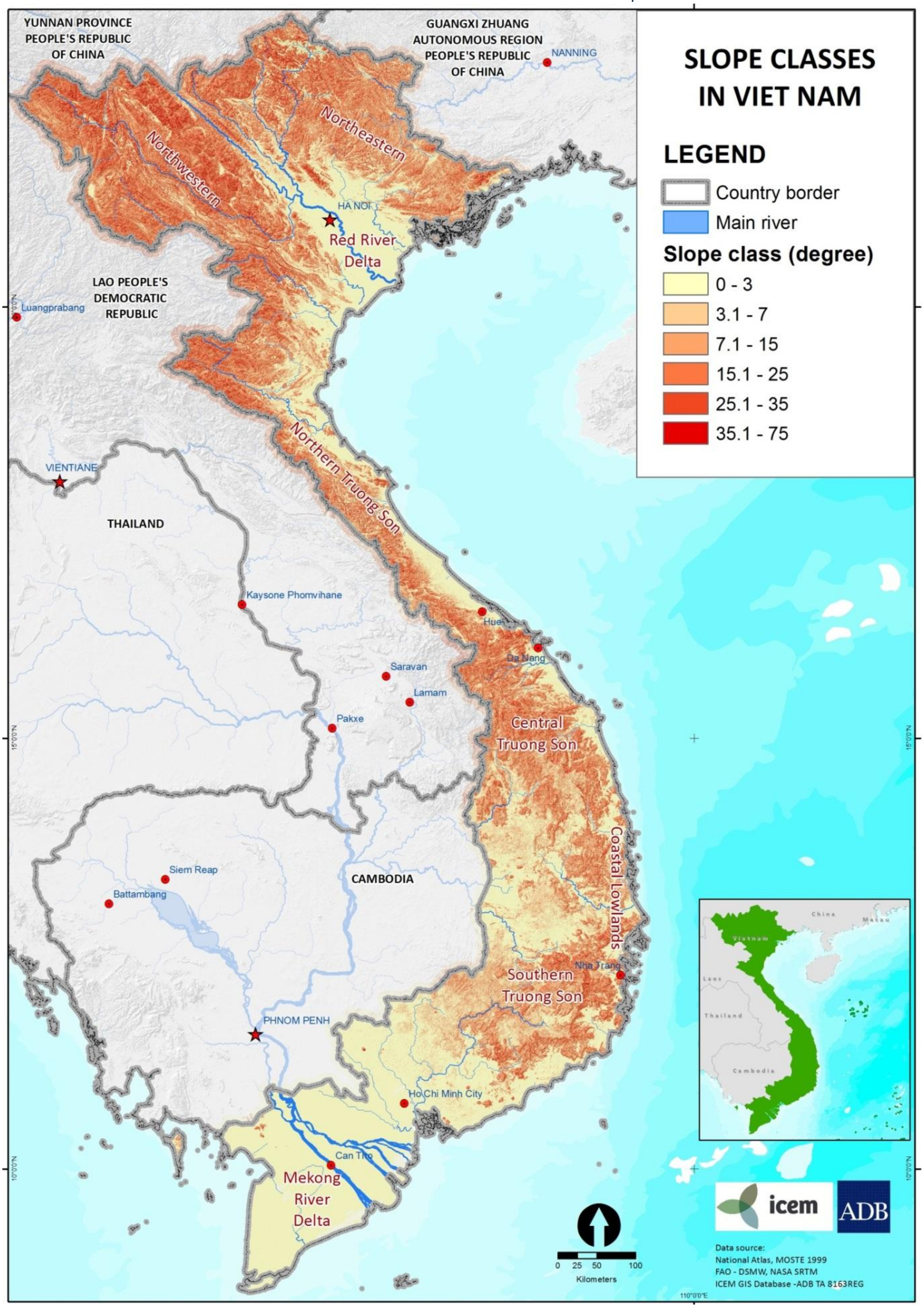
The Mekong River delta lies in the southwestern part of Viet Nam, where the Mekong River empties into the South China Sea. This region is predominantly flat flood plains not more than 3 m above sea level at any point, with an area of approximately 36,000 km^2. The enormous amount of sediment carried by the Mekong River's branches and tributaries extends the delta 60 to 80 m into the sea every year. About 10,000 km^2 of the Mekong delta are under rice cultivation, making this one of the largest rice-growing regions of the world. The southern tip, known as the Ca Mau Peninsula (Mui Bai Bung), is covered by dense jungle and mangrove swamps.

The coastal lowlands is a narrow and flat area that extend from south of the Red River delta to the Mekong River basin. The coastal lowlands are generally fertile and used for rice cultivation.

[11] http://en.wikipedia.org/wiki/Geography_of_Vietnam
[12] http://www.vietnamemb.se/en/index.php?option=com_content&view=article&id=68&Itemid=62



A-Figure 1: Topographic map of Viet Nam showing extensive area of mountains and the two deltas, the Red River delta in the north and the Mekong delta in the south.



A-Figure 2: The map of Viet Nam showing regions of varying slopes in the country.

1.3 Soils and their major properties

According to the WRB system, Viet Nam has twenty one soil groups with 61 soil units (VSSS, 2000; Thuy, 2013). Broadly Vietnamese soils can be classified into two large groups: - mountainous and hilly soils (mostly Acrisols, Ferralsols or Alisols) and delta soils (Fluvisols and Arenosols). The mountainous soils are used for annual cropping without many amendments, these soils are rapidly degrading. Delta soils are the most productive soils, with high levels of intensive cultivation and crop intensity in these soils (Mui, 2006). The rate of soil degradation in the Delta soils is low and soil fertility is supplemented annually by alluvial deposits. The application of organic manures and inorganic fertilisers is common in these soils and mineral fertilisers.

Most soils of the Red River delta are alluvial, with varying soil texture due to irregular river tides. Interposed clay, silt or sandy layers are commonly present in these soils. Soils closer to rivers usually have a lighter (sandy) texture and away from rivers have a fine textures or increased amounts of clay and silt in the particle size. In general, the alluvial soils of the Red River delta are of medium texture, bright brown in colour and have a neutral pH.

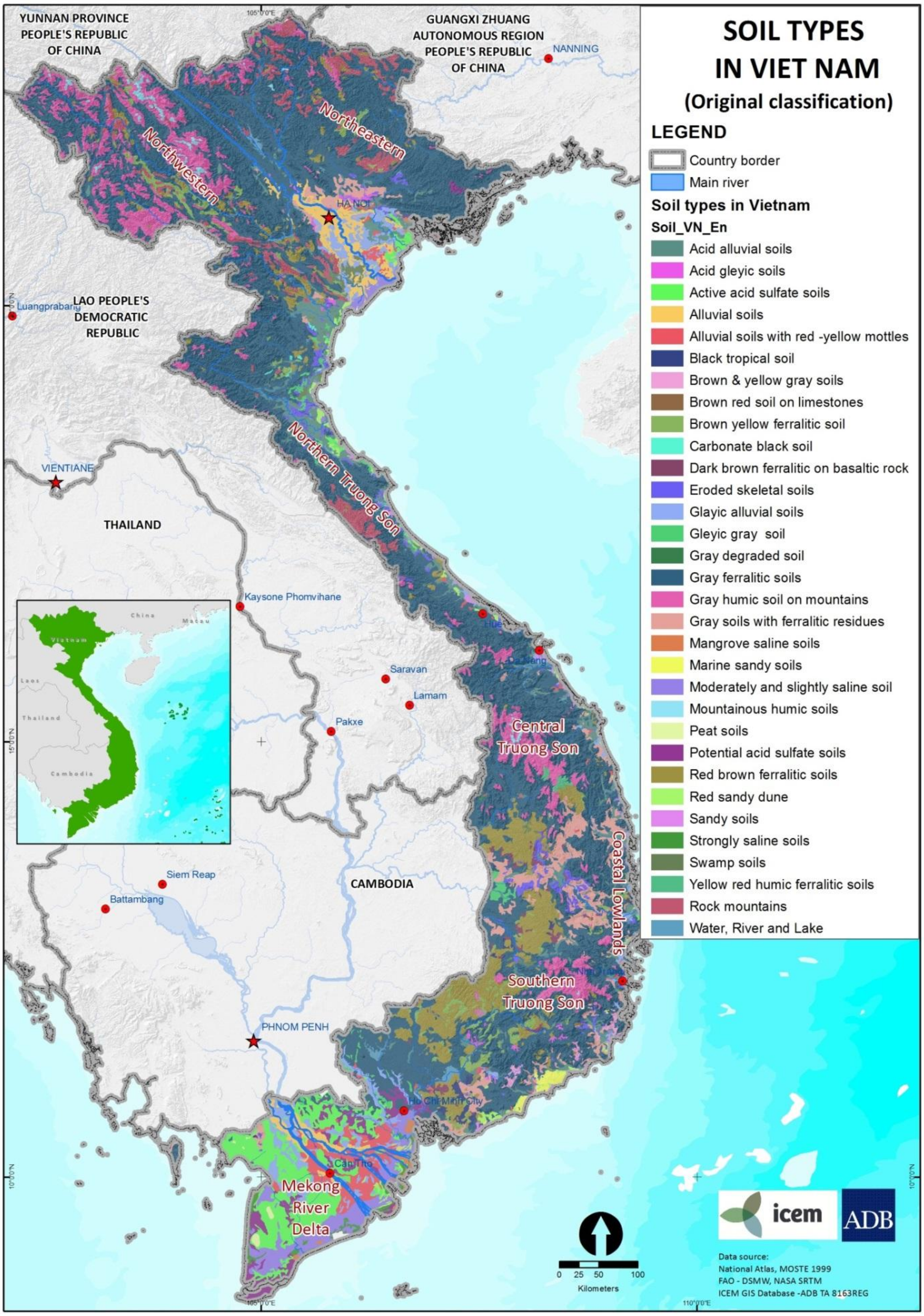
Soils in the Mekong delta are formed on young landmass and developed in the Holocene era by transgression and regression of the sea (Chiem, 1993). The soils are mainly derived from alluvial deposits of the Mekong and Bassac rivers (rivers) and the sea. The river deposits tend to form ridge-shaped natural levees with relatively coarse particles of sediment parallel to the riverbanks (Hori, 2000; Funabiki et al., 2007; Tamura et al., 2007). This effect has led to soils of different particle distributions or soil texture over different areas, generally the particle size becomes finer in areas further from the riverbanks. The Mekong delta covers an area of approximately 12% of Viet Nam's land area (~ 39.7 million ha) and about 30% of the agricultural area of Viet Nam (Quang, 2009). This delta is spread over 13 provinces of Viet Nam.

Soil map of Viet Nam was obtained from the National Atlas of Viet Nam (1999) and the local soil types were converted into FAO-UNESCO soil groups (FAO, 1997). The distribution of different soil types in Viet Nam is given in A-Figures 3 and 4, and A-Table 1. According to the FAO-UNESCO classification system, Acrisols are the most dominant soils in the country, covering nearly 60% of the land area. These soils are spread all over the country except for the southern most part of the Mekong delta region. The soils of this soil group are strongly weathered with low base saturation (< 50%) at some depth; and the clay content is usually higher at depth (≤ 100 cm). In Viet Nam, four sub-units have identified for the Acrisols Group: Haplic Acrisols, Gleyic Acrisols, Ferralic Acrisols and Humic Acrisols (VSSS, 2000).

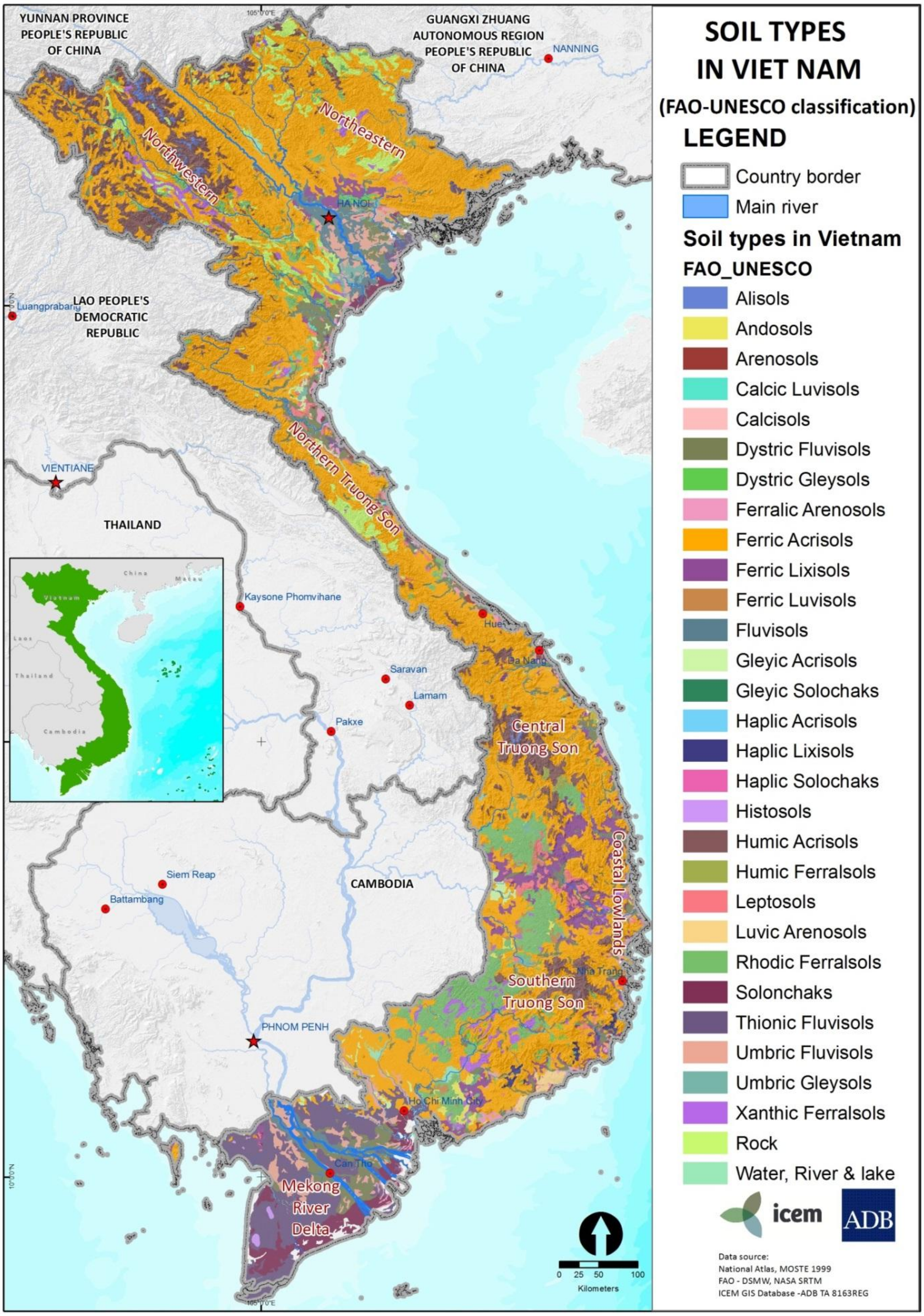
Fluvisols (including Thionic Fluvisols) are the second most dominant soil type in Viet Nam and it occupies nearly 16% of the area; these soils are young soils formed in fluvial, lacustrine or marine deposits. Fluvisols predominantly exist in the Mekong and Red River deltas. Thionic Fluvisols are soils that have the thionic horizon, an extremely acid subsurface horizon in which sulfuric acid is formed through the oxidation of sulfides. Thionic Fluvisols include both active and potential acid sulfate soils. Quang (2009) estimated that there is over 10,543 km^2 of acid sulfate soils in the Mekong delta.

A-Table 1: The extent of distribution of different soil types according to the local and the FAO-UNESCO classification (FAO, 1997) in Viet Nam.

Local soil groups	FAO Units & Sub-units	Symbol	Area (ha)	Area (%)
Gray soils	**Acrisols**	**AC**	**19,461,317**	59.22
Gray ferralitic soils	Ferralic Acrisols	ACf	16,503,437	50.22
Gleyic degraded soil	Gleyic Acrisols	ACg	189,590	0.58
Gray degraded soil	Haplic Acrisols	ACh	3,724	0.01
Gray humic soil on mountains	Humic Acrisols	ACu	2,764,566	8.41
Mountainous humic soils	**Alisols**	**AL**	**150,603**	0.46
Black tropical soil	**Andosols**	**AN**	**110,220**	0.34
Sandy soils	**Arenosols**	**AR**	**603,349**	1.84
Red sandy dune	Ferralic Arenosols	ARo	260,218	0.79
Marine sandy soil	Haplic Arenosols	ARh	240,568	0.73
White sandy soils	Luvic Arenosols	ARl	102,562	0.31
Brown red soil on limestones	**Calcisols**	**CL**	**2,536**	0.01
Alluvial soils	**Fluvisols**	**FL**	**5,186,007**	15.78
Neutral and lightly acid alluvial soils	Eutric Fluvisols	FLe	641,906	1.95
Alluvial soils with red-yellow mottles	Dystric Fluvisols	FLd	594,044	1.81
Acid alluvial soils	Dystric Fluvisols	FLd	1,171,593	3.56
Gleyic alluvial soils	Umbric Fluvisols	FLu	816,792	2.49
Active acid sulfate soils	Thionic Fluvisols	FLt	1,361,402	4.14
Potential acid sulfate soils	Thionic Fluvisols	FLt	600,270	1.82
Ferralitic soils	**Ferralsols**	**FR**	**2,687,854**	8.18
Red ferralitic soils	Rhodic Ferralsols	FRr	2,094,979	6.37
Yellow red humic ferralitic soils	Humic Ferralsols	FRu	37,064	0.11
Brown yellow ferralitic soil	Xanthic Ferralsols	FRx	555,811	1.7
Gleyic soils	**Gleysols**	**GL**	**221,639**	0.67
Acid gleyic soils	Dystric Gleysols	GLd	86,022	0.26
Smamp soils	Umbric Gleysols	GLu	135,617	0.41
Peat soils	**Histosols**	**HS**	**24,775**	0.08
Eroded skeletal soils	**Leptosols**	**LP**	**429,945**	1.31
Black soils	**Luvisols**	**LV**	**139,470**	0.42
Carbonate black soil	Calcic Luvisols	LVk	12,473	0.04
Dark brown ferralitic soils on basaltic rock	Ferric Luvisols	LVf	126,996	0.39
Brown soils	**Lixisols**	**LX**	**1,203,719**	3.66
Brown & yellow gray soils	Haplic Lixisols	LXh	67,124	0.20
Red soils in arid dry zone	Ferric Lixisols	LXf	1,136,594	3.46
Saline soils	**Solonchaks**	**SC**	**1,098,311**	3.34
Mangrove saline soils	Gleyic Solonchaks	SCg	137,299	0.42
Strong saline soils	Haplic Solonchaks	SCh	160,944	0.49
Moderately & slightly saline soils	Solonchaks	SCm	800,068	2.43
Rock mountains	Rock	Rock	1,032,403	3.14
Water, river and lake	Water & River	WB	510,981	1.55
Grand total			32,863,129	100.0



A-Figure 3: Soil map of Viet Nam according to the local soil classification system.



A-Figure 4: Soil map of Viet Nam according to the FAO-UNESCO classification system (FAO, 1997).

Ferralsols (deeply weathered red or yellow soils with diffuse horizon boundaries and low activity clays) occupy over 8% of the land area. These soils are mostly distributed in the mountainous hilly area and more concentrated in western central highland and southeastern regions in Nghe An, Thanh Hoa, Cao bang, Lang Son provinces. Ferralsols in Viet Nam include Rhodic Ferralsols, Xanthic Ferralsols, and Humic Ferralsols (VSSS, 2000).

Solonchaks are soils with a high salt content. These soils exist in the coastal area of Viet Nam covering an area of 3.3%. Gleyic, Haplic and Mollic sub-units of Solonchaks have been identified in Viet Nam.

Arenosols are deep sandy soils. These soils cover an area of over 603,000 ha (1.8% of the area) and occur along the coast extending from Thanh Hoa in the north to Ninh Thuan in the south.

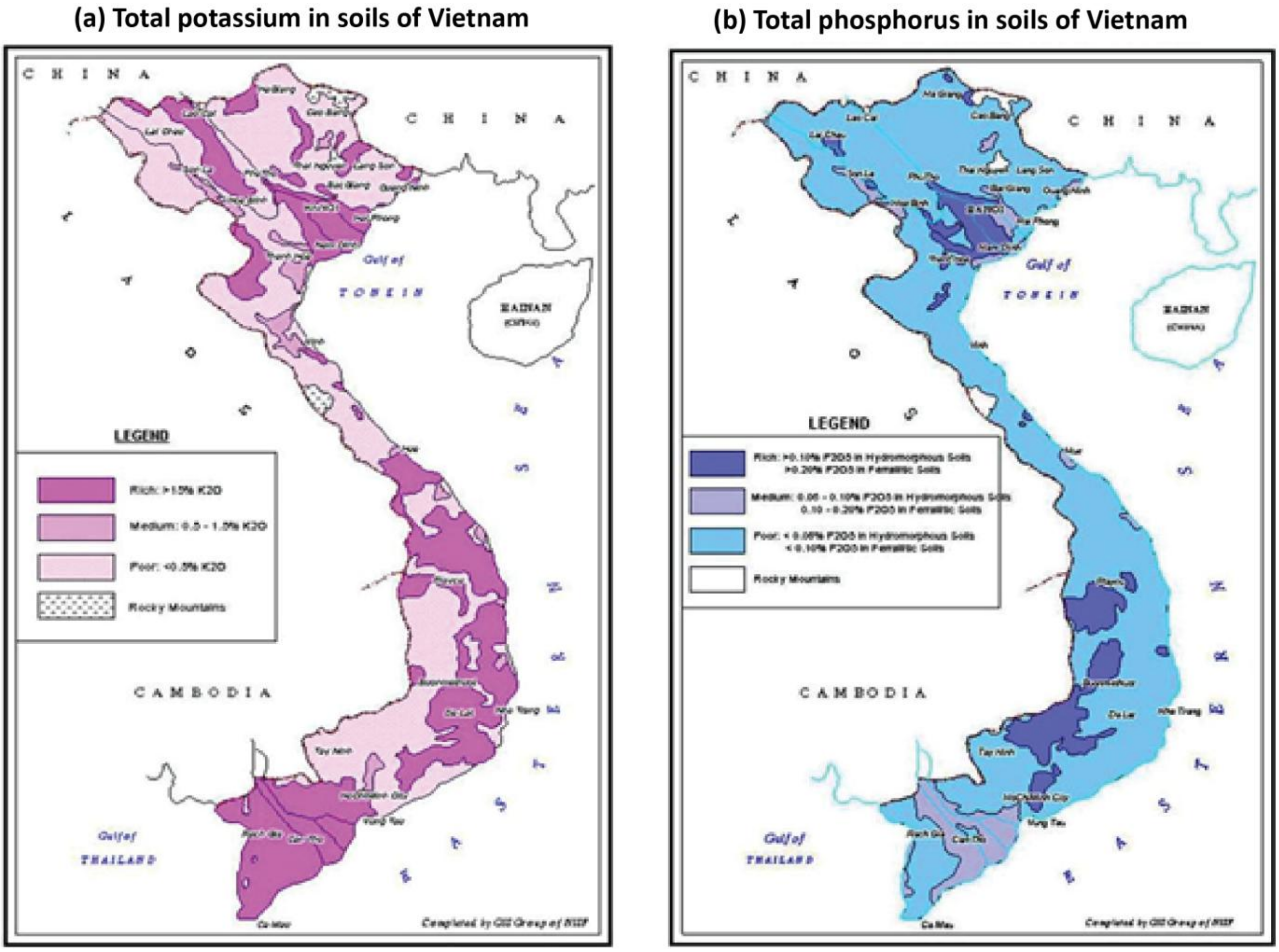
Gleysols are saturated with groundwater for long enough periods to develop reducing conditions; such soils occupy about 0.7% of the land area in Viet Nam. These soils exist mainly in the delta regions and some of these have sulfidic horizons.

Alisols have been found to cover 0.5% of the area. These soils have properties similar to Acrisols in having a clayey subsoil horizon and low base saturation percentage; however, unlike Acrisols, Alisols have high-activity clays.

1.4 Soil fertility status

Analysis of soil samples representing 26.6 Mha of potentially cultivable areas in Viet Nam revealed that the majority of soils are deficient in phosphorus (P) and potassium (K). Detailed analysis of the data reveals that 66% of the soils have very low plant-available P and 75% of the soils are low in plant-available K contents[13]. In general, soils of the Mekong and Red River deltas have adequate levels of P and K (A-Figures 5 a,b). However, even in these soils with continuous and multiple cropping of rice and other crops decreased levels of P and K are found. For example, Hoa et al. (1998) demonstrated that two to three rice crops per year removed large amounts of soil K, causing a reduction in non-exchangeable K and decomposition of K-bearing clay minerals in some of the Mekong delta region soils. Potassium fixation may become a major problem in such soils which can only be overcome by very large K applications to soil. The authors pointed out that the application of K is required in acid sulfate soils and grey (degraded) soils of the Mekong delta where K supplying power was found to be insufficient. The widespread P and K deficiency in Vietnamese soils and the negative balance found for these nutrients at the national level (A-Figures 5 a,b) indicate that fertiliser P and K nutrient response may commonly be expected on-farm.

[13] http://www.ipni.net/



A-Figure 5: The distribution of total potassium (a) and phosphorus (b) in Vietnamese soils.

Tuyen (2013) analysed data from a long-term experiment that commenced in 1986 to examine the effect of nitrogen (N), P and K applications after 34 consecutive crops in intensive rice monoculture at CLRRI, Thoi Lai, Can Tho City, Viet Nam. The results from this study showed that removing all of the rice straw from the field has led to decline in soil organic C. Overall, there was a minimal decline in total N, a 25% decline in total P and no change in total K for plots which had no fertiliser; and the total levels of these elements in the soil remained unchanged with the recommended fertiliser rates of N, P and K. Rice yield declined with time in wet seasons and increased in dry seasons. The author suggested overcoming these problems by applying necessary P and return rice straw to the field.

In the mountainous area, soil fertility is generally poor. For example, in the mountainous area (with elevations of between 300 and over 1000 m) of Son La Province in northwest Viet Nam agricultural land and secondary forest is normally found on the slopes of the valleys (Wezel et al., 2002). Most of the soils belong to the group of red and yellow soils (Ferralsols and Leptosols). Due to decreasing soil fertility in these soils, the land use has changed from upland rice production to cassava and maize. In a more recent study in Son La Province, Clemens et al. (2010) found Alisols and Luvisols as the two predominant soil groups in the study area, these soils are locally named 'red soil' and 'black soil', respectively. High fertility was found on less eroded upper parts of hills and at sites where agricultural use had commenced only recently; due to unsustainable land use, soils on middle and lower slopes are often affected by severe soil erosion, whereas foot slope soils suffer from the accumulation of eroded infertile subsoil material as well as stagnic conditions.

Ha et al. (2005) reported that more than 36% of agricultural soils in Viet Nam, which are classified Arenosols and Acrisols, have a low inherent nutrient supplying capacity, low organic matter content and limited water holding capacity. Vinh (2005) observed that coastal sandy soils in Binh Thuan Province are generally strongly acid, low in organic matter and poor in plant nutrients. Pot omission trials using corn as the indicator crop showed deficiencies of major (N, P and K) and trace (boron [B], molybdenum [Mo] and zinc [Zn]) elements in red and white sandy soils in the province.

Overall, the main characteristic of the majority of soils in Viet Nam is the limited availability of nutrients. Additionally, many soils are affected by severe soil acidity, aluminium toxicity, saline water instruction and a high level of soil alkalinity. Nguyen and Thai (1999) reported that in approximately 23 million ha area sub-soil pH is around 4.5, which indicates severe acidity problem in the Vietnamese soils. The alluvial soils of the Red River delta and Mekong River delta, and the soils derived from basalt and limestone, are generally more fertile, with larger contents of soil N (0.1-0.2%), P (>0.03%) and K (1.5-2%)[14]. Much of the upland soils are highly weathered and very low fertility and often P is the main limitation for agricultural production.

2. LAO PDR

2.1 General introduction

Lao PDR is a small landlocked country that is surrounded by Thailand, Myanmar, People's Republic of China, Viet Nam, and Cambodia. The total land area of Lao PDR is about 237,000 km^2 and the population is about 6.8 million. Lao PDR is largely (~80%) extremely mountainous and has sloping hillsides (200- 2,820 m.a.s.l.) with thickly forested landscape[15]. The Annamite Mountain Range forms most of the eastern border with Viet Nam and the Luang Prabang Range lies on the northwestern border with the Thai highlands (A-Figure 6). The Mekong River forms a large part of Lao PDR's western boundary with Thailand. About 20% of the country's land area is flatland (70 - 200 m.a.s.l.) and about 12% of the total land area may be potentially suitable for agriculture.

Lao PDR has a tropical monsoon climate, with the rainy season ranging from April to October that is followed by the dry season from November to March. The mean annual rainfall of Lao PDR ranges from less than 1,500 mm (Savannakhet and much of the north) to greater than 3,500 mm in the Bolavens Plateau (ICEM, 2003). The average maximum temperature ranges from around 40°C along the Mekong in March and April to average minimum temperature of 5°C or even lower in the uplands of Xiangkhoang and Phôngsali in January[16]. The average mean temperature for the country ranges between 19 and 26°C[17].

2.2 Physiography

Workman (1977) described the geology of Lao PDR and its relation to the region as a whole. Metamorphic rocks of Proterozoic age underlie a significant proportion of the country. Shallow and deep water marine sediments prevail as outcrop in many areas; these sediments were intruded by

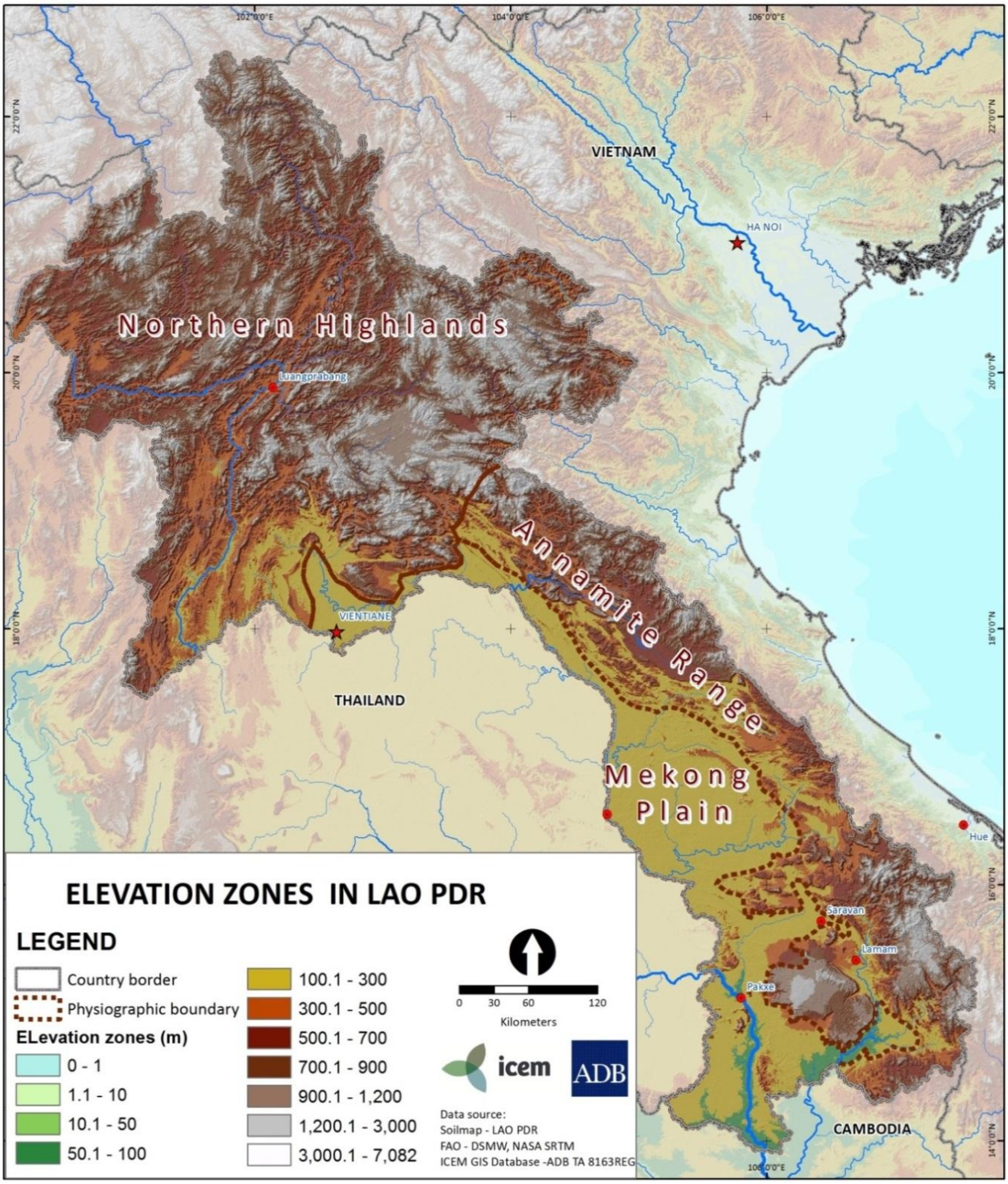
[14] http://www.apipnm.org/swlwpnr/reports/y_ta/z_vn/vn.htm#hpn
[15] http://www.fao.org/docrep/005/ac623e/ac623e0h.htm#TopOfPage
[16] http://en.wikipedia.org/wiki/Geography_of_Laos
[17] http://sdwebx.worldbank.org/climateportal

granitoid plutons during the Devonian to Triassic Period and extrusive acid rocks (predominantly dacites and rhyolites) during the Permo-Triassic (Hearn et al., 2008; Workman, 1977). The outcrop pattern is extremely complex. Rocks masses at surface are often intensely folded and faulted. The weathering of these mixed varieties of rocks has led to the development of deep weathering profiles and residual soils, especially on the metamorphic rocks (phyllites and schists).

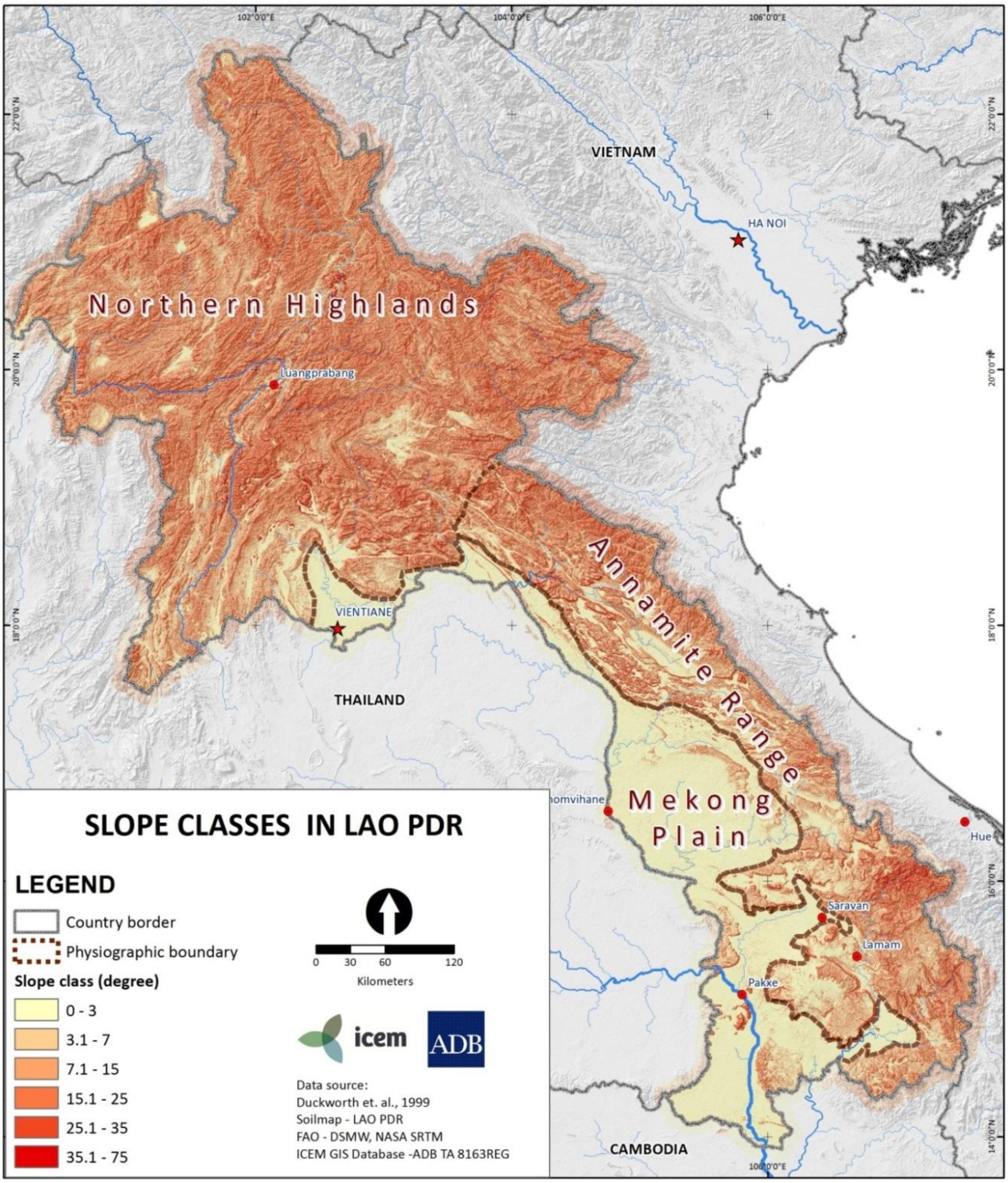
Lao PDR can be separated into three physiographic units i.e., Northern Highlands, The Annamite Range and Mekong delta (A-Figures 6 and 7; Duckworth et al., 1999).

Northern Highlands: This region has rugged mountainous topography with elevation ranging from 500 to 2,000 m. More than half of the area in the highlands has 50% slope and only 6% of the area under 20% slope (A-Figures 6 and 7). The climate is moist to dry sub-tropical with annual rainfall between 1,500 and 2,000 mm. Soils in this region are heavily leached and acidic, with low water retention capacity and generally low fertility.

The Annamite Range: The Mountain Range is in the northeast and east of the country and forms most of the eastern border with Viet Nam (A-Figures 6 and 7). The elevation range for this region is similar to Northern Highlands; however, it has less rugged terrain than the Northern Highlands. The annual rainfall in the region varies from 2,500 - 3,500 mm. Soils are generally similar to those found in the north.



A-Figure 6: The elevation map of Lao PDR showing the occurrence of a largely mountainous landscape formed by the Northern Highlands and Annamite Range.



A-Figure 7: The map of Lao PDR showing slope classes. The large mountainous area in the north and eastern parts of the country consists of steep slopes (> 15 degree) and the Mekong Plain, which is very flat (< 3 degree).

Mekong Plain: The region comprises large and small plains along the Mekong River and its larger tributaries. The climate in this region is tropical monsoon but rainfall is more varied than the Saiphou Louang. Generally flat upper levees formed by recent alluvial deposits which are acidic and shallow; the younger alluvial soils of the floodplain are fertile but are often subject to wet season inundation.

The combination of rugged terrain and relatively poor soils over much of the country offers minimal potential for intensive agricultural production (STEA, 2000). This is exacerbated by a strongly seasonal climate and together these factors result in drought being a characteristic of upland agriculture. Only the Mekong Plain offers relatively good potential for intensive agriculture but it is limited in extent. The overall natural resource base is fragile with a limited carrying capacity.

Arable and cultivated land mostly lies in the floodplains, which have formed from alluvium deposited by rivers. These soils are generally lighter textured with neutral to acidic pH. Upland soils are derived from crystalline, granitic, schistose, or sandstone parent rocks; these soils generally are acidic and have low levels of nutrients. Soils in southern Lao PDR are mostly either highly weathered (leached and iron [Fe] rich) or basaltic or sandstone soils on the Bolovens Plateau.

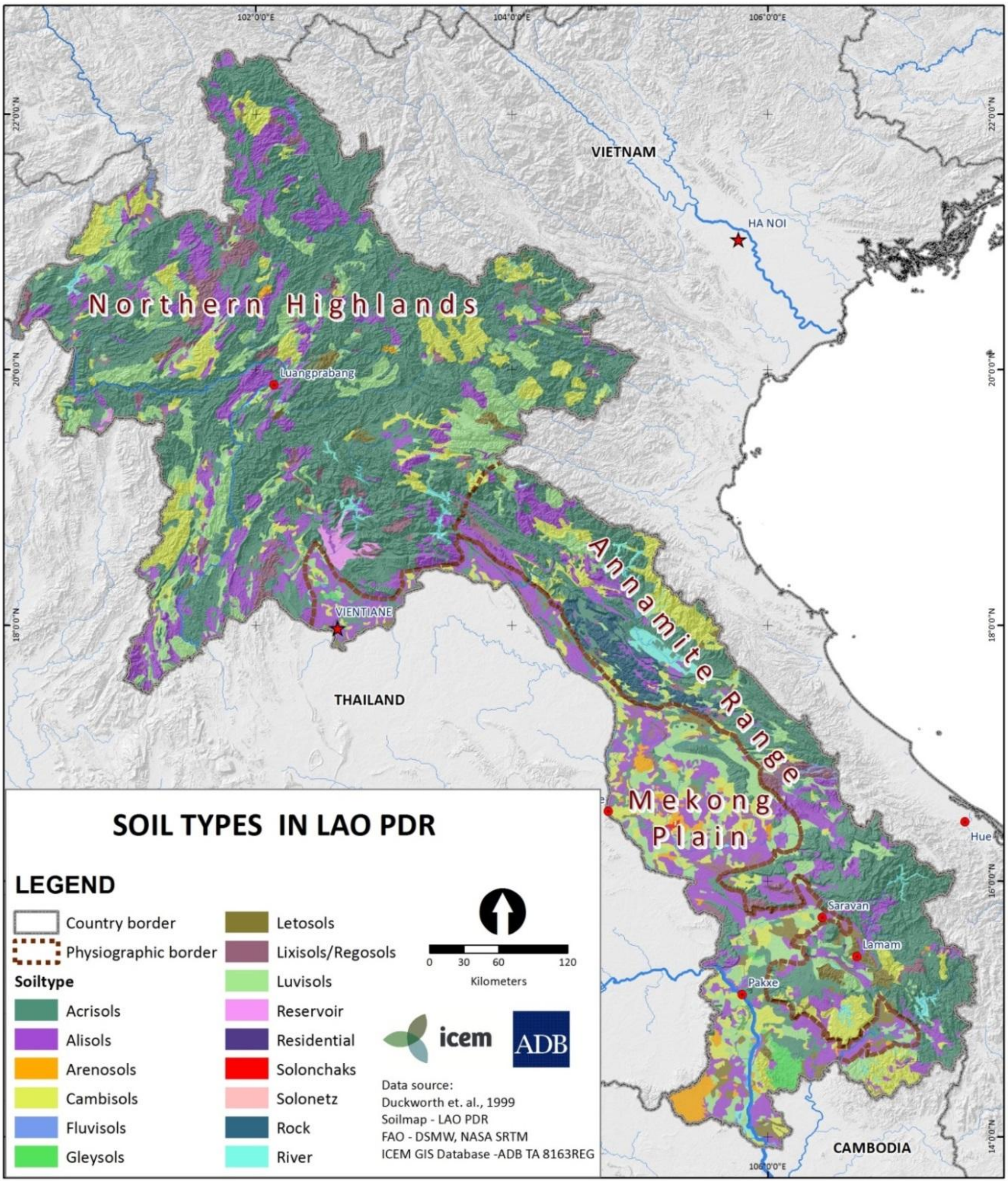
2.3 Soils and their major properties

Nearly 88% of the country is occupied by Acrisols and Cambisols (A-Figure 8 and 9). The distribution of various soil types in Lao PDR according to the FAO-UNESCO classification system is presented in A-Figure 9 and A-Table 2. Acrisols (68.2% of the area) have an argic B horizon (a subsurface horizon with distinctly higher clay content than the overlying horizon), cation exchange capacity (CEC) of less than 24 $cmol_c\ kg^{-1}$ of clay (i.e. low-activity clay) and base saturation of less than 50% in some part of the B horizon. Plinthic Acrisols, Gleyic Acrisols, Ferric Acrisols, Haplic Acrisols and Humic Acrisols soil units have been identified in Lao PDR; main features of subsoils are given in the Appendix 2. Alisols occupy only 0.5% of the area, these soils have characteristics similar to Acrisols except the CEC is equal to or more than 24 $cmol_c\ kg^{-1}$ of clay (i.e. high-activity clay). Acrisols and Alisols occur in hilly and undulating topography. In general, Acrisols are developed from the weathering of acid rocks hence low-activity clays, whereas Alisols are formed from the weathering of basic rocks and therefore high-activity clays or permanent charge clay minerals.

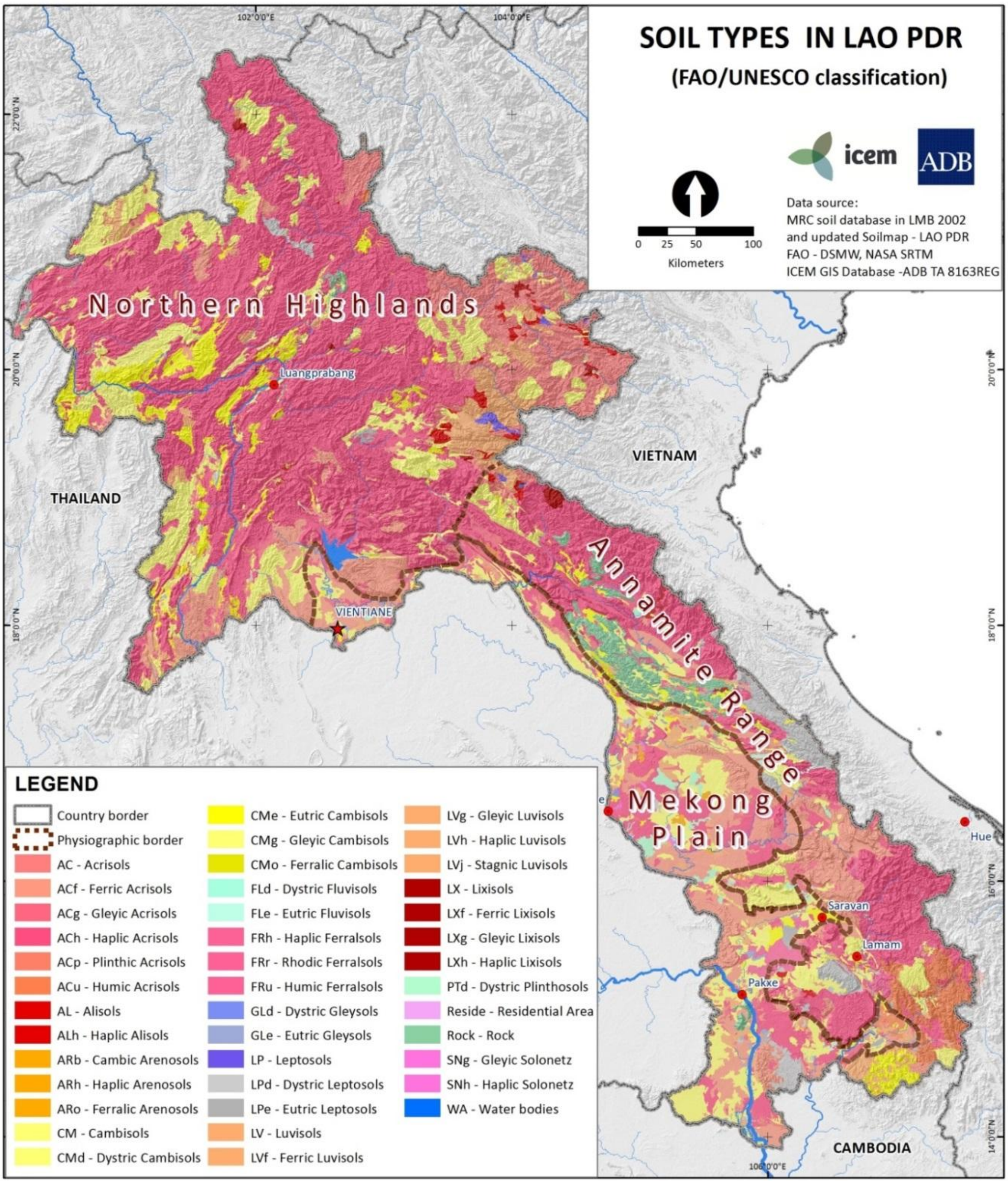
Arenosols are deep sandy soils and covers about 0.1% of the land area. Cambic, Haplic and Ferralic soil units of Arenosols are present in the country.

Cambisol are present over 20% of the area; these soils are slightly to moderately weathered, and do not have appreciable amount of clay illuviation in the subsoil (presence of cambic B horizon) unlike the other three orders described above. Dystric Cambisols, Eutric Cambisols, Gleyic Cambisols and Ferralic Cambisols soil units are present in Lao PDR. These soils exist on level to mountainous terrain.

Ferralsols are deeply weathered red or yellow soils of the tropics. These soils have high contents of sesquioxides, relatively low pH and clay mineralogy dominated by Fe oxides and kaolinite.



A-Figure 8: The distribution of soil types according to local classification system in Lao PDR.



A-Figure 9: The distribution of different soil types according to the FAO-UNESCO classification system for Soil Resources in Lao PDR (FAO, 1997).

A-Table 2: The extent of distribution of soil types according to the FAO-UNESCO Classification (FAO, 1997) in Lao PDR.

FAO Units	FAO Sub-units	Area (ha)	Area (%)
Acrisols		15,671,108	68.2
	AC – Acrisols	1,301,990	5.7
	ACf - Ferric Acrisols	2,692,353	11.7
	ACg - Gleyic Acrisols	305,731	1.3
	ACh - Haplic Acrisols	10,949,546	47.6
	ACp - Plinthic Acrisols	21,100	0.1
	ACu - Humic Acrisols	400,387	1.7
Alisols		124,861	0.5
	AL - Alisols	116,740	0.5
	ALh - Haplic Alisols	8,121	0.04
Arenosols		25,908	0.1
	ARb - Cambic Arenosols	167	0.0
	ARh - Haplic Arenosols	2,651	0.01
	ARo - Ferralic Arenosols	23,089	0.1
Cambisols		4,593,947	20.0
	CM - Cambisols	312,909	1.4
	CMd - Dystric Cambisols	2,904,344	12.6
	CMe - Eutric Cambisols	949,989	4.1
	CMg - Gleyic Cambisols	366,652	1.6
	CMo - Ferralic Cambisols	60,051	0.3
Ferralsols		173,379	0.8
	FRh - Haplic Ferralsols	47,341	0.2
	FRr - Rhodic Ferralsols	77,022	0.3
	FRu - Humic Ferralsols	49,017	0.2
Fluvisols		41,656	0.2
	FLd - Dystric Fluvisols	6,295	0.03
	FLe - Eutric Fluvisols	35,361	0.2
Gleysols		28,631	0.1
	GLd - Dystric Gleysols	6,966	0.03
	GLe - Eutric Gleysols	21,665	0.1
Leptosols		560,379	2.4
	LP - Leptosols	36,704	0.2
	LPd - Dystric Leptosols	461,486	2.0
	LPe - Eutric Leptosols	62,189	0.3
Lixisols		88,920	0.4
	LX - Lixisols	19,639	0.1
	LXf - Ferric Lixisols	540	0.0
	LXg - Gleyic Lixisols	12,482	0.1
	LXh - Haplic Lixisols	56,259	0.2
Luvisols		963,239	4.2
	LV - Luvisols	407,375	1.8
	LVf - Ferric Luvisols	182,782	0.8
	LVg - Gleyic Luvisols	137,287	0.6
	LVh - Haplic Luvisols	234,729	1.0
	LVj - Stagnic Luvisols	1,066	0.0

Plinthosols	PTd - Dystric Plinthosols	97,306	0.4
Solonetz		19,467	0.1
	SNg - Gleyic Solonetzs	2,315	0.0
	SNh - Haplic Solonetzs	17,152	0.1
Water	WA - Water bodies	173,120	0.8
Residential Ar	Reside - Residential Area	3,948	0.02
Grand Total		22,994,129	100.0

Ferralsols exist over 0.8% of the area, and Haplic, Rhodic and Humic sub-units have been identified in Lao PDR.

Gleysols are soils that are saturated with groundwater for long enough periods to develop reducing conditions resulting in gleyic properties, including underwater and tidal soils. Dystric Gleysols and Eutric Gleysols soil units are present in Lao PDR, both covering an area of 0.1%.

Leptosols are thin soils over continuous rocks, and cover approximately 2.4% of the area. Dystric and Eutric units of Leptosols have been identified in Lao PDR; the key properties of these units are presented in the Appendix 2.

Lixisols have an argic (clay-rich) subsoil horizon, low-activity clays in the argic horizon and a high base saturation. Lixisols cover about 0.4% of the area in Lao PDR. Typically these soils are formed under a tropical, subtropical or warm temperate climate with a pronounced dry season. Three soil units, i.e. Gleyic Lixisols, Ferric Lixisols and Haplic Lixisols have been identified.

Luvisols cover an area of 4.2% in Lao PDR. Similar to Acrisols and Alisols, Luvisols also have an argic B horizon. However, these soils have high-activity clays (unlike Acrisols) and base saturation of equal or more than 50% in the B horizon (unlike both Acrisols and Alisols). Gleyic Luvisols, Ferric Luvisols, Haplic Luvisols and Stagnic Luvisols units of the Luvisols group are present in Lao PDR.

Plinithosols cover about 0.4% of the total area in Lao PDR. These soils have a layer containing a Fe-rich mixture of clay minerals (predominantly kaolinite) and silica in subsoil, which hardens on exposure into ironstone concretions known as plinthite.

Solonetz have a dense, strongly structured, clayey subsurface horizon that has a high proportion of adsorbed Na on exchange sites. Two soil units, Gleyic Solonetz and Haplic Solonetz, have been identified in Lao PDR. Gleyic Solonetz show gleyic properties whereas the Haplic Solonetz has an ochric A horizon; both of these soils cover 0.1% of the area.

2.4 Soil fertility status

There is limited soil fertility data for soils from Lao PDR. Soil fertility has been inferred based on the rice yield and yield responses to fertilisers (Bell and Seng, 2004). Rice growing soils show a gradient in soil texture (and perhaps other properties) from the northern regions where 80% are loamy in texture to the southern region where only 25% are loams (Linquist et al., 1998). The response of rainfed lowland rice crops to NPK fertiliser increased from 85% in the northern region to 100% in the central and southern regions (Linquist et al., 1998). Nitrogen is the most limiting nutrient in all regions of Lao PDR, with 86% of experiment sites responding to N in the central and southern regions, and 50% in the northern region (Schiller et al., 2001). Phosphorus is considered to be the second most limiting nutrient in all parts, with 80% of sites responding to P in the central and southern regions, and 33% in the northern region. Potassium was the least limiting of the major nutrients, with only 27% of sites in the central and southern regions responding to K application, and 13% in the north (Schiller et al., 2001).

Soils in the central and southern agricultural areas within the Mekong River Valley generally exhibit more widespread deficiencies and greater responses to nutrient inputs than soils in the northern agricultural area (Schiller et al., 2001). There is some evidence suggesting sulfur (S) and magnesium (Mg) deficiency for rice in Lao PDR. Lowland rice soils in the southern part of Lao PDR are predominantly Acrisols and often these soils are highly weathered, have a low inherent fertility, a low pH and low CEC (Linquist and Sengxua, 2001). Surface soil data (0-20 cm) suggest that 80% of soils in the south contain less than 2% organic matter, 68% are coarse textured or sandy and 87% have a pH of less than 5.5 (Roder et al., 2005).

Upland soils (Acrosols and Alisols) are generally poor, mainly red-yellow, podzolic, and reddish brown lateritic, leached and acidic, with low water-holding capacity (Roder, 2001) and soil fertility is generally cited as a major constraint in upland rice production. According to Roder et al. (2005) upland rice growers do not apply any fertiliser or manure, which is causing a gradual decline in the soil organic matter content.

3. CAMBODIA

3.1 General introduction

Cambodia is located in the southwest corner of the Indochina Peninsula with a total land area of 181,035 km^2. According to 2013 estimates, the population of Cambodia is approximately 15.2 million[18]. It is an agrarian country, where about 80% of the total population resides in rural areas and is dependent on agriculture for its livelihood (Clausen, 2009).

Cambodia has a tropical climate, with a wet season from May through October and a dry season from November-December to April. Usually the wet season is disrupted by a short dry spell during two weeks in July or August. Temperatures are fairly uniform throughout the Tonlé Sap Basin area, with values ranging from 23 to 28°C, and an annual mean temperature of around 25°C. Maximum temperatures greater than 32°C, however, are common before the onset of the rainy season, and minimum temperatures rarely fall below 10°C. January is the coolest month, and April is usually the warmest month in Cambodia[19]. The annual average rainfall is between 1200 and 1500 mm in the central basin and it is very high (up to 5080 mm) in the southwestern mountains[20].

3.2 Physiography

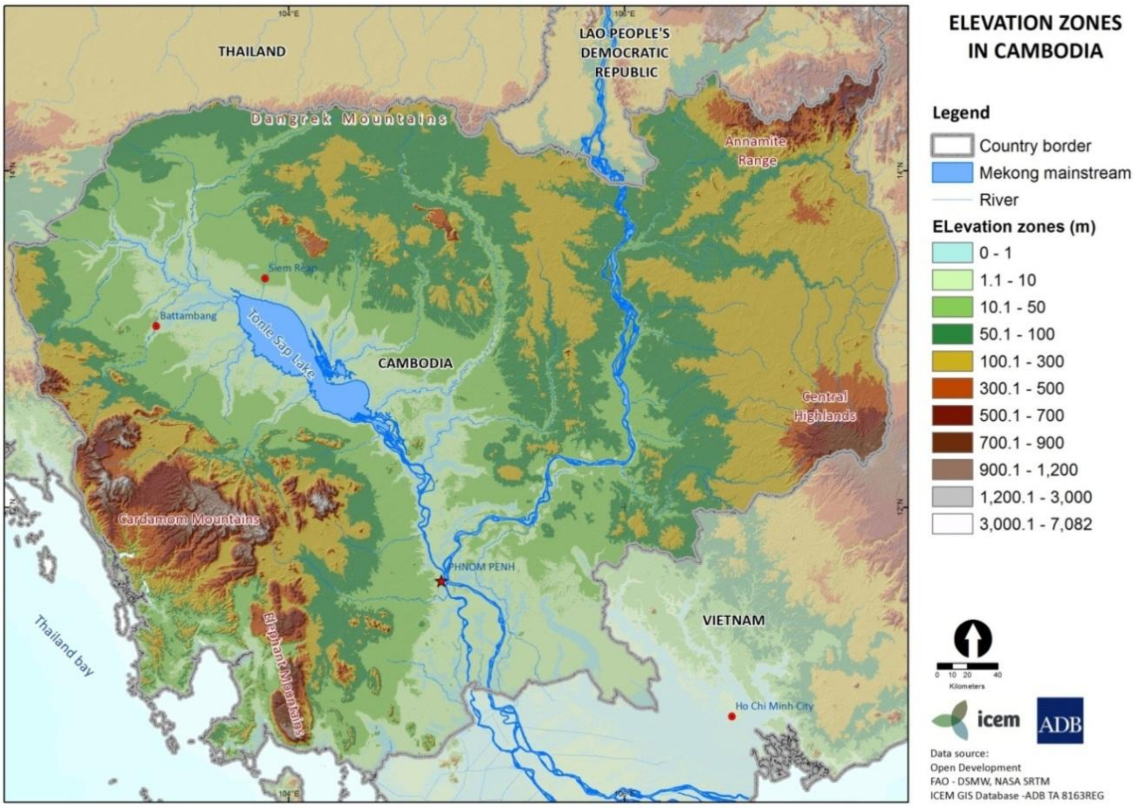
A topographic map of Cambodia is presented in A-Figure 10. Cambodia is surrounded by relatively densely forested mountains on three sides and a gigantic basin in the large central plain consisting of the Tonlé Sap Lake and river complexes[15] (Nesbitt, 1997). On the west and southwest are the Cardamom Mountains and the Elephant Mountains (Damrei Mountains), the Dangrek Mountains range lies along the Thai border in the north, and the lower reaches of the Central Highlands of Viet Nam (the Eastern Highlands of Cambodia) are found in the east (A-Figures 10 and 11).

[18] http://data.worldbank.org/country/cambodia
[19] http://en.wikipedia.org/wiki/Geography_of_Cambodia#Climate
[20] http://www.encyclopedia.com/topic/Cambodia.aspx

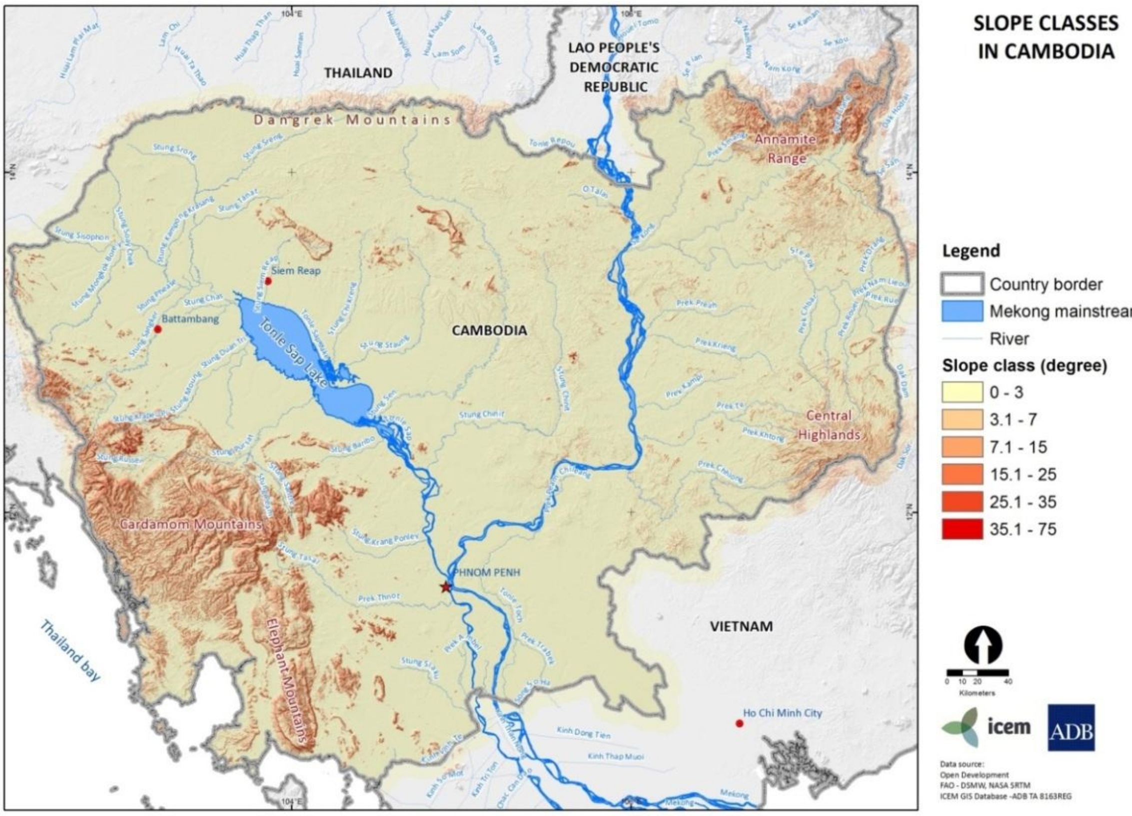
The Cardamom Mountains are generally oriented in a northwest-southeast direction and have elevation greater than 1,500 m. Phnom Aural, is the highest mountain (1,813 m) in the country and it is part of the Cardamom Mountains. The Elephant Mountains occur in the south and the southeast from the Cardamom Mountains and have a lower elevation (500-1000 m). The Dongrek Mountains extends in the east–west direction from the Mekong River westward for approximately 320 km, merging with the highland area near San Kamphaeng, Thailand. The Dongrek Mountains consist of a steep escarpment of the sandstone Khorat Plateau with an average elevation of about 500 m and the highest point exceeding 750 m. The Mekong Valley separates the eastern end of the Dongrek Mountains and the northeastern highlands (Clausen, 2009).

Major rivers flow from the north to the south through the country and drain into the Tonlé Sap or into the Mekong River (A-Figures 10 and 11). The Cardamom Mountains and Elephant Mountains have a separate drainage divide; the rivers in the east region flow into the Tonlé Sap, while on the west side they drain into the Gulf of Thailand. During the wet season, the Mekong and other rivers overflow and deposit vast quantities of alluvium in the plains. The water level in the Mekong River rises and becomes higher than the Tonlé Sap River, and the Mekong flows 'upstream' overfilling the Tonlé Sap Lake and flooding the surrounding lowlands. During this part of the annual flood-cycle, the area of the Tonlé Sap Lake increases from 2500 km^2 to 15,000 km^2 and its volume from 1.5 km^3 to between 60 and 70 km^3 (MRC, 2010). After the wet season ends, the discharge of the Mekong River decreases and the flow of the Tonlé Sap River reverts to the normal downstream direction, draining excess water from the Tonlé Sap Lake and the surrounding floodplains.

The central plains are extremely flat (5-10 m difference in elevation) resulting from long-term alluvial deposition originating from mountains within Cambodia and from sediments carried into the plain by the Mekong River. The Mekong and the Tonlé Sap Lake are extremely important for the agriculture and economy of Cambodia, and over 80% of the population resides in this area.



A-Figure 10: Topographic map of Cambodia showing mountains on three sides of the large central plain and the Tonlé Sap Lake.

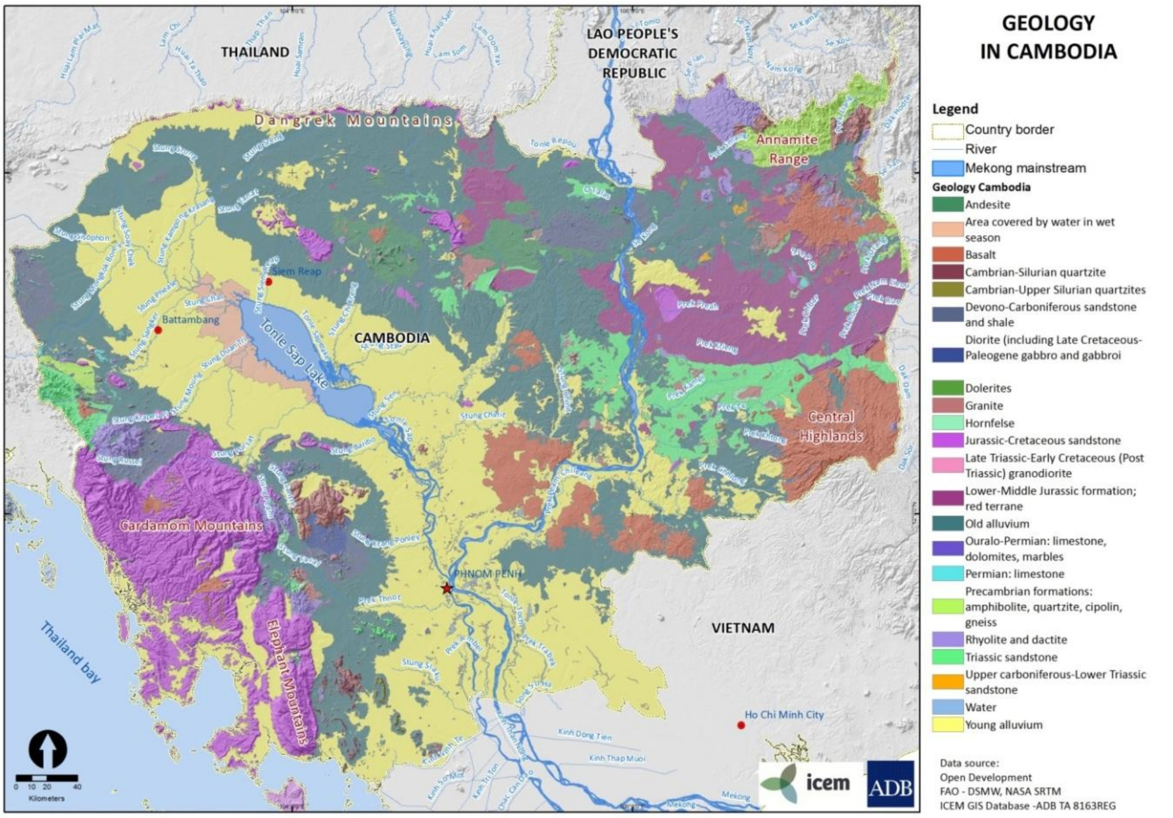


A-Figure 11: Slope classes in Cambodia showing steep mountains the south-west and north-east of the country.

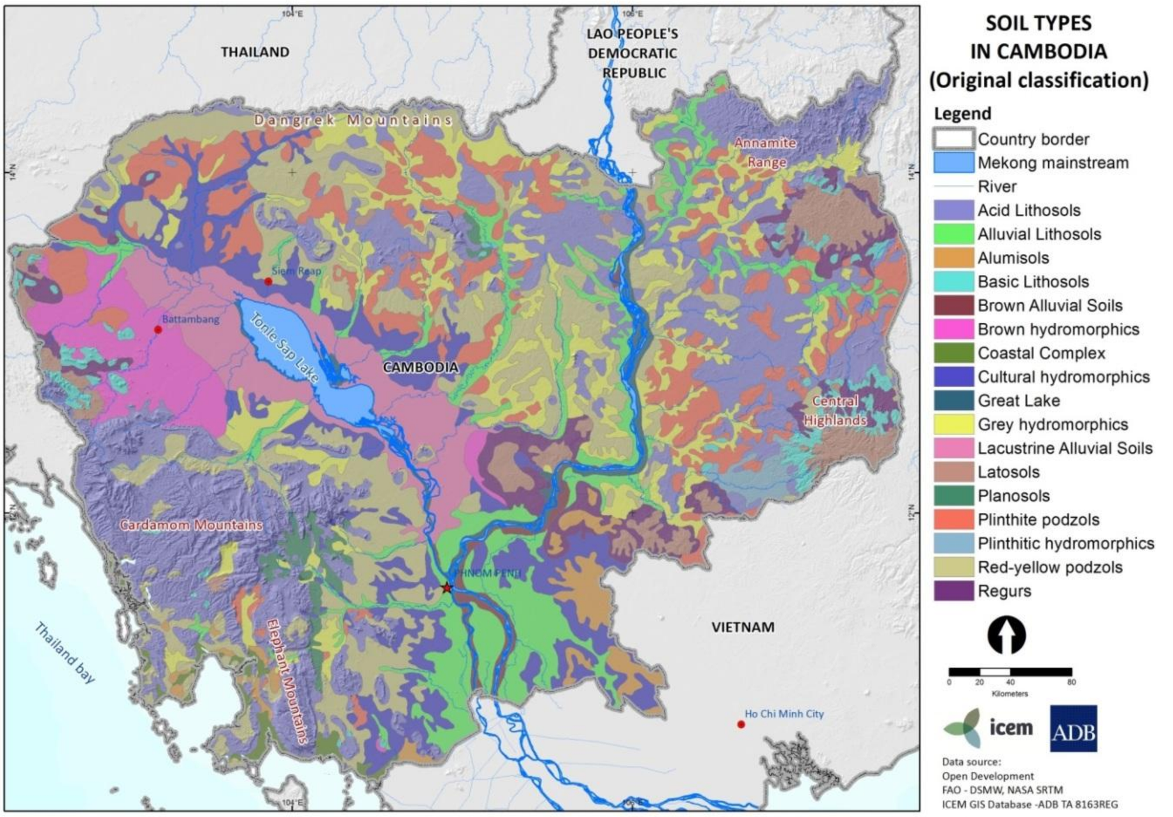
Mesozoic sandstone dominates the basement geology in Cambodia (A-Figure 12) and this has contributed sandy material that covers a large proportion of Cambodia (Workman, 1972). White et al. (1997) suggested that Mesozoic sandstone also influence the properties of lowland agricultural soils, because the contemporary and Pleistocene sediments that form the parent material of these soils have mostly originated from the weathering and erosion of the Mesozoic sandstone. Some of the siliceous sediments have also originated from felsic igneous intrusions particularly in south and south-east Cambodia (White et al., 1997; Seng et al., 2007). Basaltic lava flows from the Pleistocene have covered significant areas of older alluvial terraces in the north-east and south-east of the country (White et al., 1997; Bell and Seng, 2004; Seng et al., 2007). The soils derived from the weathering of weathered basalt and the sediments (alluvial or colluvial) derived from basalt have significantly different properties and are more fertile than those of the siliceous parent materials (White et al., 1997). There are some pockets of other rocks in Cambodia, for example substantial areas of siltstone limestone and marl exist in the western side of Cambodia bordering Thailand. The central part of Cambodia is largely dominated recent alluvial or lacustrine sediments which are derived from both the Mekong River basin and the immediate basin of the Tonle Sap (Oberthür et al., 2000).

3.3 Soils and their major properties

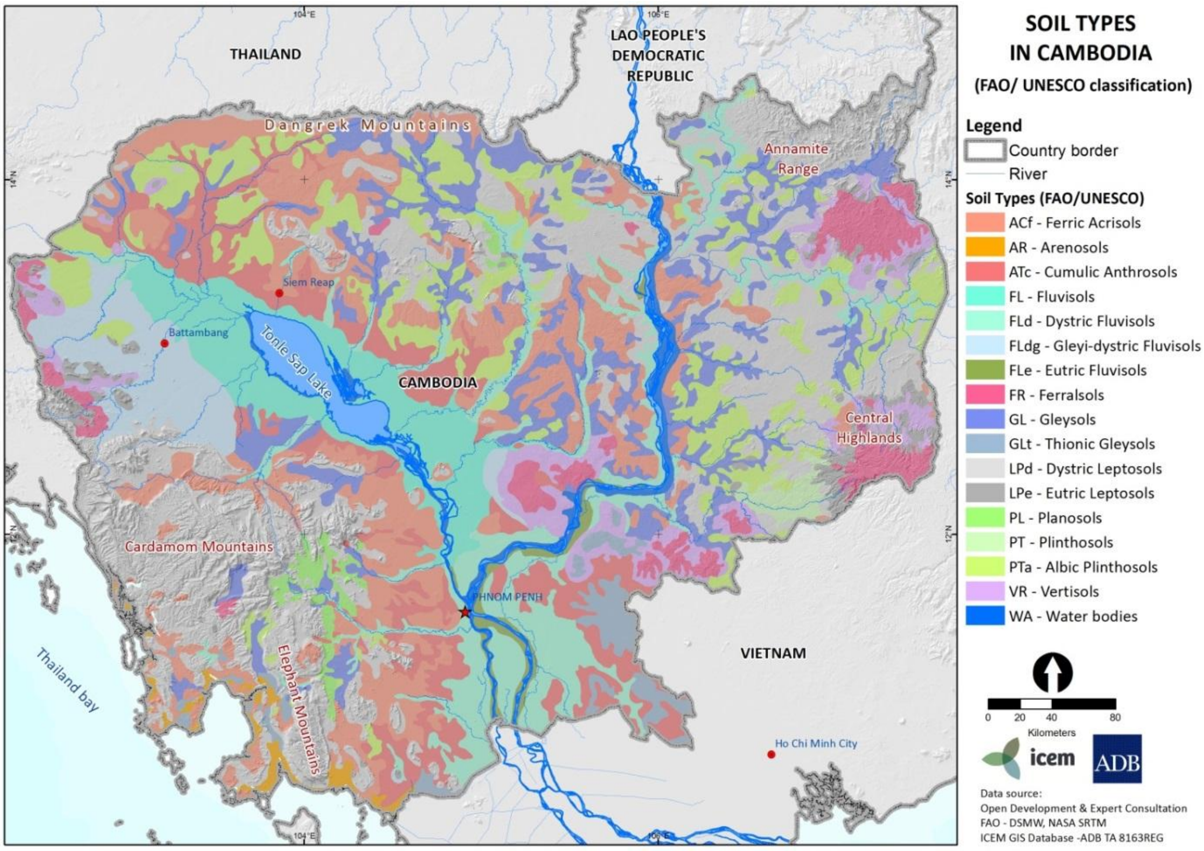
The distribution of different soil types in Cambodia is presented in A-Figures 13 and 14 and A-Table 3. Leptosols covers more than 26% of the total area in the country. These are very thin soils over continuous rocks and coarse fragments are very common in such soils. Considering the presence of mountains in significant portion of Cambodia, the dominance of Leptosols is expected. Most of these soils (Dystric Leptosols) have base saturation percentage < 50% but a small proportion of the soils (Eutric Leptosols) have base saturation percentage ≥ 50%. Gleysols constitute over 11% of the area and are present along river tributaries in the mountainous regions. These soils are saturated with groundwater and reduced for long enough periods to develop reducing conditions. Fluvisols are common along the main rivers (Dystric Fluvisols 8.3%) and around the Tonlé Sap Lake (Fluvisols 5.8%) in the central part of the country. Ferralsols covers 3.5% of the area and occurs in the north-east and south-east of the country. Ferralsols are deeply weathered soils with high contents of Fe and aluminium (Al) oxides and kaolinite; these soils are derived from the weathering of basalt in Cambodia. Cumulic Anthrosols occupy nearly 8% of the area and exist together with Gleysols and Fluvisols in the river systems. Anthrosols have resulted from or profoundly modified through long-term human activities and these includes paddy soils where long-term wet cultivation has been practiced in the country. Acrisols exist all over the country and cover about 14% of the area. Typically, Acrisols have higher clay content in the subsoil due to the migration of clay from the topsoil; the clay fraction has low-activity and a low base saturation in the subsoil (50-100 cm). Plinthosols covers 10.4% of the area; these soils occur on level to gently sloping areas with fluctuating groundwater or stagnating surface water. These soils have a plinthic horizon, which is a subsurface horizon that is rich in Fe and poor in humus.



A-Figure 12: The geological map of Cambodia.

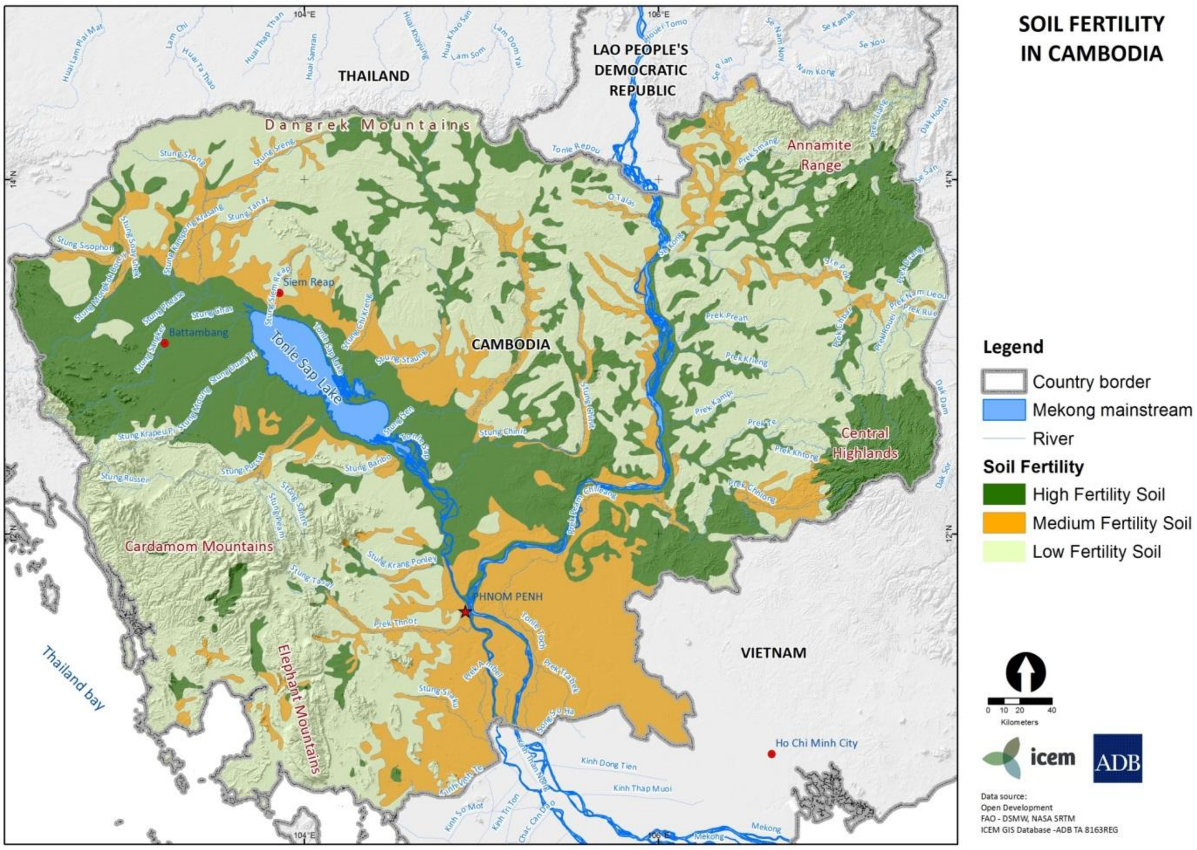


A-Figure 13: The distribution of different soil types according to the local classification system in Cambodia.

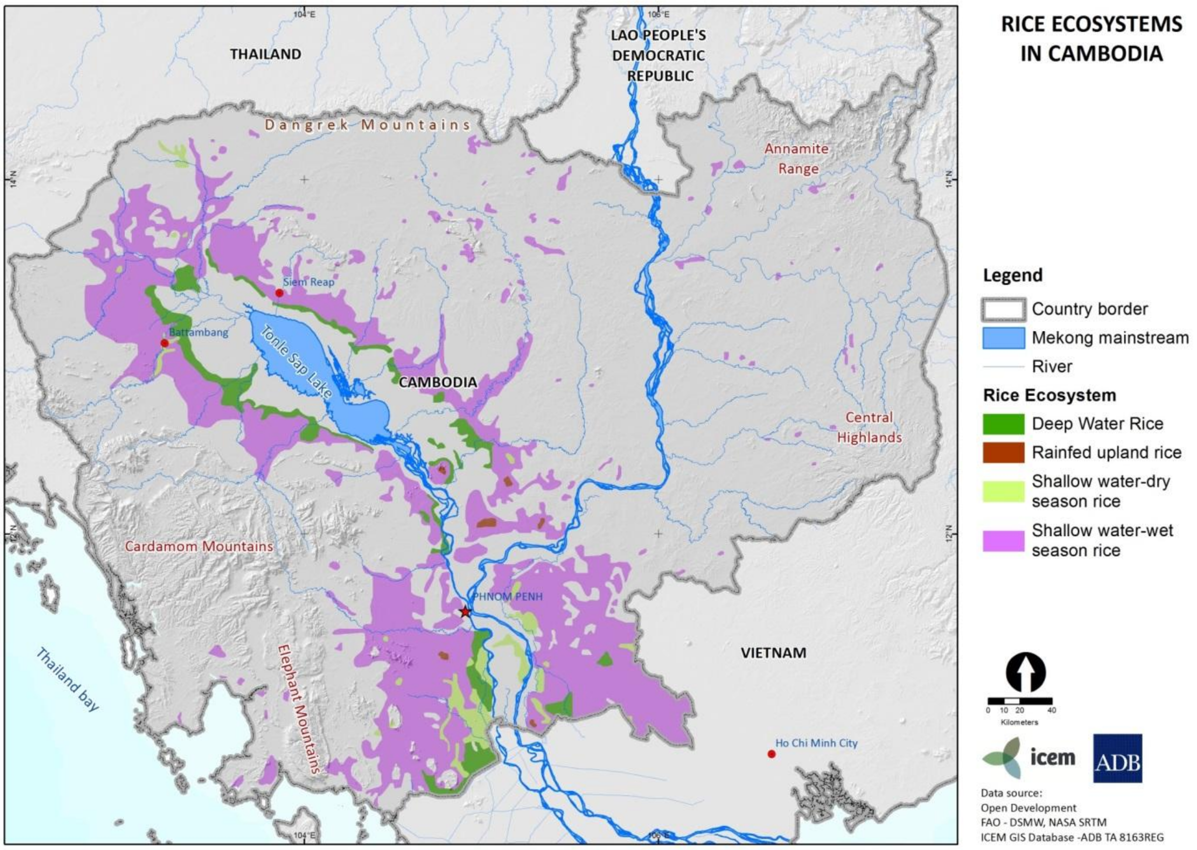


A-Table 3: The extent of distribution of soil types according to the local and the FAO-UNESCO classification (FAO, 1997) in Cambodia.

Local soil types	FAO Units	FAO Sub-units	Area (ha)	Area (%)
Acid Lithosols	Leptosols	Dystric Leptosols	4,399,528.6	24.3
Alluvial Lithosols	Fluvisols	Dystric Fluvisols	1,500,225.3	8.3
Alumisols	Gleysols	Thionic Gleysols	316,368.3	1.7
Basic Lithosols	Leptosols	Eutric Leptosols	331,842.7	1.8
Brown Alluvial Soils	Fluvisols	Eutric Fluvisols	131,478.8	0.7
Brown hydromorphics		Gleyi-dystric Fluvisols	681,349.1	3.8
Coastal Complex	Arenosols	Arenosols	184,013.4	1.0
Cultural hydromorphics	Anthrosols	Cumulic Anthrosols	1,405,534.1	7.8
Grey hydromorphics	Gleysols	Gleysols	1,701,314.1	9.4
Lacustrine Alluvial Soils	Fluvisols	Fluvisols	1,044,565.6	5.8
Latosols	Ferralsols	Ferralsols	630,851.9	3.5
Planosols	Planosols	Planosols	166,536.4	0.9
Plinthite podzols	Plinthosols	Albic Plinthosols	1,778,242.0	9.8
Plinthitic hydromorphics	Plinthosols	Plinthosols	116,189.0	0.6
Red-yellow podzols	Acrisols	Ferric Acrisols	2,544,420.6	14.1
Regurs	Vertisols	Vertisols	629,185.4	3.5
Great Lake		Water body	539,012.2	3.0
Total			18,100,657.6	100.0



A-Figure 14: The soil fertility map of Cambodia.



A-Figure 15: Rice ecosystems in Cambodia.

3.4 Soil fertility status

The soils of Cambodia could be grouped into three broad classes based on their fertility status – low, medium and high fertility soils (A-Figure 15). Generally, the soils (Fluvisols, Vertisols and Gleysols) formed on young alluvium surrounding the Tonlé Sap Lake and the soils derived from basic rocks have high fertility. Lithic alluvial soils (Fluvisols) on the southern end of the Mekong delta are classified as medium in soil fertility. The large area comprising thin and often sandy soils, formed on acidic rocks in the mountainous region, the sandy soils are considered to be low in soil fertility. Mesozoic sandstone dominates most of the basement geology in Cambodia (Workman, 1972), which has a dominating influence on the properties of upland soils. Low nutrient status, soil acidity and low water holding capacity have been identified as significant constraints for crop production on sandy soils (Seng et al., 2007).

Analysis of Cambodia's soil database indicates that more than 90% of the soils are very low to low in total N, about 88% are low in extractable (plant available) P, and about 86% are low in organic C (CARDI, 2009). There has been more research on the land capability for rice production in the lowlands of Cambodia which has been discussed under rice production.

Rice soils of Cambodia have been grouped into three categories (low, medium and high) based on their chemical and physical limitations for rice production (Bell and Seng, 2004; White et al., 1997). More than 75% of the soils in rice ecosystems have low to medium potential in terms of rice production (A-Table 4).

A-Table 4: Proportion of low-, medium- and high-potential soils in various rice ecosystems of Cambodia (White et al., 1997).

Soil Potential	Rice ecosystem (Refer to A-Figure 16)			
	Shallow water, wet season	Deepwater	Irrigated	Upland
Low	56	18	20	55
Medium	21	10	14	34
High	23	72	66	8

Low-potential soils have low CEC, strongly to moderately acidic (Al or Mn toxicity problems), very low in organic C and total N contents, very low to moderate available P and very low to low in exchangeable K. Many of these constraints are difficult to overcome through land management. The chemical and physical constraints of medium-potential soils are low CEC, strongly acidic pH, very low in organic C and total N, and low levels of available P and K and low in total N, and poor soil structure. Some of the constraints of medium potential soils can be managed or corrected. High potential soils have few limitations for rice productions, which includes very low in organic C content, low to very low in total N content, moderate to low in P, low in K, and moderate to low CEC; these soils have few limitations on rice yields.

4. THAILAND

4.1 General introduction

Thailand lies between latitudes 5° 37 ′ to 20° 27 ′ north and longitudes 97° 22 ′ to 105° 37 ′ east. It has a total area[21] of 513,115 km^2, extending about 1,620 km from north to south and 775 km at the greatest breadth from east to west. The current population of Thailand is approximately 68 million.

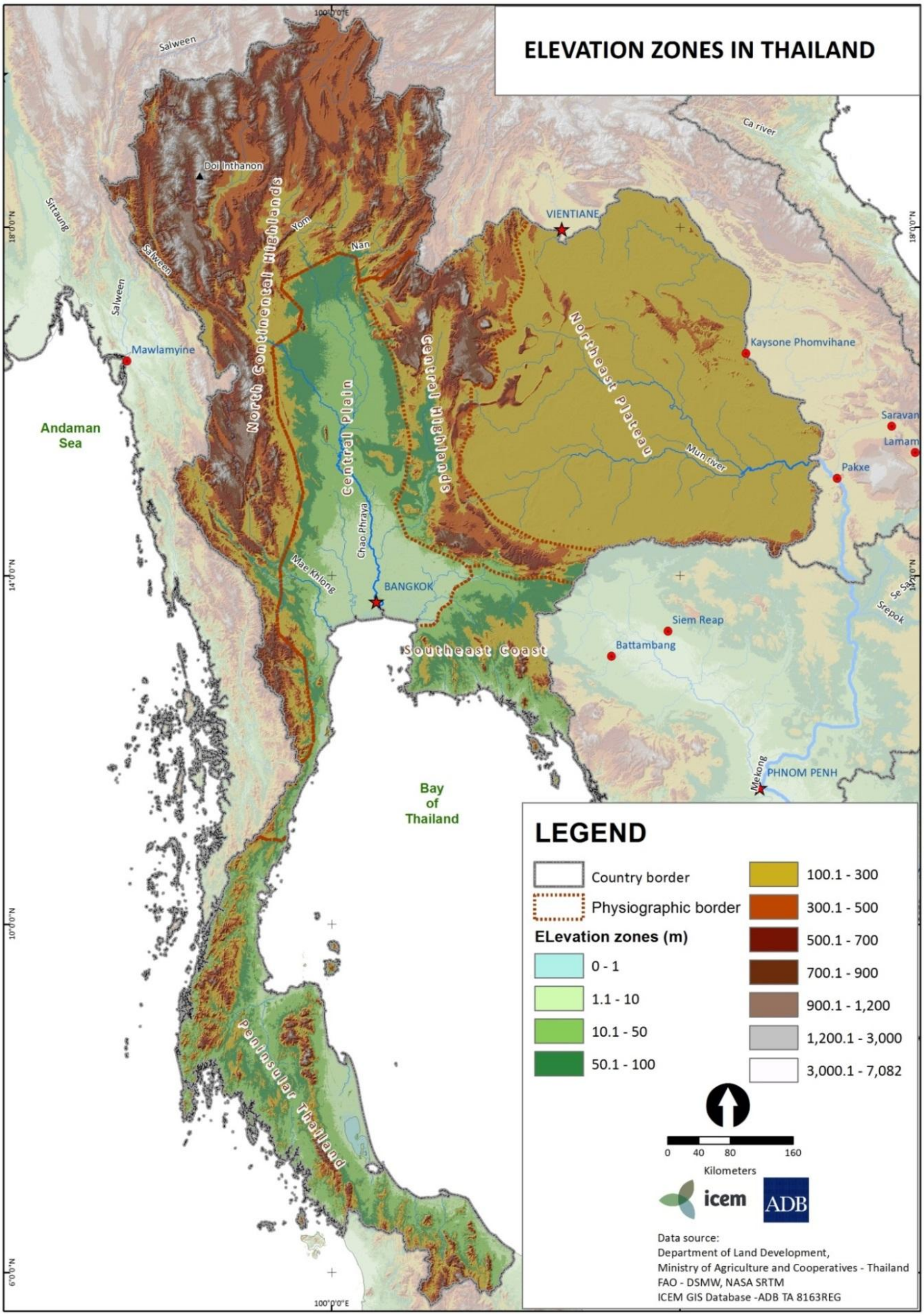
Most of Thailand has a tropical wet and dry (or savannah type) climate except for the south and the eastern tip which has a tropical monsoon climate[22]. There are three distinct seasons over most of the country: the hot season from March through May; the rainy season monsoon from June to October; and the cool season from November to February[23]. The peninsular Thailand receives rainfall during all seasons, with the largest amount along the west coast from May to October and along the east coast from October to January. The majority of the rainfall in the continental region of Thailand occurs between June and October. The highest temperatures of the year are registered during the inter-monsoon season between March and April, when day temperatures are usually above 32°C. The average temperature in Thailand varies between 19 and 38°C. The mean annual rainfall ranges from 1000 to 1500 mm over much of the country, in the south and southeast exceeds 2000 mm and over 3800 mm in the peninsula.

Thailand is a part of the Yunnan-Malayan Geosyncline (also called the Burma-Malaya Geosyncline) that has gone through a long series of structural changes between the Pre-Cambrian period (570 million years ago) and the Tertiary epoch (1.5 million years ago). According to the Plate tectonic theory, Thailand lies on an inner perimeter of the south-east Asia Plate, which is being compressed from opposite directions by the Indian Plate from the west and the Philippine Plate from the east. Based on structural geology, Thailand has been divided into four domains[24] – (i) the folded belt of mountains in the north, west, and south of the country; (ii) the folded belt of mountains east of the Chao Phraya Plain, delimiting it against the higher Khorat Plain and continuing eastward to delineate lower Kampuchea; (iii) the Korat Plain with two major basins- the northern Sakhon Nakhon Basin, and the southern Khorat Basin; and (iv) the Chao Phraya alluvial plain, with two major basins and a southerly continuation into the Gulf of Thailand.

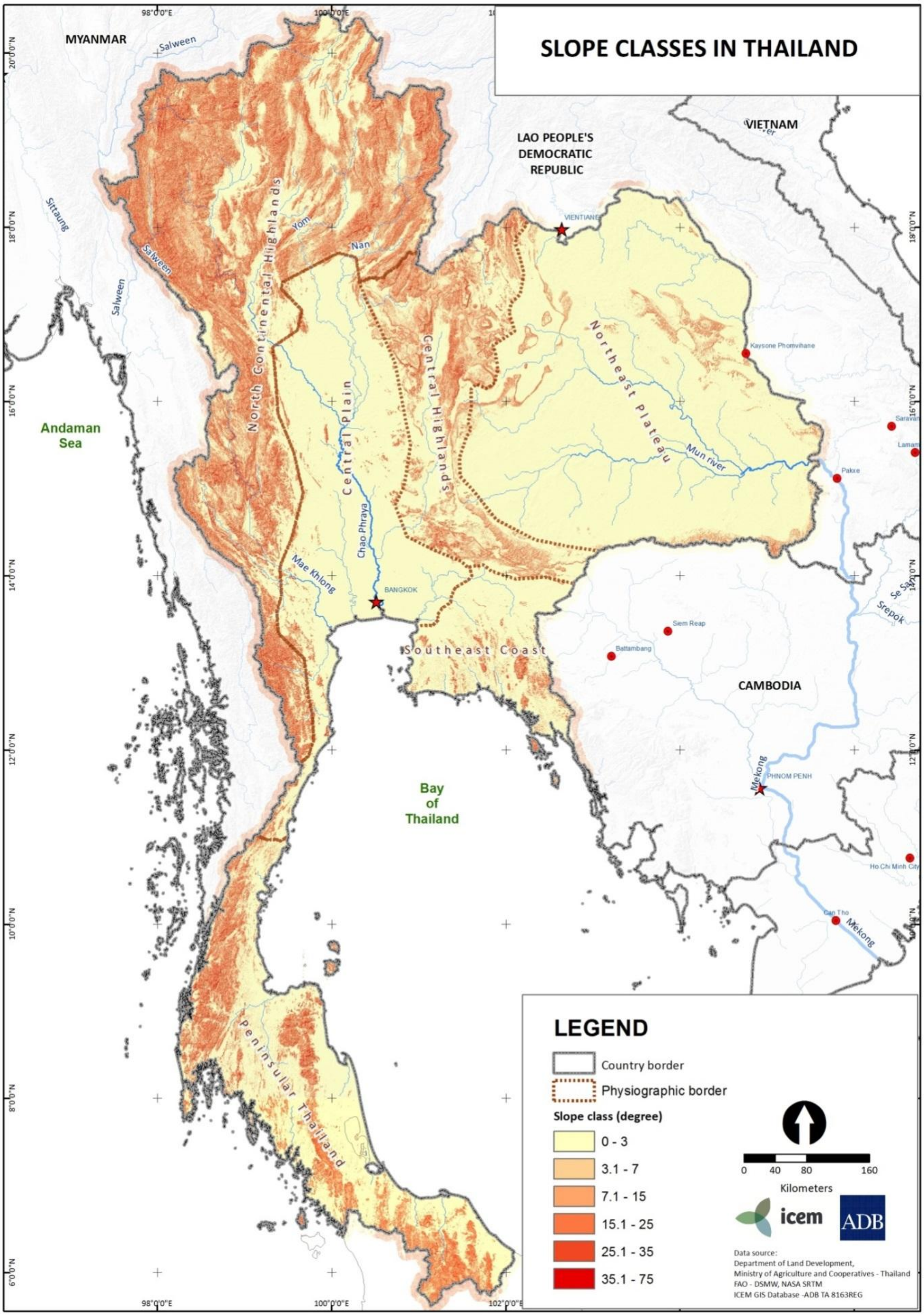
4.2 Physiography

Thailand has been divided into six main physiographic regions (Moormann and Rojanasoonthon, 1968): North and West Continental Highlands, Central Highlands, Northeast Plateau, Central Plain, Southeast Coast and Peninsular Thailand (A-Figures 17, 18 and 19).

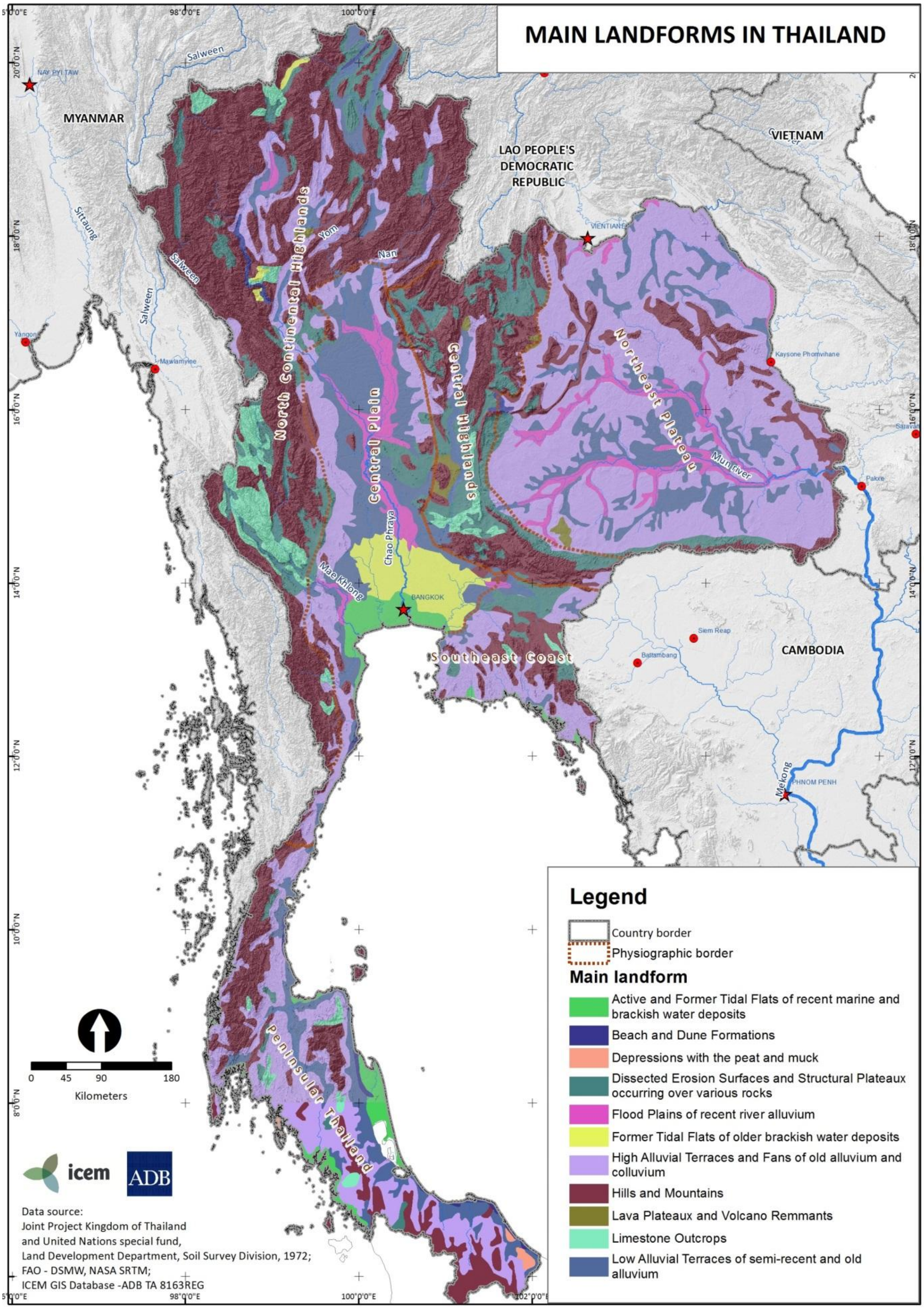
[21] http://www.ldd.go.th/fao/z_th/th.htm#overview
[22] http://en.wikipedia.org/wiki/Thailand#Climate
[23] http://www.encyclopedia.com/topic/Thailand.aspx
[24] http://www.ldd.go.th/



A-Figure 16: The elevation map of Thailand.



A-Figure 17: The slope classes map of Thailand.



A-Figure 18: Main landforms in Thailand.

(i) North and West Continental Highlands: The continental highlands consist of a series of parallel ranges, with a north-south trend, and occupy the northern and western portions of the country. Hence, this region is usually subdivided into two sub-regions, i.e. the western mountains and the northern hills and valleys. The western mountains consist of part of the rugged Central Cordillera along the Myanmar border. DoiInthanon, which is the highest mountain (elevation 2595 m) in Thailand, occurs in the western highlands (A-Figure 17). A number of rivers flow southward between the deep and narrow valleys of the roughly parallel mountain ranges that create the central valley. The western most of these ridges is the Tanaosi range and east of this ridge there is an extensive area of rugged limestone hills.

The northern hills and valleys are made up of north-south oriented hill ridges and high plateaus, alternating with elongated basins. The western part of this sub-region is mainly hilly to mountainous, with wide incised plateaus and narrow inter-montane valleys. To the eastern side, several valleys, including Chiang Mai, Chiang Rai, Lampang, Phrae and Nan are present. Recent and sub-recent alluvial plains occur in the basins and wider plains. Three larger steep limestone areas and a number of craggy limestone ridges are found in the hilly parts, whereas in Lampang and Phrae provinces, three larger volcanic plateaus are observed, with more or less weathered basalt generally at a very shallow depth.

(ii) Central Highlands: This region has a complex physiography, which includes hills, plateaus, peneplains, and a number of valleys. The Central Highlands are bordered to the east by the Northeast Plateau and to the west by the North and West Continental Highlands, the Central Plain, and the Southeast Coast. The boundary between the Central Highlands and the North and West Continental Highlands is somewhat arbitrary.

The northern portion of the region is mainly composed of hills and more or less strongly incised plateau, found at elevation ranging from approximately 300 m to 1,200 m. The plateau areas are undulating to rolling; the intervening hilly areas are steep, with some very steep areas of craggy limestone buttes. The middle part of the Central Highlands comprises low undulating peneplains, which are also interrupted by steep limestone ridges and buttes as in the plateau region. North of Chai Badan, an important volcanic area is found, the central hilly part of which is surrounded by rolling to undulating terrains. The southeastern portion of the Central Highlands includes mainly hilly lands with incised plateaus. Pa Sak River Valley is the most important valley in this region.

(iii) Northeast Plateau: The northeast region, often called The Khorat Plateau, consists of undulating platform approximately 120 to 210 m.a.s.l. in the north and west that gradually declines to about 60 m in the southeast. The Northeast Plateau is mainly composed of river terraces of the Mekong and its tributaries. This region is bordered to the west by the hills and plateau of the Central Highlands, and to the north and east by the Mekong River. The southern boundary along the Thai-Cambodian border is marked by the San Kamphaeng and Dong Rek scarps. The quaternary river terraces have been placed into three categories, i.e. the low, middle and high terraces. The low terrace is dominant in the catchment area of the Mun River system. The northern part of the plateau is predominantly occupied by middle terraces. Isolated remnants of high terrace occur in many parts on the Northeast Plateau. However, the largest area of high terraces occurs south of Nakhon Ratchasima (Khorat). River alluvium of varying widths is found along all streams. The region lies in the rain shadow of the Indochina Cordillera and suffers from shortage of water and has generally thin and poor soils.

(iv) Central Plain: The Central Plain or valley is enclosed by hills and mountains on the east, north and west, and the Gulf of Thailand lies to the south. The valley formed by alluvium deposits of the Chao Phraya River and several of its tributaries and distributaries, extends 365 km from north to south and has an average width of 160-240 km. The south-central part of the region is occupied by the broad alluvial delta of the Chao Phraya River system, and is called as the Bangkok Plain. Quaternary alluvial deposits in the Bangkok Plain reach to a depth of well over 300 m and the surface layers are composed of recent and semi-recent alluvial deposits. Recent and semi-recent fresh water surface sediments dominate in the deltas of the major rivers, including the Chao Phraya River system, the Maeklong and the Pa Sak. Sediments deposited in brackish water dominate a wide zone in the middle of the plain. The Bangkok Plain and the alluvial valleys of the Ping, Wang, Yom and Nan rivers to the north are surrounded by alluvial terraces of different ages. In the southern section of the Central Plain, particularly the lower reaches of the alluvial terraces are of marine origin, and farther north terraces are mainly composed of overlapping alluvial fans from the surrounding highlands. Isolated hills are scattered through the marginal and northern parts of the central plain. The central plain is agriculturally the most productive part of Thailand.

(v) Southeast Coast: This region lies south of the Central Plain and Central Highlands and it borders the Banthat Range in the east by, which also makes the Thai-Cambodian border. The east-central part of the region is formed by dissected highlands, which are a continuation of the Cardaman Mountains of southwest Cambodia. The highlands are surrounded by marine originated terraces in the western and southern side, and shallow river-deposited terraces in the northern side of the region. In the terrace dominated region, numerous isolated hills and ranges are commonly found. Along the coast, small non-connecting marine and brackish water alluvial plains occur. This region has plentiful water supply and the vegetation in most part is lush and tropical.

(vi) Peninsular Thailand: The Peninsular Thailand extends nearly 960 km from the central valley in the north to the boundary of Malaysia in the south and varies in width from 16 to 217 km between the Gulf of Thailand on the east and the Andaman Sea (in Indian Ocean) and Myanmar on the west. There are a number of distinct ranges of hills and mountains en echelon in the region; the Phuket and the Nakhon Si Thammaratare are the two main ranges in the Peninsular Thailand. The landscape between the main ranges is mainly made up of lower hills and of undulating terraces, principally of fluviatile origin. The widest and most pronounced of these depressions stretches from Surat Thani to Trang.

On the west coast, the coastal terraces and plains are narrow, with the mountains extending down to the sea in many places. The coast itself is much indented and often very swampy. The eastern coastal plain is much wider (up to 32 km), and the coast is smooth, with long beach stretches and few bays. The largest coastal plain stretches from Nakhon Si Thammarat to Songkhla, including important elongated beaches and a large lagoon, the Tha-le Sap or Songkhla Lake.Well-watered (especially the west coast), hot, and densely forested, the Peninsula, unlike most of Thailand, lies within the humid tropical forest zone.

4.3 Soils and their major properties

The first provisional soil map of the Kingdom of Thailand was produced in 1946 at a scale 1:1,000,000. Although the information on the western part and in other largely uninhabited mountainous regions was scanty, the first soil map of Thailand was based upon actual field work and laboratory research. In 1949, a soil map was published on a scale of 1:2,500,000 and in 1953 it accompanied an extensive discussion of Thai soils and notes on field work in all sections of the kingdom. Moorman and Rojanasoonthon (1967) improved and amended the soil maps of Thailand by the application of soil units of the Great Soil Group level. Soil maps (1:1,000,000) with soil classification based on the Soil Taxonomy system were produced in 1979 by Dr. Pisoot Vijarnsorn and Mr. Chingchai Jongphakdee[25]. Dr. Pisoot Vijarnsornfurther improved the soil map of Thailand and in 1994 produced a soil classification map (1:1,250,000) using the soil taxonomy system of 1992 (Soil Survey Staff, 1991). We have used this map (A-Figure 20) for the general description of Thai soils in this report. The soil map based on FAO-UNSECO classification system is presented in A-Figure 21.

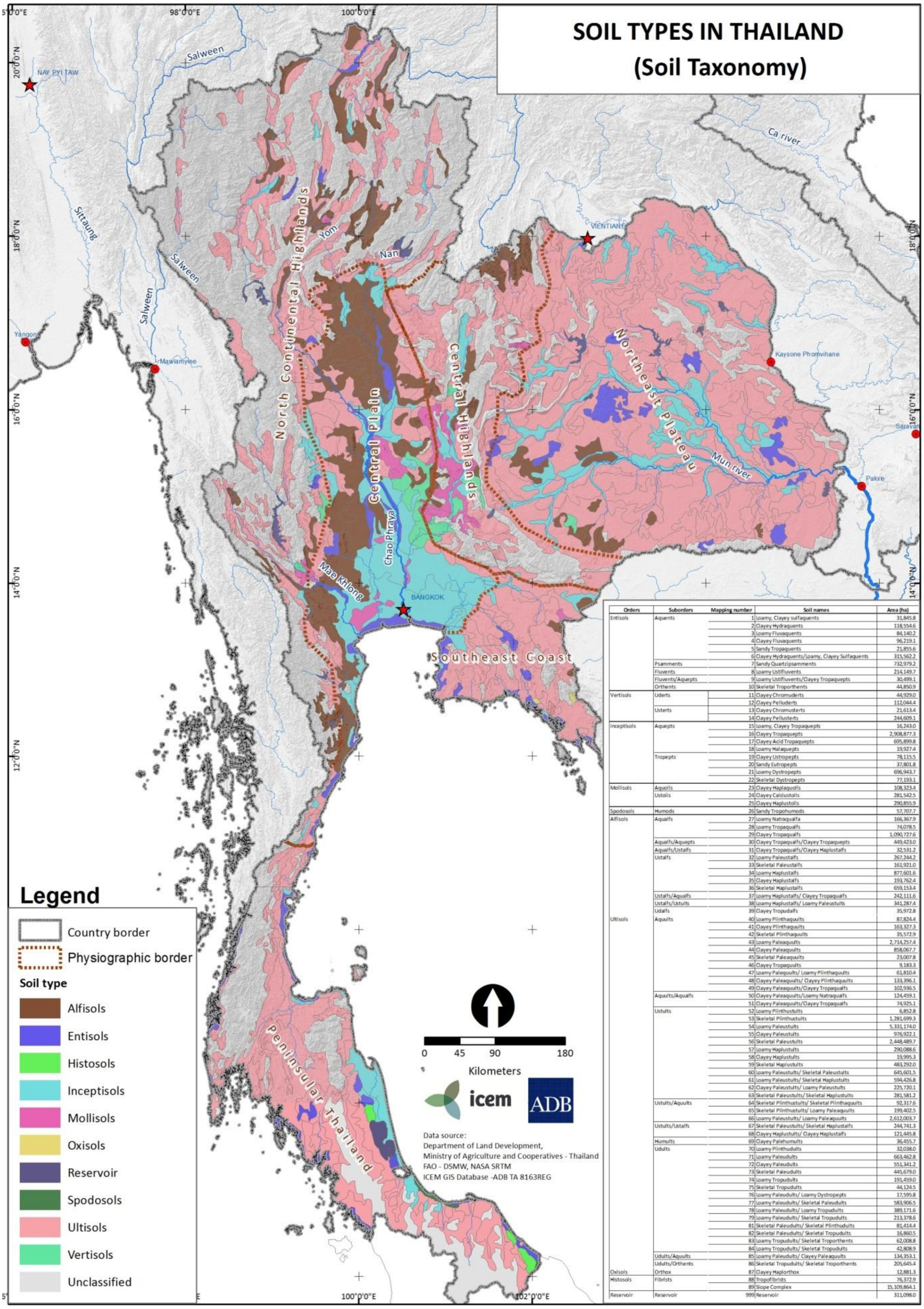
Soils in Thailand fall into 9 orders out of the total 12 soil orders of the Soil Taxonomy. The main features of the soil orders that exist in Thailand are described below and the distribution of the soils is given in A-Figure 20 and A-Table 5.

(i) Alfisols: These soils are moderate to well developed, with characteristics of clay accumulation in the subsoil, i.e. argillic horizon and more than 35% base saturation. These soils develop in areas that are stable for quite a long time without soil disturbance under the humid climate to cause various material movements within the soil but simultaneously, it must be dry enough to limit the loss of base material out of the soil surface. The suborders of Alfisol are distinguished based on soil temperature and soil moisture (Soil Survey Staff, 1991).

Occupying nearly 9% of the land area of Thailand, these soils occur in both lowland and highland, especially where rainfall in not frequent and the humidity between the rainy and dry seasons is very different.

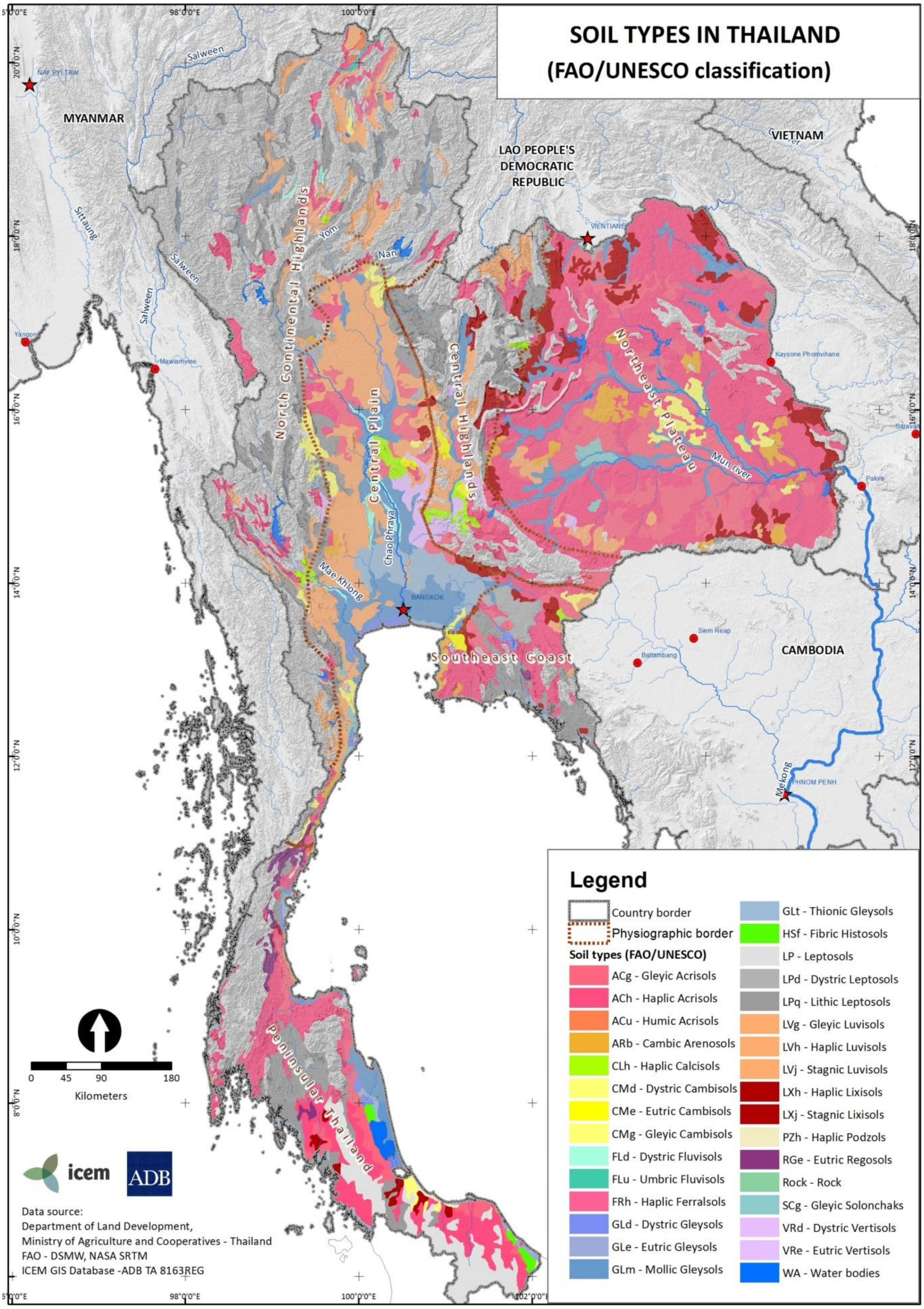
(ii) Entisols: This group's soils are defined by the absence or near absence of horizons; such soils may result from too short time for soil development or in areas such as steep slopes where soils are lost frequently or in areas where sediments are accumulated frequently so that soil horizons cannot be developed. Entisols in Thailand occur in both low- and high-lands covering 3.3% of the total area. Based on their environment, Entisols have been divided into four groups in Thailand: (i) soils in the lowland marshes subjected to sea tide fluctuations; (ii) soils formed on alluvial flood plains, natural water channel bank bar and alluvial fan dune; (iii) sandy soils formed in the continental and coastal vicinities; and (iv) soils in the vicinity of very steep slopes of mountain shoulders where regular loss of soil surface occurs.

[25] http://www.ldd.go.th/ldd_en/en-US/soil-maps/



Orders	Suborders	Mapping number	Soil names	Area (ha)
Entisols	Aquents	1	Loamy, Clayey sulfaquents	31,845.8
		2	Clayey Hydraquents	118,554.6
		3	Loamy Fluvaquents	84,140.2
		4	Clayey Fluvaquents	96,219.1
		5	Sandy Tropaquents	21,855.6
		6	Clayey Hydraquents/Loamy, Clayey Sulfaquents	315,562.2
	Psamments	7	Sandy Quartzipsamments	732,979.2
	Fluvents	8	Loamy Ustifluvents	214,149.7
	Fluvents/Aquepts	9	Loamy Ustifluvents/Clayey Tropaquepts	30,499.1
	Orthents	10	Skeletal Troporthents	44,850.9
Vertisols	Uderts	11	Clayey Chromuderts	44,929.0
		12	Clayey Pelluderts	112,044.4
	Usterts	13	Clayey Chromusterts	21,613.4
		14	Clayey Pellusterts	244,609.1
Inceptisols	Aquepts	15	Loamy, Clayey Tropaquepts	16,243.0
		16	Clayey Tropaquepts	2,908,877.3
		17	Clayey Acid Tropaquepts	695,899.8
		18	Loamy Halaquepts	19,927.4
	Tropepts	19	Clayey Ustropepts	78,115.5
		20	Sandy Eutropepts	37,801.8
		21	Loamy Dystropepts	696,943.7
		22	Skeletal Dystropepts	77,193.1
Mollisols	Aquolls	23	Clayey Haplaquolls	108,323.4
	Ustolls	24	Clayey Caldustolls	281,542.5
		25	Clayey Haplustolls	290,855.9
Spodosols	Humods	26	Sandy Tropohumods	57,707.7
Alfisols	Aqualfs	27	Loamy Natraqualfa	166,367.9
		28	Loamy Tropaqualfs	74,078.5
		29	Clayey Tropaqualfs	1,090,727.6
	Aqualfs/Aquepts	30	Clayey Tropaqualfs/Clayey Tropaquepts	449,423.0
	Aqualfs/Ustalfs	31	Clayey Tropaqualfs/Clayey Haplustalfs	32,531.2
	Ustalfs	32	Loamy Paleustalfs	267,244.2
		33	Skeletal Paleustalfs	161,921.0
		34	Loamy Haplustalfs	877,601.6
		35	Clayey Haplustalfs	193,762.4
		36	Skeletal Haplustalfs	659,153.4
	Ustalfs/Aqualfs	37	Loamy Haplustalfs/ Clayey Tropaqualfs	242,111.6
	Ustalfs/Ustults	38	Loamy Haplustalfs/ Loamy Paleustults	341,287.4
	Udalfs	39	Clayey Tropudalfs	35,972.8
Ultisols	Aquults	40	Loamy Plinthaquults	87,824.4
		41	Clayey Plinthaquults	163,327.3
		42	Skeletal Plinthaquults	35,572.9
		43	Loamy Paleaquults	2,714,257.4
		44	Clayey Paleaquults	858,067.7
		45	Skeletal Paleaquults	23,007.8
		46	Clayey Tropaquults	9,183.3
		47	Loamy Palequults/ Loamy Plinthaquults	61,810.4
		48	Clayey Paleaquults/ Clayey Plinthaquults	133,396.1
		49	Clayey Paleaquults/Clayey Tropaqualfs	102,936.5
	Aquults/Aqualfs	50	Clayey Paleaquults/Loamy Natraqualfs	124,459.1
		51	Clayey Paleaquults/Clayey Tropaqualfs	74,925.1
	Ustults	52	Loamy Plinthustults	6,852.8
		53	Skeletal Plinthustults	1,281,699.3
		54	Loamy Paleustults	5,331,174.0
		55	Clayey Paleustults	976,922.1
		56	Skeletal Paleustults	2,448,489.7
		57	Loamy Haplustults	290,088.6
		58	Clayey Haplustults	19,995.3
		59	Skeletal Haplustults	483,292.0
		60	Loamy Paleustults/ Skeletal Paleustults	645,601.5
		61	Loamy Paleustults/ Skeletal Haplustults	594,426.8
		62	Clayey Paleustults/ Loamy Paleustults	225,720.1
		63	Skeletal Paleustults/ Skeletal Haplustults	281,581.2
	Ustults/Aquults	64	Skeletal Plinthustults/ Skeletal Plinthaquults	92,317.6
		65	Skeletal Plinthustults/ Loamy Paleaquults	199,402.5
		66	Loamy Paleustults/ Loamy Paleaquults	2,612,003.7
	Ustults/Ustalfs	67	Skeletal Paleustults/ Skeletal Haplustalfs	244,741.3
		68	Clayey Haplustults/ Clayey Haplustalfs	121,445.8
	Humults	69	Clayey Palehumults	36,455.7
	Udults	70	Loamy Plinthudults	32,038.0
		71	Loamy Paleudults	663,462.8
		72	Clayey Paleudults	551,341.2
		73	Skeletal Paleudults	445,679.0
		74	Loamy Tropudults	191,459.0
		75	Skeletal Tropudults	44,124.5
		76	Loamy Paleudults/ Loamy Dystropepts	17,595.8
		77	Loamy Paleudults/ Skeletal Paleudults	583,906.5
		78	Loamy Paleudults/ Loamy Tropudults	389,171.6
		79	Loamy Paleudults/ Skeletal Tropudults	213,378.6
		81	Skeletal Paleudults/ Skeletal Plinthudults	81,414.4
		82	Skeletal Paleudults/ Skeletal Tropudults	16,860.5
		83	Loamy Tropudults/ Skeletal Troporthents	62,008.8
		84	Loamy Tropudults/ Skeletal Tropudults	42,808.9
	Udults/Aquults	85	Loamy Paleudults/ Clayey Paleaquults	134,353.1
	Udults/Orthents	86	Skeletal Tropudults/ Skeletal Troporthents	205,645.4
Oxisols	Orthox	87	Clayey Haplorthox	12,881.3
Histosols	Fibrists	88	Tropofibrists	76,372.9
		89	Slope Complex	15,109,864.1
Reservoir	Reservoir	999	Reservoir	311,098.0

A-Figure 19: The distribution of different soil types according to the Soil classification system in Thailand (Soil Survey Staff, 1991).



A-Figure 20: The distribution of different soil types according to the FAO-UNESCO classification system in Thailand (FAO, 1997).

A-Table 5: The extent of distribution of soil types according to the USDA and the FAO-UNESCO classification (FAO, 1997) in Thailand.

USDA Orders & sub-orders	Mapping number	Local soil names	FAO Units & Sub-units	Area (ha)	Area (%)
Entisols			**Gleysols**		
Aquents	1	Loamy, Clayey sulfaquents	Thionic Gleysoils	31,858	0.06
	2	Clayey Hydraquents	Dystric Gleysoils	118,555	0.23
	3	Loamy Fluvaquents	Eutric Gleysols	84,140	0.16
	4	Clayey Fluvaquents	Dystric Gleysols	96,219	0.19
	5	Sandy Tropaquents	Thionic Gleysols	21,856	0.04
	6	Clayey Hydraquents or Loamy, Clayey Sulfaquents	Thionic Gleysols	316,650	0.62
			Arenosols		
Psamments	7	Sandy Quartzipsamments	Cambic Arenols	733,016	1.42
			Fluvisols		
Fluvents	8	Loamy Ustifluvents	Dystric Fluvisols	214,150	0.42
Fluvents/ Aquepts	9	Loamy Ustifluvents or Clayey Tropaquepts	Umbric Fluvisols	30,499	0.06
			Regosols		
Orthents	10	Skeletal Troporthents	Eutric Regosols	44,851	0.09
Vertisols			**Vertisols**		
Uderts	11	Clayey Chromuderts	Dystric Vertisols	44,929	0.09
	12	Clayey Pelluderts	Eutric Vertisols	112,044	0.22
Usterts	13	Clayey Chromusterts	Dystric Vertisols	21,613	0.04
	14	Clayey Pellusterts	Eutric Vertisols	244,609	0.48
Inceptisols			**Cambisols**		
Aquepts	15	Loamy, Clayey Tropaquepts	Gleyic Cambisols	16,243	0.03
			Gleysols		
	16	Clayey Tropaquepts	Mollic Gleysols	2,908,898	5.65
	17	Clayey Acid Tropaquepts	Thionic Gleysols	695,900	1.35
	18	Loamy Halaquepts	Mollic Gleysols	19,927	0.04
			Cambisols		
Tropepts	19	Clayey Ustropepts	Eutric Cambisols	78,116	0.15
	20	Sandy Eutropepts	Eutric Cambisols	37,802	0.07
	21	Loamy Dystropepts	Dystric Cambisols	696,989	1.35
	22	Skeletal Dystropepts	Dystric Cambisols	77,193	0.15
Mollisols			**Luvisols**		
Aquolls	23	Clayey Haplaquolls	Gleyic Luvisols	108,323	0.21
			Calcisol		
Ustolls	24	Clayey Calciustolls	Haplic Calcisols	281,543	0.55
			Luvisols		
	25	Clayey Haplustolls	Haplic Luvisols	290,856	0.57
Spodosols			**Podzols**		
Humods	26	Sandy Tropohumods	Haplic Podzols	58,390	0.11

Alfisols			**Solonchaks**		
Aqualfs	27	Loamy Natraqualfs	Gleyic Solonchaks	166,368	0.32
			Luvisols		
	28	Loamy Tropaqualfs	Gleyic Luvisols	74,078	0.14
	29	Clayey Tropaqualfs	Gleyic Luvisols	1,090,728	2.12
Aqualfs/ Tropohumods	30	Clayey Tropaqualfs or Clayey Tropaquepts	Gleyic Luvisols	449,423	0.87
Aqualfs/Ustalf s	31	Clayey Tropaqualfs or Clayey Haplustalfs	Gleyic Luvisols	32,531	0.06
Ustalfs	32	Loamy Paleustalfs	Haplic Luvisols	267,244	0.52
	33	Skeletal Paleustalfs	Stagnic Luvisols	161,921	0.31
	34	Loamy Haplustalfs	Haplic Luvisols	877,606	1.71
	35	Clayey Haplustalfs	Haplic Luvisols	193,762	0.38
	36	Skeletal Haplustalfs	Stagnic Luvisols	659,153	1.28
Ustalfs/Aqualf s	37	Loamy Haplustalfs or Clayey Tropaqualfs	Gleyic Luvisols	242,112	0.47
Ustalfs/Ustult s	38	Loamy Haplustalfs or Loamy Paleustults	Haplic Luvisols	341,287	0.66
Udalfs	39	Clayey Tropudalfs	Haplic Luvisols	35,973	0.07
Ultisols			**Lixisols**		
Aquults	40	Loamy Plinthaquults	Stagnic Lixisols	87,824	0.17
	41	Clayey Plinthaquults	Stagnic Lixisols	163,327	0.32
	42	Skeletal Plinthaquults	Stagnic Lixisols	35,573	0.07
			Acrisols		
	43	Loamy Paleaquults	Gleyic Acrisols	2,714,257	5.28
	44	Clayey Paleaquults	Gleyic Acrisols	858,068	1.67
	45	Skeletal Paleaquults	Gleyic Acrisols	23,008	0.04
	46	Clayey Tropaquults	Gleyic Acrisols	9,183	0.02
	47	Loamy Palequults or Loamy Plinthaquults	Gleyic Acrisols	61,844	0.12
	48	Clayey Paleaquults or Clayey Plinthaquults	Gleyic Acrisols	133,396	0.26
	49	Clayey Paleaquults or Clayey Tropaqualfs	Gleyic Acrisols	102,936	0.20
Aquults/Aqual fs	50	Clayey Paleaquults or Loamy Natraqualfs	Gleyic Acrisols	124,459	0.24
	51	Clayey Paleaquults or Clayey Tropaqualfs	Gleyic Acrisols	74,925	0.15
			Lixisols		
Ustults	52	Loamy Plinthustults	Haplic Lixisols	6,853	0.01
	53	Skeletal Plinthustults	Haplic Lixisols	1,281,699	2.49
			Acrisols		
	54	Loamy Paleustults	Haplic Acrisols	5,331,174	10.36
	55	Clayey Paleustults	Haplic Acrisols	976,922	1.90
			Leptosols		
	56	Skeletal Paleustults	Lithic Leptosols	2,448,490	4.76
			Acrisols		
	57	Loamy Haplustults	Haplic Acrisols	290,089	0.56

	58	Clayey Haplustults	Haplic Acrisols	19,995	0.04
			Leptosols		
	59	Skeletal Haplustults	Dystric Leptosols	483,292	0.94
	60	Loamy Paleustults or Skeletal Paleustults	Lithic Leptosols	645,846	1.26
	61	Loamy Paleustults or Skeletal Haplustults	Lithic Leptosols	594,427	1.16
			Acrisols		
	62	Clayey Paleustults or Loamy Paleustults	Haplic Acrisols	225,720	0.44
			Leptosols		
	63	Skeletal Paleustults or Skeletal Haplustults	Dystric Leptosols	281,581	0.55
			Lixisols		
Ustults/Aquults	64	Skeletal Plinthustults or Skeletal Plinthaquults	Haplic Lixisols	92,318	0.18
	65	Skeletal Plinthustults or Loamy Paleaquults	Haplic Lixisols	199,402	0.39
			Acrisols		
	66	Loamy Paleustults or Loamy Paleaquults	Haplic Acrisols	2,612,004	5.08
			Leptosols		
Ustults/Ustalfs	67	Skeletal Paleustults or Skeletal Haplustalfs	Dystric Leptosols	244,741	0.48
			Acrisols		
	68	Clayey Haplustults or Clayey Haplustalfs	Haplic Acrisols	121,446	0.24
Humults	69	Clayey Palehumults	Humic Acrisols	36,456	0.07
			Lixisols		
Udults	70	Loamy Plinthudults	Haplic Lixisols	32,042	0.06
			Acrisols		
	71	Loamy Paleudults	Haplic Acrisols	663,499	1.29
	72	Clayey Paleudults	Haplic Acrisols	551,461	1.07
			Leptosols		
	73	Skeletal Paleudults	Lithic Leptosols	445,835	0.87
			Acrisols		
	74	Loamy Tropudults	Haplic Acrisols	191,459	0.37
			Leptosols		
	75	Skeletal Tropudults	Lithic Leptosols	44,124	0.09
			Acrisols		
	76	Loamy Paleudults or Loamy Dystropepts	Haplic Acrisols	17,681	0.03
			Leptosols		
	77	Loamy Paleudults or Skeletal Paleudults	Lithic Leptosols	583,906	1.13
			Acrisols		
	78	Loamy Paleudults or Loamy Tropudults	Haplic Acrisols	389,172	0.76
	79	Loamy Paleudults or Skeletal Tropudults	Haplic Acrisols	213,379	0.41

	81	Skeletal Paleudults or Skeletal Plinthudults	Haplic Acrisols	81,414	0.16
			Leptosols		
	82	Skeletal Paleudults or Skeletal Tropudults	Lithic Leptosols	16,860	0.03
	83	Loamy Tropudults or Skeletal Troporthents	Lithic Leptosols	62,009	0.12
	84	Loamy Tropudults or Skeletal Tropudults	Lithic Leptosols	42,809	0.08
			Acrisols		
Udults/Aquult s	85	Loamy Paleudults or Clayey Paleaquults	Haplic Acrisols	134,353	0.26
			Regosols		
Udults/Orthen ts	86	Skeletal Tropudults or Skeletal Troporthents	Eutric Regosols	205,645	0.40
Oxisols			**Ferralsols**		
Orthox	87	Clayey Haplorthox	Haplic Ferralsols	12,881	0.03
Histosols			**Histosols**		
Fibrists	88	Tropofibrists	Fibric Histosols	76,373	0.15
Slope Complex	89	Slope Complex	**Leptosols**	15,113,557	29.38
Reservoir			**Water Body**	311,098	0.60
Grand Total				51,448,169	100.00

(iii) Inceptisols: These soils have a minimal development of horizons. The environmental conditions that inhibit the soil development in Inceptisols are similar to the Entisols. In Thailand, Inceptisols covers 8.8% of the area and are found in both the lowlands and mountainous areas. However, occurrence of Inceptisols is more widespread in the lowland particularly in the vicinity of the central plain.

(iv) Vertisols: These are clay-rich soils that undergo significant vertical cracking when drying. Within subsoils, soil aggregates develop glossy smooth surfaces (slickensides) due to the soil's elongation and shrinkage from wetting and drying of the soil, respectively. Vertisols covers less than 0.9% area in Thailand; these soils occur in the central plain, central high mountainous range, the high plateaus of the northern and northeastern parts of the country. The parent materials in the vicinities of these soils have high base content or are influenced directly from the base reactive rocks such as limestone, marl, basalt and andecites.

(v) Histosols: Histosols are present over 0.15% of the area in Thailand, covering mostly mountainous terrain on the eastern side of the country over the whole length of the country. These soils have a very high content of organic C in the top one metre of the soil and thus are considered to be organic rather than mineral soils. Histosols are formed from the accumulation of organic matter under waterlogged conditions typical of peat bogs and swamps. Under such conditions, the accumulated organic materials and their decomposition products are preserved, resulting in soils of high organic content.

(vi) Spodosols: These soils are characterised by the presence of a spodic sub-horizon, which represents accumulation of a mixture of organic matter with Al and/or Fe oxides. The surface soil is made up of a grey sand layer with acid reaction. This soil always occurs in areas with adequate rainfall to cause movement of material from the topmost of soil surface to be accumulated in the subsoil; additionally there must be organic matter and sandy parent material. In Thailand, these soils are mostly scattered (0.1% area) around the southern part, south-eastern coast and the upper part of the north-eastern region especially along Mekong River.

(vii) Mollisols: Mollisols have a significant accumulation of humus in the surface horizon usually formed under native grass vegetation. Natural grass land vegetation and climatic conditions that do not promote the continuous washing process so that divalent cations, particularly calcium (Ca^{2+}), accumulate in the soil. These soils cover about 1.3% of the area in Thailand and they exist only the vicinity of the parent material source having alkaline reaction. Mollisols occur in swamps that have previously been subject to the fluctuation of sea tide and arisen from the alkaline sediments and in the vicinity of high mountainous range in the central and northern part of Thailand.

(viii) Oxisols: These soils have an oxic or kandic horizon that contains kaolin-group clay minerals and Fe/Al oxides in a finely textured matrix with very little or no easily weathered silicates. Such soils result from strong and prolonged in-situ weathering of the parent rock. The mineral components found in most of these soils have low activities such as, kaolinite, Fe and/or Al oxides and quartz. Oxisols in Thailand are dispersed in few areas (0.03%) mostly in the Northern Continental Highlands, Central Highlands, Southeast Coast and Peninsular Thailand. Most of the Oxisols occur on basalt or shale in association with limestone.

(ix) Ultisols: Similar to Alfisols, Ultisols have an argillic or a kandic horizon, however, these soils more developed and more leached than the Alfisols. Ultisols are highly leached and typically exist on older and stable landscapes in humid, temperate and tropical areas. Intense weathering of primary minerals has leached much of Ca, Mg, and K from these soils. Ultisols have a subsurface horizon in which clays have accumulated, often with strong yellowish or reddish colours resulting from the presence of Fe oxides.

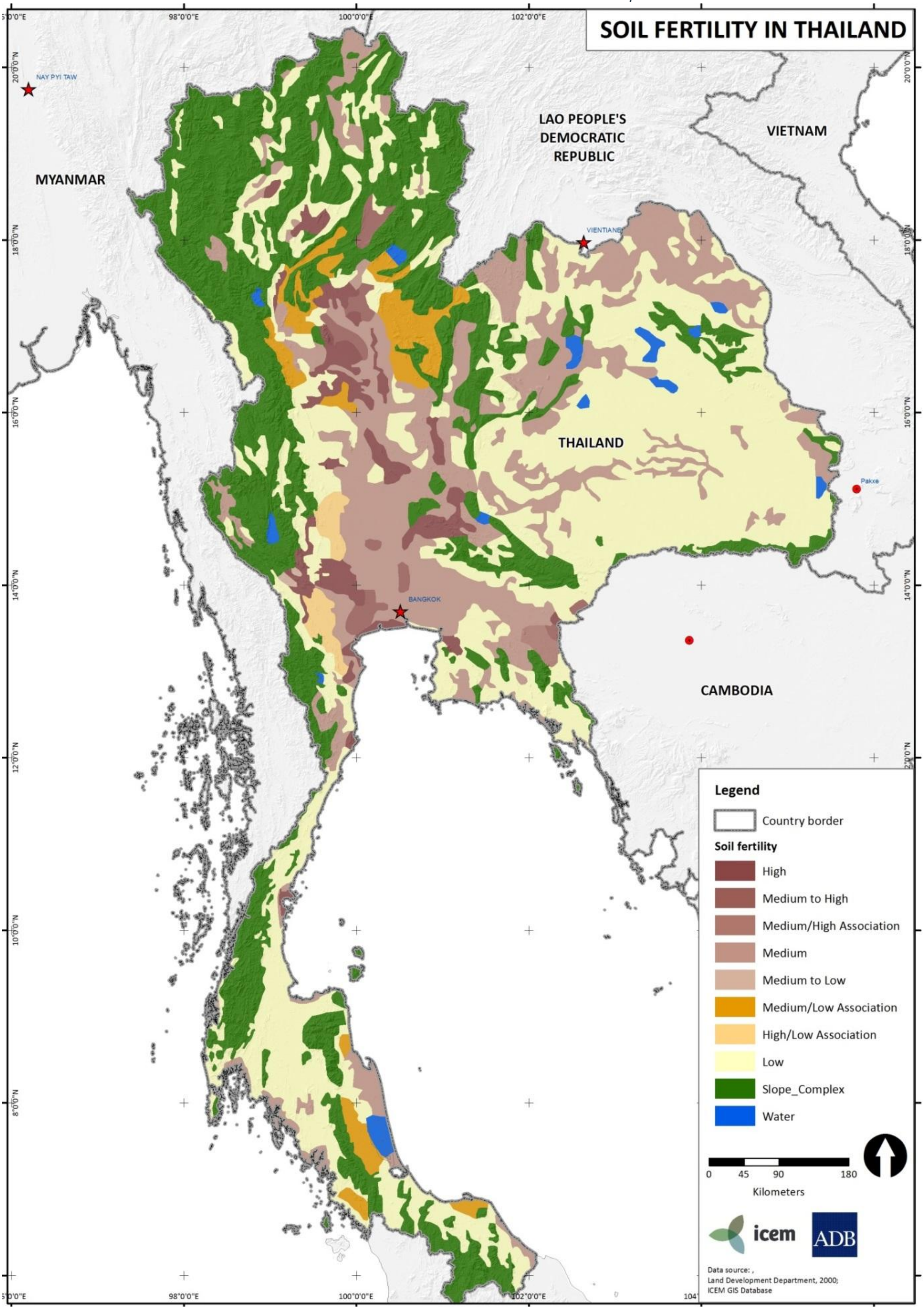
Ultisols are the most dominant soils in Thailand covering 46.6% of the area. These soils are found in large areas of the northeastern, southeastern coast and southern part of the country. Ultisols are also prevalent in the central and northern parts, and exist both in the high and low-lands.

4.4 Soil fertility status

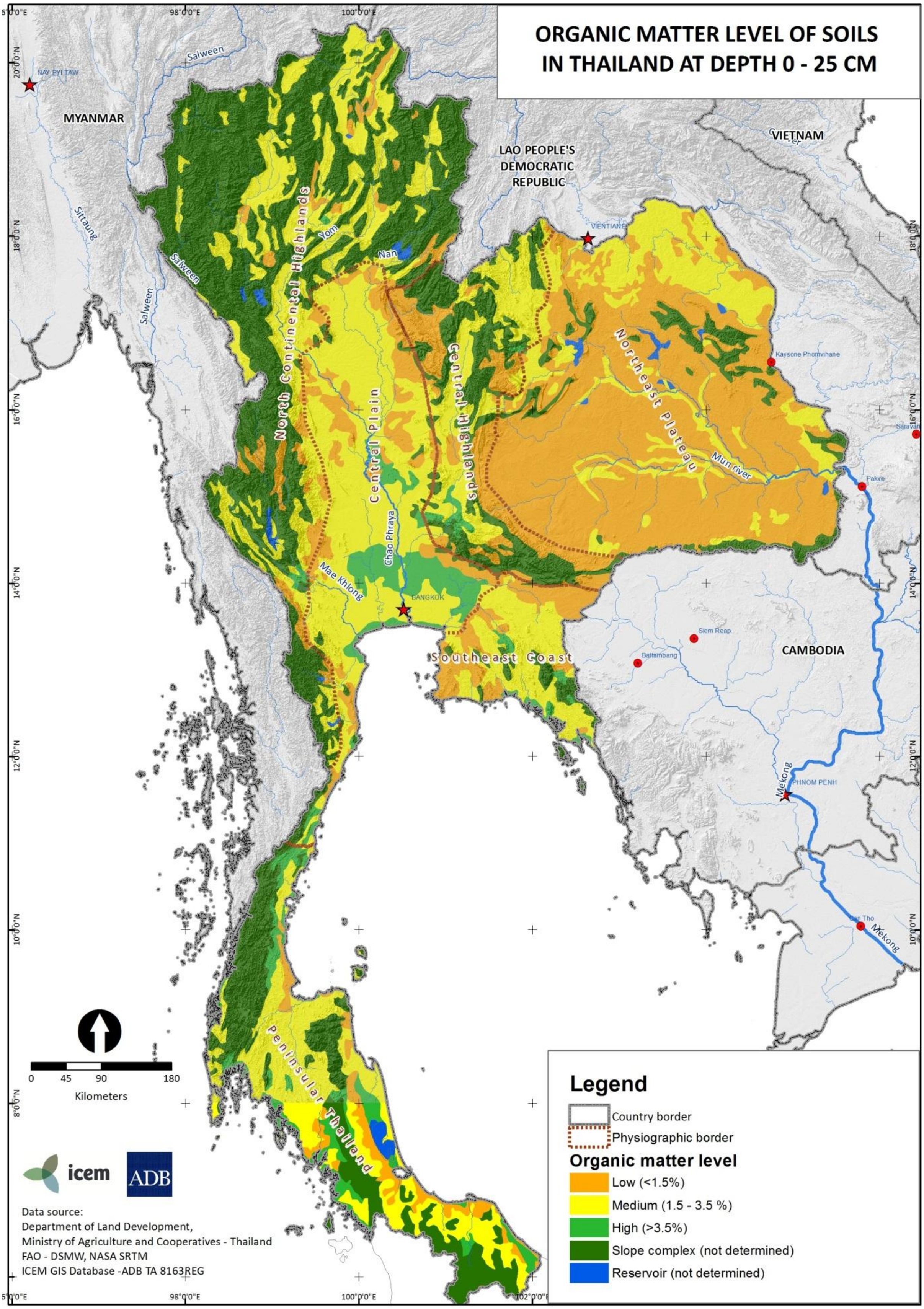
Most soils in Thailand have low or medium fertility (A-Figure 22), largely as a result of intense leaching caused by heavy rainfall. However, there are variations in the fertility status of different soil types, particularly due to differences in the parent material, amount of rainfall, the length of wet and dry seasons and land use. A large portion of the mountainous area in Thailand is occupied by stony and shallow (Slope Complex/Leptosols) soils, which are poor in nutrient supply. These soils have been traditionally used by hill peoples for shifting cultivation to restore soil fertility. The valley soils are generally better, some with fairly high or moderate fertility; these are used mainly to grow irrigated rice. Shallow lighter textured (sandy to sandy loams) soils cover a large part of the Khorat Plateau; these soils have generally low fertility. Most soils in the Khorat Plateau are Ultisols; these are highly weathered soil with low inherent fertility. Alluvial soils along the major rivers are generally more fertile. The central plain and the delta of the Mae Nam (river) Chao Phraya have clayey soils of high to moderate fertility. Low-lying and flat, much of the area is flooded during the rainy season. Higher areas on the edges of the plain are generally well-drained soils of high to moderate fertility that are suitable for intensive cultivation. There are some well-drained clayey and loamy soils with moderate soil fertility levels in parts of the peninsula.

According to the Land Development Department in Thailand, approximately 51% of Thai soils are classified as problem soils. Common soil constraints or soil with soil constraints includes – low soil organic matter, soil erosion, soil salinity, acid sulfate soils, sandy texture and shallow soils. Except for soils from mountainous region, the organic matter contents in Thai soils is low (< 1.5%) to medium (1.5-3.5%) (A-Figure 23). Most soils in the Khorat Plateau have low organic matter content. Due to their low organic matter content, sandy texture, highly weathered nature and low CEC, the soils in the Khorat Plateau have very low to low fertility status. They are characterised by a low level of plant nutrients particularly of N, P, K and S while Cu, and Mo are limiting in some soils (Topark-Ngarm and Gutteridge, 1986). The mountainous soils, particularly where slopes are steeper than 35%, have severe erosion problems. In the south, most soils are infertile and deficient in the major nutrients – N, P, K, S, Mg and micronutrients – Zn and Cu (Sophanodora 1995, 1997). Studies of legume crops in farmers' fields in Thailand have shown that a high proportion suffer from one or more deficiencies of the macro-elements N, P, K and S and the micronutrients – B and Mo (Bell et al., 1990). These low nutrient levels would undoubtedly reduce productivity of forage legumes according to species, site and management.

Salt affected soils exist in the coastal regions and inland parts of Thailand. The coastal saline soils mostly occur in the peninsula, along the coast in the areas that the tide can still reach or previously inundated by the sea that had caused salt accumulation in the soil. The inland saline soils are found mostly in the low lying areas or at the shoulders of mounds in the north-eastern part of Thailand, and occasionally in some provinces of the central part of the country. Acid sulfate soils occur in parts of the coastal lowlands, main areas include the southern part of the Central Plain, eastern part and along the South Coast. In the Chao Phraya Delta of Thailand, acid sulfate soils occupy an area of 600,000 ha.



A-Figure 21: Soil fertility status of soils in Thailand.



A-Figure 22: Organic matter content in the surface soils (0-25 cm) of Thailand.

5. MYANMAR

5.1 General introduction

Myanmar is situated between latitudes 09° 32' to 28°31' north and longitudes 92°10' to 101° 11' east. It is the largest country in mainland south-east Asia with a total area of 676,590 km^2. The total population of Myanmar is about 53.3 million[26]

Myanmar shares its border with People's Republic of China, Lao PDR, Thailand, Bangladesh and India. Most of Myanmar lies between the Tropic of Cancer and the Equator, and it is dominated by the south west monsoon. Myanmar has three well-defined seasons – the monsoon or rainy season, from May to October; the cool season, from November to February; and the hot season, generally from March to April[27]. The average annual rainfall in Myanmar varies considerably both seasonally and totally due to the influence of the height and direction of mountain ranges running from north to south. The annual rainfall in the coastal and deltaic regions is very high (up to 5,000 mm) whereas it is only about 600 mm in the central dry zone[28]. During the summer season, the highest temperature in the central Myanmar is above 43° C while it is about 36° C in northern part and 29°C on Shan Plateau in the east. The annual mean temperature in Myanmar is 27°C[23]. The northern regions of Myanmar are the coolest, with average temperatures of 21°C, and the coastal and delta regions are generally hot and humid with an average temperature of 32°C.

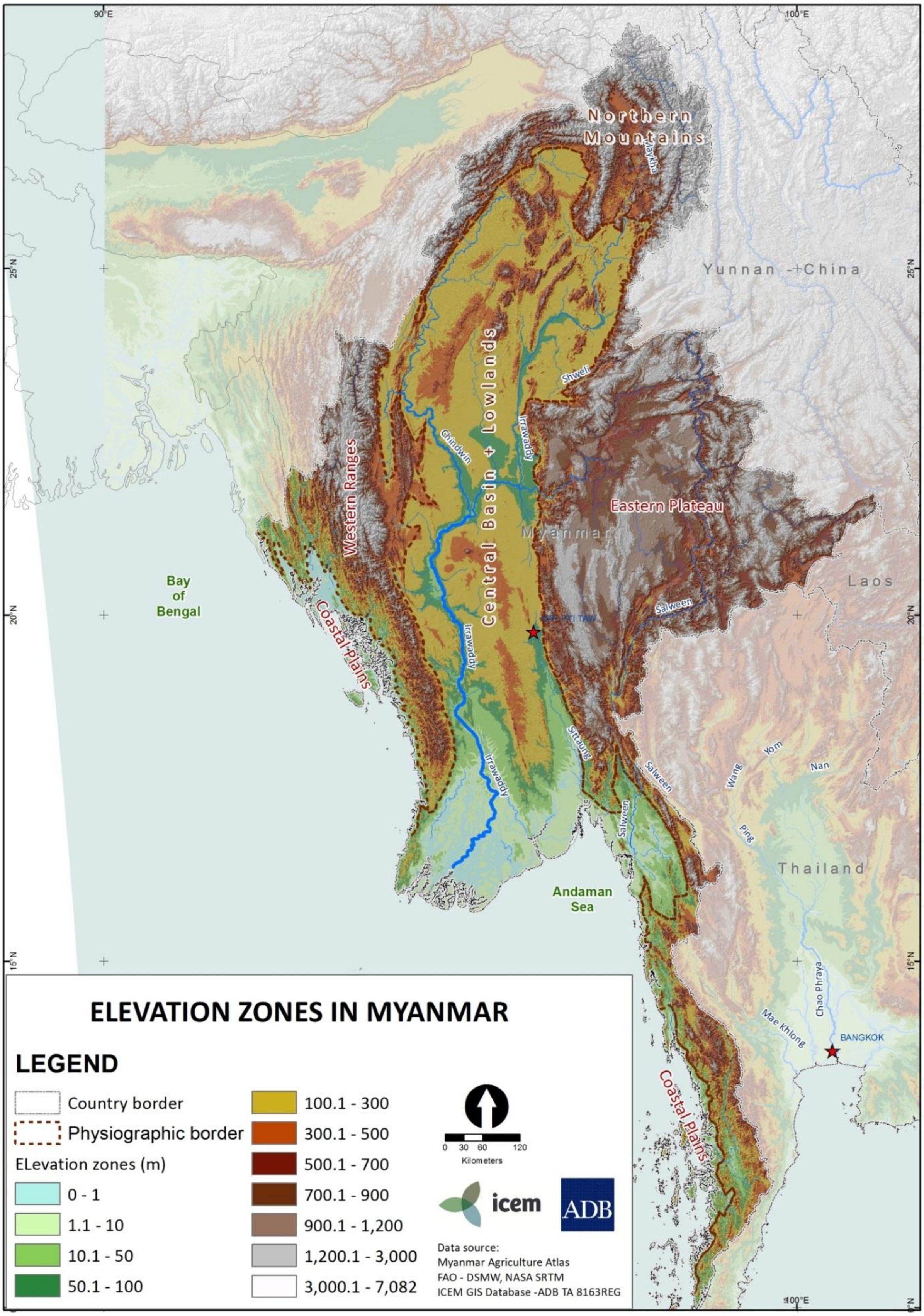
Myanmar slopes downward in elevation from the north to the south (A-Figures 24 and 25), and it is naturally divided into "Upper Myanmar" and "Lower Myanmar" (Hadden, 2008). The country's terrain consists of central lowlands ringed by steep, rugged highlands. Hengduan Shan Mountains are situated in the north forming the border with People's Republic of China. Mount Hkakabo Razi is the highest point in the country and it is located at an elevation of 5,881 m. The mountain ranges in Myanmar generally run from north to south as well. In the northern part of Myanmar, there are three parallel chains of mountain ranges beginning at the eastern end of the Himalayas and running from north to south: these are the Rakhine Yoma, the Bago Yoma and the Shan Plateau. The northern mountain chains divide the country into three river systems: the Irrawaddy (Ayeyarwady), the Sittoung (Sittang) and the Thanlwin (Salween). The Irrawaddy River is Myanmar's longest river, nearly 2,170 km long, and it flows through the country and into the Gulf of Martaban. Fertile plains exist in the valleys between the mountain chains. The majority of Myanmar's population lives in the Irrawaddy valley, which is situated between the Rakhine Yoma and the Shan Plateau.

5.2 Physiography

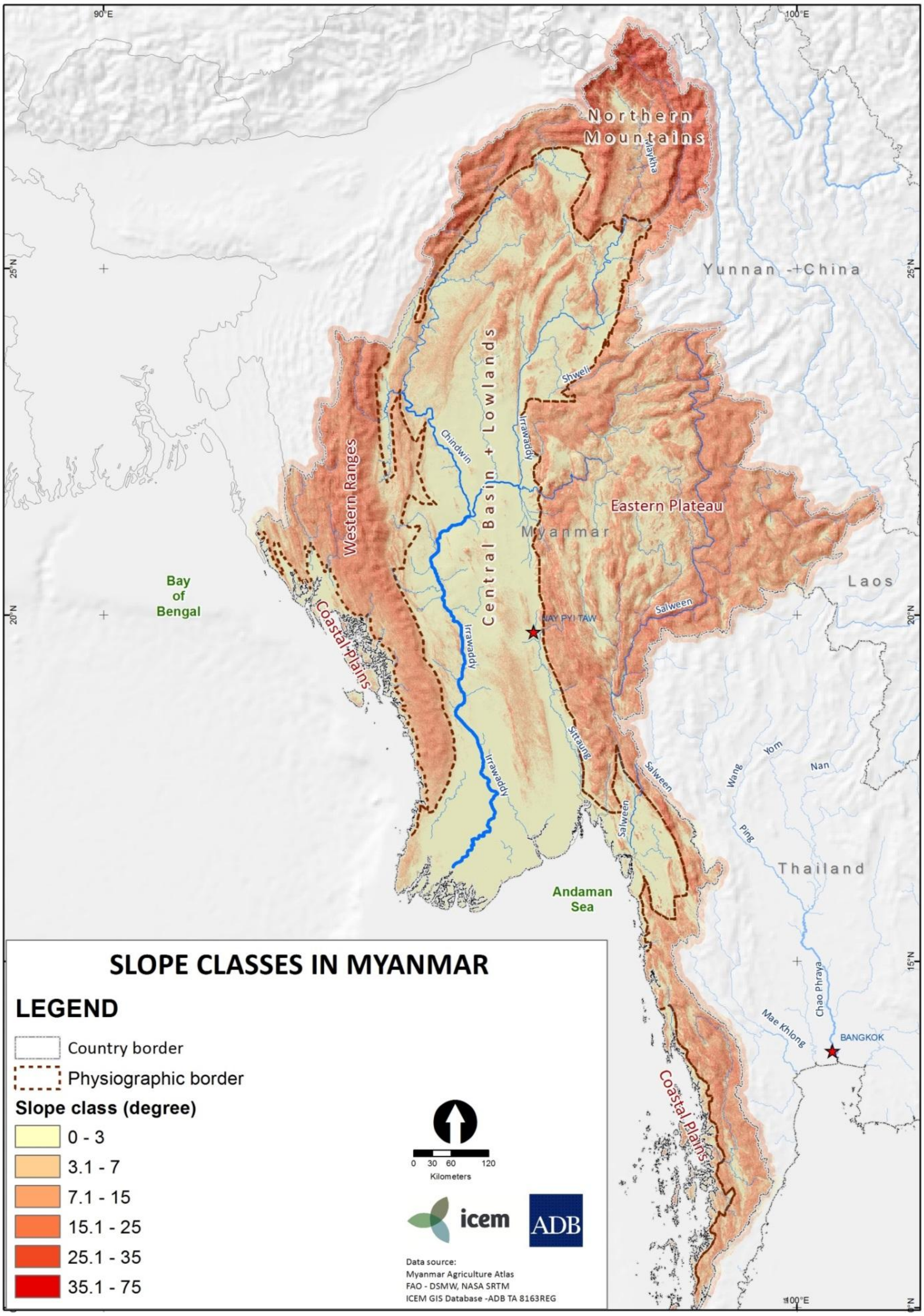
Myanmar can be divided into five physiographic regions (Hadden, 2008; Tun and Than, 1996): the northern mountains; the western ranges; the eastern plateau; the central basin and lowlands, and the coastal plains (A-Figures 24 and 25).

---

[26] http://www.fao.org/nr/water/aquastat/data/cf/readPdf.html?f=MMR-CF_eng.pdf
[27] http://www.encyclopedia.com/topic/Myanmar.aspx
[28] http://en.wikipedia.org/wiki/Burma



A-Figure 23: The elevation map of Myanmar showing mountains surrounding the central basin consisting of major rivers of the country.



A-Figure 24: Slope classes and physiographic regions in Myanmar showing mountains surrounding the central basin and lowlands.

(i) Northern Mountains: The Northern Mountains consist of a series of ranges that form a geological complex or “geologic knot” at Mount Hkakabo. In terms of plate tectonics, this knot marks the northeastern limit of the encroaching Indian-Australian Plate, which has been pushing into the southern edge of the Eurasian Plate for approximately the past 50 million years and thrusting up the mountain ranges of Myanmar and beyond. The northern mountains contain the sources of several of Asia's great rivers, including the Irrawaddy, which rises and flows wholly within Myanmar, and the Salween, which rises to the north in People's Republic of China. The upper courses of these rivers all flow through deep gorges within a short distance of each other, separated by steep, sheer peaks.

(ii) Western Ranges: The Western Ranges traverse the entire western side of Myanmar, from the northern mountains to the southern tip of the Rakhine (Arakan) Peninsula, where they run under the sea and reappear as the Andaman and Nicobar Islands (Indian Territories). The average elevation of the Western Ranges is about 1,800 m, although some peaks are as high as 3,000 m or higher. These mountains consist of old crystalline rocks surrounded by hard, tightly folded sedimentary rocks on either side. From north to south, the Patkai Range, Naga Hills, and Chin Hills form the border between India and Myanmar. To the south of these are the Rakhine Mountains (Arakan Mountains), which are situated entirely within Myanmar and separate the coastal strip from the central basin.

(iii) Eastern Plateau: The Eastern Plateau or The Shan Plateau occupies the eastern half of the country and the average elevation of this region is about 900 m. The Shan Plateau rises abruptly from the central basin, often in a single step of about 600 m. The plateau was formed during the Mesozoic Era (250 to 65 million years ago) and thus is a much older feature than the western mountains. However, the plateau also shows more recent and intensive folding, with north-south longitudinal ranges rising steeply to elevations of 1,800 to 2,600 m above the plateau surface. Northward, the plateau merges into the Northern Mountains, and southward it continues into the Dawna Range and the peninsular Tenasserim Mountains (Tanintharyi Mountains), each a series of parallel ranges with narrow valleys.

(iv) Central Basin and Lowlands: The Central Basin and Lowlands lie between the Rakhine Mountains and the Shan Plateau and these are structurally connected with the folding of the Western Ranges. The basin was deeply excavated by ancient rivers. Irrawaddy, Chindwin, and Sittang rivers currently occupy the basin and the alluvial deposits of these rivers cover the ancient soft sandstones, shales, and clays.

The landscape in the deltas is formed by the Irrawaddy and Sittang rivers, which is absolutely flat, with occasional blocks of erosion-resistant rocks that are never more than 20 m high. The Bago Mountains divides the basin into two unequal parts, the larger Irrawaddy valley and the smaller Sittang valley. In the centre of the basin and structurally connected with the Bago Mountains and their northern extension is a line of extinct volcanoes with small crater lakes and eroded cones, the largest being Popa Hill at 1,518 m.

(vi) Coastal Plains: The Coastal Plains consist of the narrow Rakhine and Tenasserim plains, which are backed by the high ranges of the Rakhine and Tenasserim mountains, respectively. Both plains are fringed with numerous islands of varying sizes.

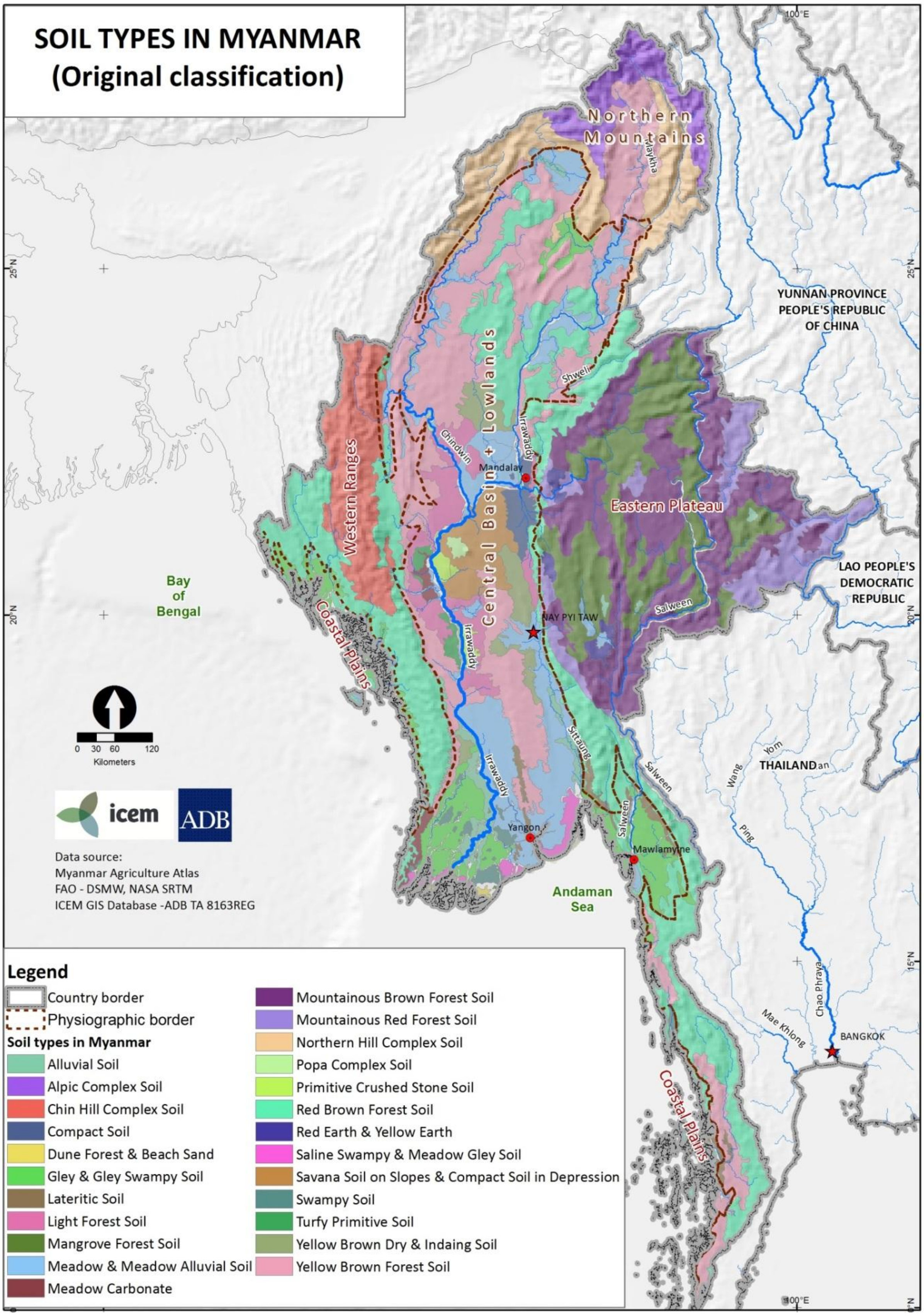
5.3 Soils and their major properties

According to the revised classification of the Land Use Division of Myanmar, there are 24 main soil types[29] in the country. The spatial distribution of soil types and the area occupied by each of the soil types is given in A-Figures 26-27, and A-Table 6. Main features of major soil types according to the FAO classification system are discussed in the following sections (A-Figure 27 and A-Table 6).

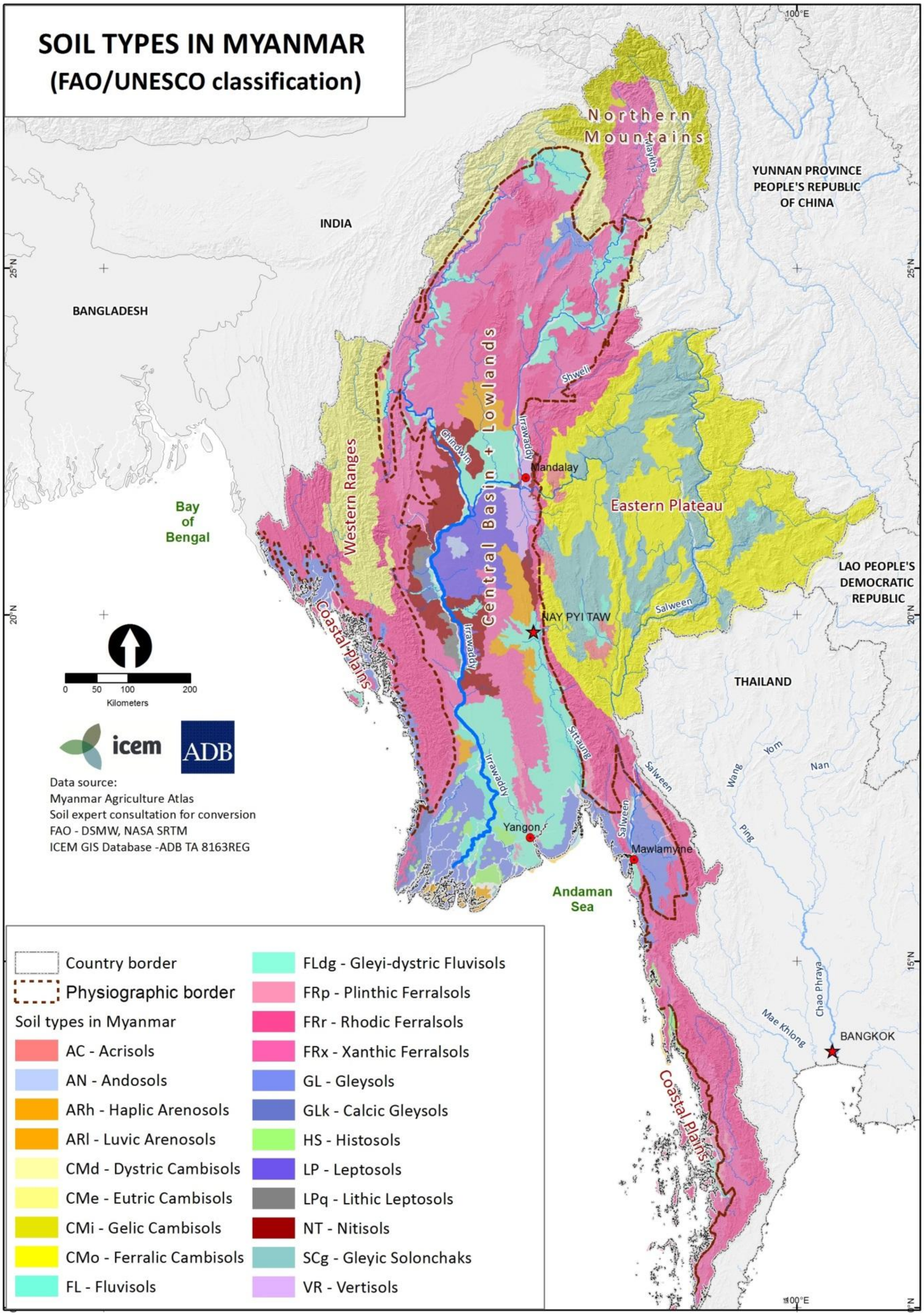
Ferralsols are the most predominant soil in Myanmar occupying over 37.5% of the land area. These soils represent deeply weathered red or yellow soils and the clay fraction is dominated by low activity clays. Rhodic Ferralsols, Xanthic Ferralsols and Plinthic Ferralsols have been identified in Mynamar. Rhodic Ferralsols have a red to dusky red B horizon (FAO, 1988) and these are the typical soils of tropical ever green forest of Myanmar. These soils occur on the well-drained hillslopes at elevation of 300 to 1500 m above sea level. These soils also occur in the northern hilly region and on the hill slopes of Rakhine mountain range, Tenassarim and Donna ranges. Xanthic Ferralsols have a yellow to pale yellow B horizon (FAO, 1988). These soils extensively occur on the low hills of Pegu Yoma, foot hills of Taninthayee Yoma, Rakhine Yoma and sloping areas at the bottom of northern hilly region of Myanmar. These soils are typical for the monsoon or tropical mixed deciduous forests. Xanthic Ferralsols contain more clay and humus than the Rhodic Ferralsols. Plinthic Ferralsols (0.79%) are soils with a plinthic horizon (mottled clay material that hardens irreversibly upon exposure). These soils occur mostly in the lower Myanmar in the lower slopes of the hills of Pegu Yoma, Rakhine Yoma and Donna hill range. They usually occur on well drained low uplands and at the foot of low hills at elevation not higher than 100 m. These soils have formed under wet tropical monsoon climatic conditions.

Cambisols are characterised by slight to moderate weathering of parent material and by the absence of appreciable accumulation of clay, organic matter, Fe and/or Al compounds. These soils are only at the beginning of the horizon differentiation (Cambic B horizon) in the subsoil and are common in many parts of Myanmar covering over 29% of the area. Dystric Cambisols, Eutric Cambisols, Ferralic Cambisols and Gelic Cambisols sub-units have been suggested by the Land Use Division. These soils are common on the high mountainous terrain at the elevation in the Shan Plateau, Northern Mountainous region and Chin Hills. Most of these soils are suitable for forest conservation and plantation crops.

[29] http://www.apipnm.org/swlwpnr/reports/y_ta/z_mm/mm.htm#soils



A-Figure 25: The distribution of different soil types according to the local classification system in Myanmar.



A-Figure 26: The distribution of different soil types according to the FAO-UNESCO classification system in Myanmar (FAO, 1997).

A-Table 6: The extent of distribution of soil types according to the local and the FAO-UNESCO classification (FAO, 1997) in Myanmar.

	FAO Units	FAO Sub-units	Area (ha)	Area (%)
Red Brown Forest Soil	Ferralsols	Rhodic Ferralsols	12,631,505	19.30
Yellow Brown Forest Soil	Ferralsols	Xanthic Ferralsols	11,539,177	17.63
Lateritic Soil	Ferralsols	Plinthic Ferralsols	517,364	0.79
Mountainous Brown Forest Soil	Cambisols	Ferralic Cambisols	7,976,016	12.18
Mountainous Red Forest Soil	Cambisols	Ferralic Cambisols	2,731,848	4.17
Northern Hill Complex Soil	Cambisols	Dystric Cambisols	3,517,546	5.37
Chin Hill Complex Soil	Cambisols	Eutric Cambisols	3,068,399	4.69
Alpic Complex Soil	Cambisols	Gelic Cambisols	1,884,716	2.88
Yellow Brown Dry & Indaing Soil	Arenosols	Haplic Arenosols	1,019,738	1.56
Alluvial Soil	Fluvisols	Fluvisols	730,769	1.12
Mangrove Forest Soil	Solonchaks	Gleyic Solonchaks	5,472,493	8.36
Meadow & Meadow Alluvial Soil	Gleysols	Gleysols	5,164,059	7.89
Gley & Gley Swampy Soil	Gleysols	Umbric Gleysols	3,211,304	4.91
Saline Swampy & Meadow Gley Soil	Gleysols	Mollic Gleysols	495,141	0.76
Meadow Carbonate	Gleysols	Calcic Gleysols	374,689	0.57
Swampy Soil	Histosols	Histosols	447,377	0.68
Light Forest Soil	Nitisols	Nitisols	1,900,391	2.90
Savana Soil on Slopes & Compact Soil in Depression	Leptosols	Leptosols	1,180,412	1.80
Primitive Crushed Stone Soil	Leptosols	Leptosols	279,646	0.43
Turfy Primitive Soil (Lithosols)	Leptosols	Lithic Leptosols	196,074	0.30
Compact Soil	Vertisols	Vertisols	432,020	0.66
Red Earth & Yellow Earth	Acrisols	Ferric Acrisols	323,248	0.49
Dune Forest & Beach Sand	Arenosols	Luvic Arenosols	274,212	0.42
Popa Complex Soil	Andosols	Andosols	92,701	0.14
Grand Total			65, 460,846	100.0

Fluvisols are young soils formed in fluvial, lacustrine and marine deposits. These soils exist over 1.1% of the total land area in the river plains, deltas, former lakes and coastal areas. The soil pH is usually neutral and being young soils developed from recent alluvial deposits of the river plains, these soils are rich in plant nutrients. Fluvisols are easily to till and fertile, thus highly suitable for agriculture.

Gleyic Solonchaks are soils that have formed from recent alluvial deposits, high soluble salt contents and an ochric (pale) A horizon (FAO-UNESCO, 1974). In Myanmar, these soils cover 8.4% of the total area and they exist in marine flat lowlands which are affected by daily tides. Some notable areas are along the coasts in the region of Irrawaddy delta, Myeik archipelago and islands of Rakhine coast line.

Gleysols comprise soils formed on unconsolidated material exclusive of recent alluvial deposits and showing hydromorphic (reducing) properties within 50 cm of the surface (FAO-UNESCO, 1974). Several sub-units of Gleysols have been identified in Myanmar, these include - Umbric Gleysols, Calcic Gleysols and Mollic Gleysols; some of the sub-units are not recognised in the revised FAO-UNSECO classification system (1997). These soils widely exist (14.1% area) in different parts of Myanmar in river plains, delta and low coastal plains and valleys. All these soils usually have thick solumn, mostly clayey texture and pH usually varies from neutral to alkaline. Some soils may have high salt contents and sulfidic horizon within 125 cm from the surface.

Histosols have a very high content (50 % or more) of organic C in the top soil and thus are considered to be organic rather than mineral soils. These soils are formed from the accumulation of organic matter under waterlogged conditions typical of peat bogs and swamps. Histosols covers over 0.68% of the area and exists near the coast in the southern parts of Mynamar in Irrawaddy and Tanintharyi states.

Nitisols (Nitosol according to FAO-UNESCO, 1974) are deep well drained soil with argillic B horizon (clay rich) with diffuse horizon boundaries between A and B horizons (FAO, 1988). These soils covers 2.9% of the area and mostly occur on the very gently sloping alluvial-colluvial under mountainous plains in the dry zone area and are also found on the lowest parts of the slopes in the Shan Plateau.

Leptosols are limited in depth by the presence of continuous hard rock within 10 cm of the surface (FAO-UNESCO, 1974). These soils cover 2.5% of the area and widely occur in the area of low hills and sharpest and eroded slopes of the eastern side Rakhine Yoma in Magway Division. The surface layer of these soils consists of a mixture of crushed sandstone and lime concretions with some quantity of slightly humidified fine earth. These soils are not suitable for cultivation and are covered with the open cover of low shrubs with spines and sparse dry grasses.

Vertisols exist in the dry zone (0.66% area) in the level plains of Sagaing, Mandalay and Magway divisions of Myanmar. These soils have more than 30% clay in the top 20 cm layer and develop cracks from soil surface downwards at some period in most years. They occur on the lowlands near the rivers and broad depression in the areas of Red Brown Savanna Soils. The soils are alkaline and having pH ranging from 7 to 9 so they are strongly calcareous.

Acrisols (Red and Yellow Earths) according to the FAO-UNESCO (1974) definition have clay rich B horizon that has a base saturation of less than 50% at least in the low part of the B horizon. Acrisols exist over 0.5% of the area in Mynamar. These are the most dominating soils of Shan Plateau and of the northern mountainous region at an elevation of more than 900 m. The Shan Plateau is almost completely covered with these soils. The Yellow Earths occur on the level lower slopes in the Shan Plateau. They occupy a relatively small area, changing the Red Earths down the slopes. The Red Earths have a very deep profile having the texture varying from sandy and silty to silty clay loam and with good structure. The soil pH varies from slightly acid to neutral (6-7). However, the Yellow Earths soils are more acidic, have greater clay, Fe and Al contents. The Red Earths are the typical agricultural soil in Shan state, however, due to relief and slopes, erosion control measures are needed. The Yellow Earths soils can only be utilised for gardens, flowers and forests.

Areonsols are deep sandy soils and they cover over 0.42% of the area. These soils occur in the coastal areas in southern Myanmar in Irrawaddy, Mon, Yangon and Tanintharyi states.

Andosols have very low bulk density (< 0.85 g cm^{-3}) and clay dominated by amorphous materials or 60% or more vitric volcanic ash in the soil. These soils have limited presence (0.14%) in Myanmar, only found in the volcanic region of Popa in the Central Myanmar.

5.4 Soil fertility status

Although the fertility data for Myanmar soils are not current, the historical data suggest wide spread deficiency of nutrient elements. The analysis of soil samples collected in 1992 from different states and divisions of the country showed that about 30% of all soil samples have lower pH 5.5 and aluminium toxicity may affect plant yield growth in these highly acidic soils. Organic matter content in most soils is low. About 70% of the paddy soils were found to be deficient in phosphorus. In 50% of soils, potassium was also low and very low condition and the rest 40% are moderate. Widespread deficiency of micronutrients was also found in the analysed samples. Poor fertility of the Myanmar soils has been attributed to wind and water erosion of soils, highly acidic pH in high rainfall areas such as mountainous regions, and lack of proper agronomic practices. Additionally, most of the farmers in Myanmar are resource poor and can not afford to purchase inorganic fertlisers and rely on the inherent soil fertility.

6. YUNNAN PROVINCE AND GUANGXI ZHUANG AUTONOMOUS REGION (PRC)

6.1 General introduction

Yunnan Province and Guangxi Zhuang Autonomous Region (or Guangxi) are located in the southwest part of the People's Republic of China (PRC) and border Myanmar, Lao PDR and Viet Nam (Figure 28). They cover an area of approximately 637,070 square kilometers and have a combined population of close to 98 million.

Yunnan province is located in the tropical latitude but it has a generally mild climate because of its situation in high elevation. The average temperature in winter months (December-January) is 9 °C and ranges from 8 to 17 °C; and in the summer (June-July) months the average temperature is about 22 °C and generally varies from 21 to 27 °C[30,31]. In the tropical south temperatures generally exceed 30 °C in the warmer months. Yunnan receives rain-bearing monsoonal winds from both the Pacific and Indian oceans, and thus gets good precipitation. The average annual rainfall ranges from 600 to 2,300 mm, and more than half of the rainfall occurs during June to August period.

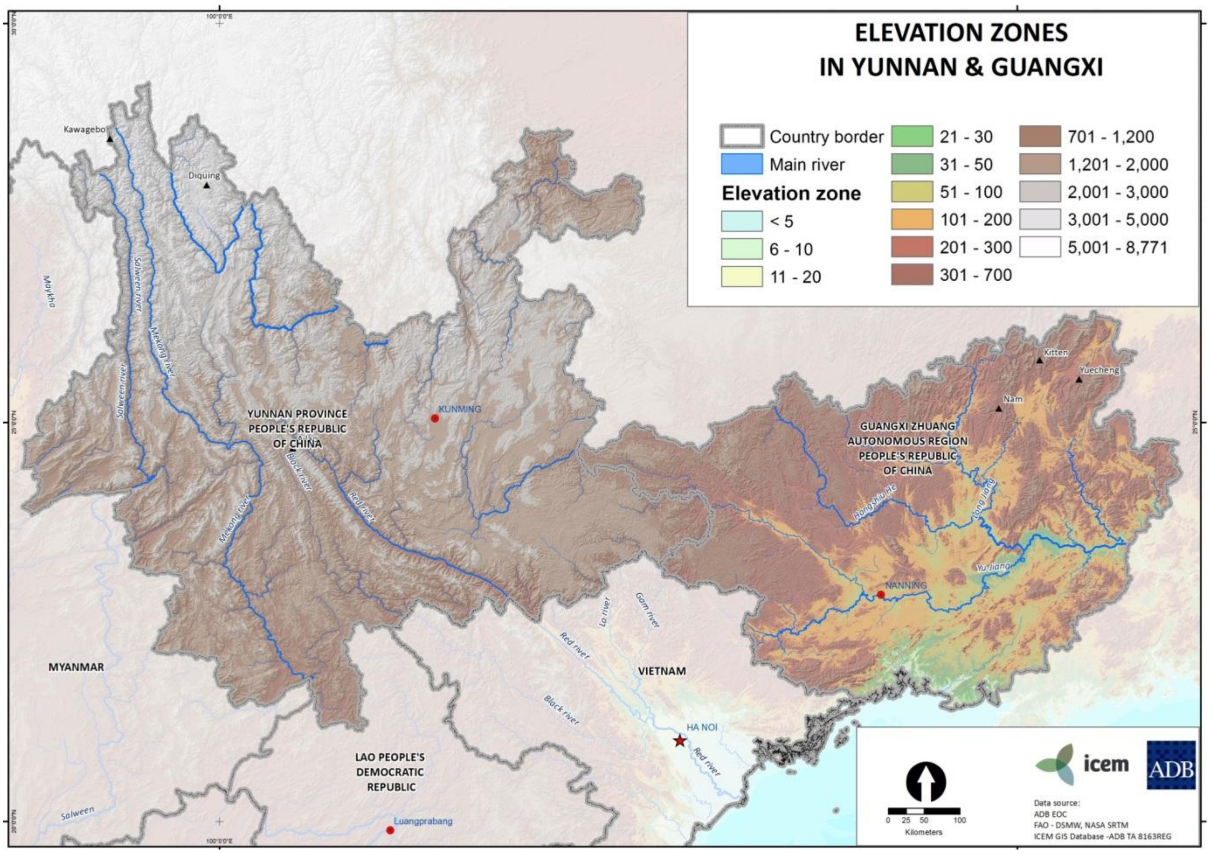
Guangxi lies in a region with low latitudes and borders a tropic sea in the south, and mountain ranges in the north. The climate is characterised by a long summer from April to October, and a short and mild winter[32]. The average annual temperature varies from 16 to 23 °C; in July temperature generally lies between 27 and 32 °C and in January temperatures range between 4 and 16 °C. Guangxi is influenced by monsoonal wind that blows from the south and southwest from late April to the end of September; precipitation is abundant[33]. The average annual rainfall varies from about 1,250 mm in the drier areas to 1,750 mm in wetter areas, with a maximum of 2,760 mm on the seaward side of mountains. Most of the precipitation (80 per cent) occurs from April to September.

6.2 Physiography

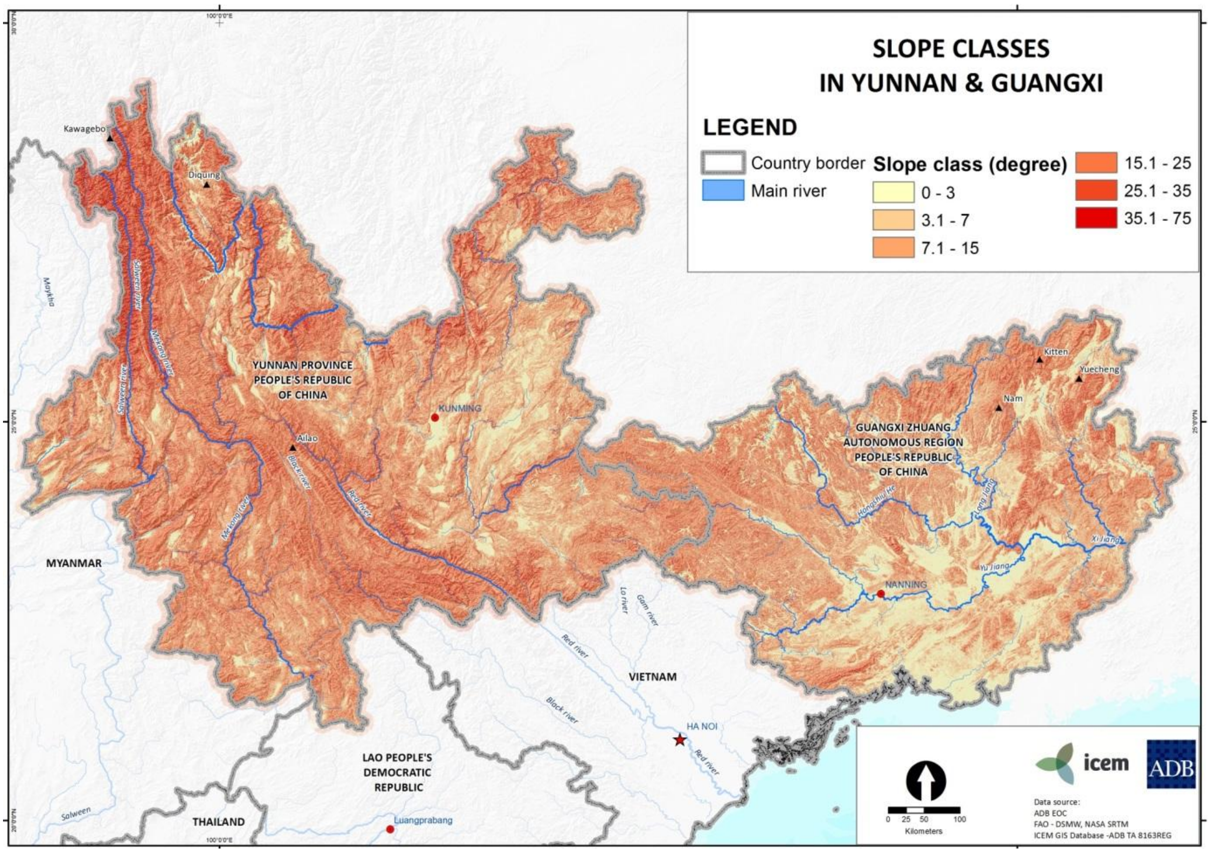
Yunnan Plateau was formed by a strong uplift of the surface in the late Pliocene and early Pleistocene. The topography of the province is highly varied, however, the terrain in Yunnan province is largely mountainous (about 95%), particularly in the north and west (A-Figures 28 and 29). The Province is separated by the Ailao Mountains into two distinct regions—the canyon region to the west of it and the Yunnan-Guizhou (Yungui) Plateau to the east. In the canyon region, major rivers, i.e. the Salween (Nu), Mekong (Lancang) and Black (Lixian) flow through deeply incised valleys between the mountains. The average elevation in the province is approximately 2,000 metres;

[30] https://en.wikipedia.org/wiki/Yunnan#Climate
[31] http://www.britannica.com/place/Yunnan
[32] https://en.wikipedia.org/wiki/Guangxi
[33] http://www.britannica.com/place/Guangxi

mountains are highest in the north (more than 5,000 m) and in the south the elevation is less than 3,000 m. The highest point in the north is the Kawagebo peak (about 6,740 m) on the Diqing Plateau and the lowest (76 m) point is in the Red River Valley close to the Vietnamese border[27].



A-Figure 27: The elevation map of Yunnan Province and Guangxi Zhuang (Guangxi) autonomous region of the PRC. Mountainous terrain is dominant in Yunnan Province and high tableland in the northwest and low tableland in the southeast in Guangxi.



A-Figure 28: The topographic map of Yunnan Province and Guangxi Zhuang Autonomous Region of the PRC showing regions of varying slopes in the country.

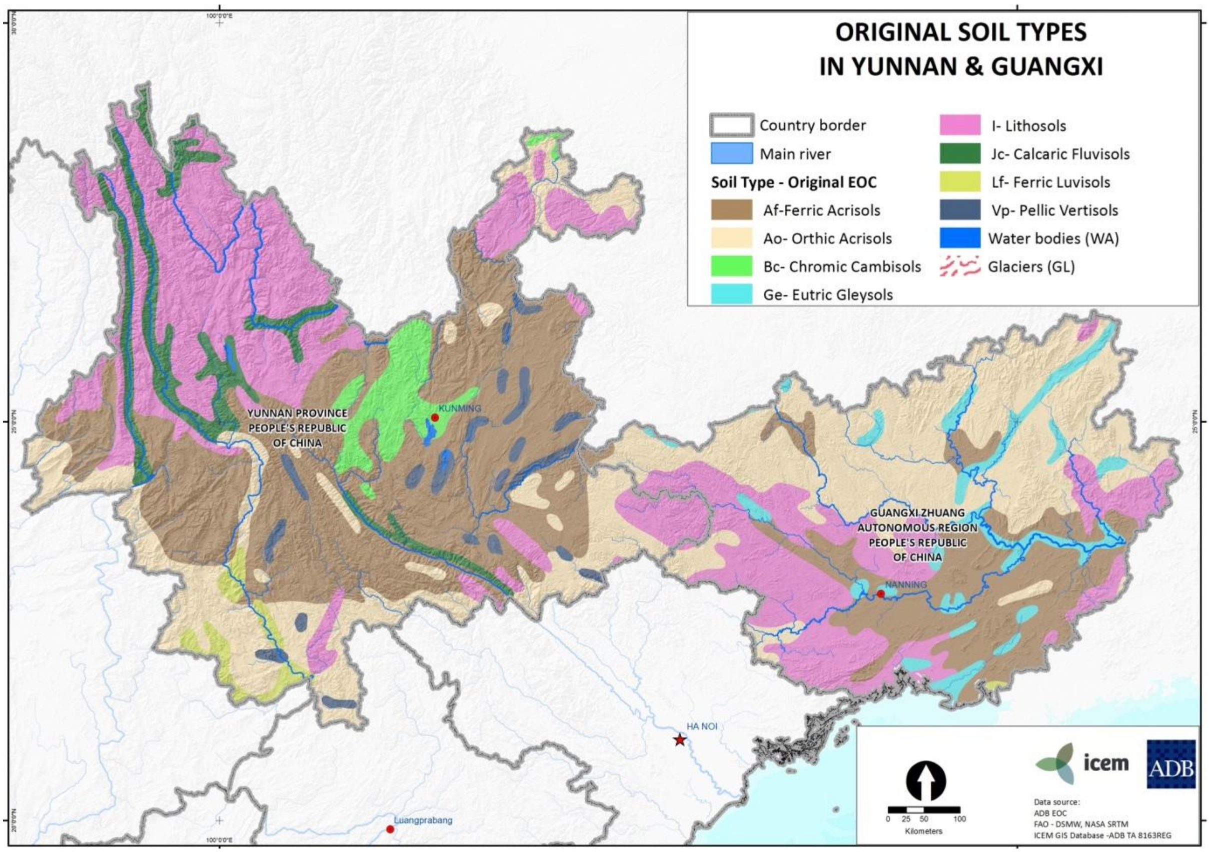
The eastern Yungui Plateau region is a limestone plateau with karst scenery that stretches from the Ailao Mountains to the Guizhou-Guangxi border. On the western fringe of the plateau streams drain into the Red River that runs along the eastern slope of the Ailao Mountains. The elevation of the plateau ranges from about 2,130 metres on the western end to 1,370 metres on the Guizhou border. There are several lakes in Yunnan province formed by filling of water in grabens.

About 95% of land is moderately to steeply sloping and only 6.8% of Yunnan's land area is suitable for agricultural activities (A-Figure 29).

Guangxi is situated on the southeast ring of the Yunnan-Guizhou Plateau and forms a tableland that stands high in the northwest and low in the southeast. The highest point in Guangxi is Kitten Mountain with an elevation of 2,141 m and it lies in the Yuecheng Mountains (A-Figure 28). The Nanling Mountains form the north-east border, the Duyao and Fenghuang Mountains occur in the north, and Yunkai Mountains exist on the southeaster border[3]. Many rivers flow in the valleys of the mountains, with most of these rivers forming the tributary basin of the West River. The existence of limestone in more than half of the region has created a spectacular type of landscape, known as karst, in many parts of Guangxi. There are numerous pinnacles and spires, caves and caverns, sinkholes, and subterranean streams in the karst region[30].

6.3 *Soils and their major properties*

Soil maps of Yunnan Province and Guangxi Zhuang Autonomous Region of PR C are given in A-Figures 30 and 31. The area and distribution of various soil types in the two provinces according to the FAO-UNESCO classification system is presented in A-Figure 31 and A-Table 7. Acrisols (60.3% of the area) have an argic B horizon (a subsurface horizon with distinctly higher clay content than the overlying horizon), cation exchange capacity (CEC) of less than 24 $cmol_c\ kg^{-1}$ of clay (i.e. low-activity clay) and base saturation of less than 50% in some part of the B horizon. Ferric Acrisols and Haplic Acrisols soil units have been identified in the PRC; main features of these subsoils are given in the Appendix 2.



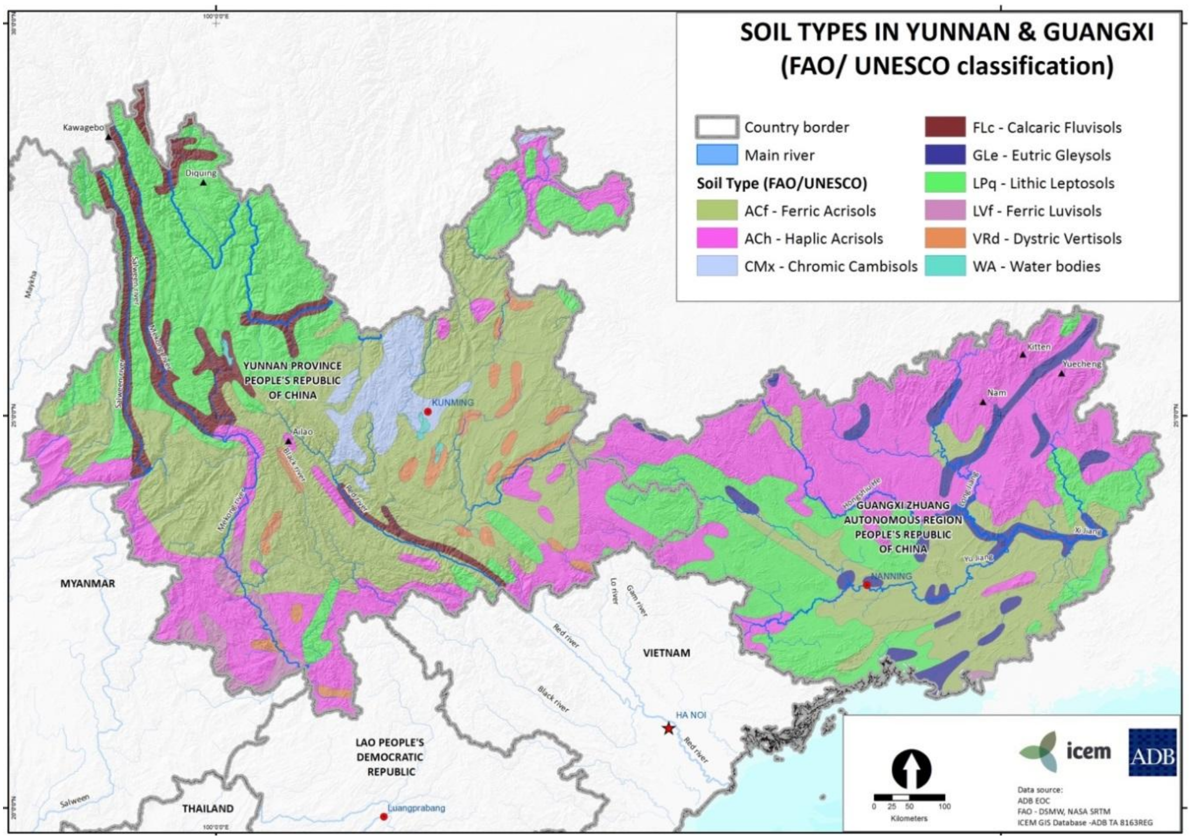
A-Figure 29: The distribution of different soil types according to the old FAO classification system in Yunnan and Guangxi provinces of the People's Republic of China.

Leptosols (Lithic sub-unit) cover 26% of the area; these soils are limited in depth by the presence of continuous hard rock within 10 cm of the surface (FAO-UNESCO, 1988). Such soils occur on the highly slopping landscapes in the mountainous regions, which are common in this region. Lithic Leptosols predominantly exits in the north and north-west of Yunnan Province and southern half of Guangxi Province.

Cambisols are characterised by slight to moderate weathering of parent material and by the absence of appreciable accumulation of clay, organic matter, Fe and/or Al compounds. These soils are only at the beginning of the horizon differentiation (Cambic B horizon) in the subsoil. Chromic Cambisol sub-unit has been identified and these soils are found in the region around Kunming city in Yunnan Province covering over 2.6% of the area.

Luvisols are present over an area of 1.4% in PRC. Similar to Acrisols, Luvisols also have an argic B horizon. However, unlike Acrisols these soils have high-activity clays and base saturation of equal or more than 50% in the B horizon. Ferric Luvisols have been identified in Yunnan province along the Mekong River and along the Mynamar border.

Fluvisols, Vertisols and Gleysols cover 9.6% of the total areas, and these soils are present along the rivers or in the lowest part of the landscape. Fluvisols are relatively young soils formed in river sediments; Calcaric Fluvisols are present in the deeply incised valley between mountains in Yunnan Province. Vertisols are clay rich soils with characteristics shrinking and swelling properties, and they develop deep wide cracks from the surface downward upon drying. Dystric Vertisols have been identified in PRC and these are present (1.9%) only in Yunnan. Gleysols are saturated with groundwater and reduced for long enough periods to develop reducing conditions. Eutric Gleysols are present along rivers or river tributaries in Guangxi, covering 3.2% of the area.



A-Figure 30: The distribution of different soil types according to the FAO-UNESCO classification system in Yunnan and Guangxi provinces of the People's Republic of China (FAO, 1997).

A-Table 7: The extent of distribution of soil types in Yunnan and Guangxi provinces of the People's Republic of China according to the FAO-UNESCO Classification (FAO, 1997).

FAO Units	FAO Sub-units	Area (ha)	Area (%)
Acrisols		37,532,501	60.3
	ACf - Ferric Acrisols	20,504,155	32.9
	ACh - Haplic Acrisols	17,028,346	27.4
Cambisols		1,603,186	2.6
	CMx - Chromic Cambisols	1,603,186	2.6

Fluvisols		2,828,728	4.5
	FLc - Calcic Fluvisols	2,828,728	4.5
Gleysols		1,990,850	3.2
	GLe - Eutric Gleysols	1,990,850	3.2
Leptosols		16,197,818	26.0
	LPq - Lithic Leptosols	16,197,818	26.0
Luvisols		841,688	1.4
	LVf - Ferric Luvisols	841,688	1.4
Vertosols		1,168,436	1.9
	VRd - Dystric Vertosols	1,168,436	1.9
Water	WA - Water bodies	75,587	0.1
Grand Total		62,238,795	100.0

6.4 Soil fertility status

According to the Chinese classification system, the hilly terrain in both Yunnan Province and Guangxi is dominated by Red Soils (Acrisols and Leptosols). These soils are generally highly weathered with low nutrient contents and very vulnerable to soil erosion if vegetation cover is removed (He et al., 2004). These soils have several inherent constraints to crop production such as nutrient deficiencies, element toxicities, undesirable physical constrains and susceptibility to erosion. Red Soils have low cation exchange capacity and generally high exchangeable acidity. In the PRC the Red Soils are quite acidic (pH between 4 and 6), low organic matter content (< 2%) and low nutrient availability (He et al., 2004). Deficiencies of major nutrients (N, P, K, Ca and Mg) and micro-nutrients (particularly B and Mo) are common and the toxicity of Al and Mn are widespread. Physical constraints, such as the presence of argillic or oxic horizon in the rooting zone, are additional limiting factors in the use of these soils for agricultural use. Yunnan is largely mountainous and there are severe soil erosion problems in agricultural use of soils.

Zhang et al. (1998) reported that soils in Guangxi have low cation exchange capacity, low organic matter, and generally low contents of phosphorus, potassium and sulfur. Because of the highly weathered nature of the acid red soils, the total (0.86%) and available (53 mg/kg) potassium contents are very low (Tan et al., 1995; Xie et al., 2000). Similarly, plant available Mg in the soils commonly used for crop production was reported to be less than 70 mg/kg (Xie & Du, 1991). The results of 86 trials in Guangxi show the application of potassium fertilizer significantly increased yield more than the application of NP fertilizer only, and also increased the quality of crops and fruit markedly (Tan, 2004).

APPENDIX 2: MAJOR SOIL GROUPINGS AND SOIL UNITS

Major soil groupings and soil units

The indicative characteristics of the major soil groups and soil units are given in this section, more details are available in FAO-UNESCO (1988).

FLUVISOLS (FL)[34]

Soils showing fluvic properties and having no diagnostic horizons other than an ochric, a mollic or an umbric A horizon, or a histic H horizon, or a sulfuric horizon, or sulfidic material within 125 cm of the surface.

Eutric Fluvisols (FLe) Fluvisols having a base saturation (by NH_4OAc) of 50 percent or more at least between 20 and 50 cm from the surface but which are not calcareous at the same depth; lacking a sulfuric horizon and sulfidic material within 125 cm of the surface; lacking salic properties.

Calcaric Fluvisols (FLc) Fluvisols which are calcareous at least between 20 and 50 cm from the surface; lacking a sulfuric horizon and sulfidic material within 125 cm of the surface; lacking salic properties.

Dystric Fluvisols (FLd) Fluvisols having a base saturation (by NH_4OAc) of less than 50 percent at least between 20 and 50 cm from the surface; lacking a sulfuric horizon and sulfidic material within 125 cm of the surface.

Mollic Fluvisols (FLm) Fluvisols having a mollic A horizon or a eutric histic H horizon; lacking a sulfuric horizon or sulfidic material within 125 cm of the surface; lacking salic properties.

Umbric Fluvisols (FLu) Fluvisols having a umbric A horizon or a dystric histic H horizon; lacking a sulfuric horizon or sulfidic material within 125 cm of the surface; lacking salic properties.

Thionic Fluvisols (FLt) Fluvisols having a sulfuric horizon or sulfidic material, or both, at less than 125 cm from the surface.

Salic Fluvisols (FLs) Fluvisols having salic properties; lacking a sulfuric horizon or sulfidic material within 125 cm of the surface.

GLEYSOLS (GL)

Soils formed from unconsolidated materials, exclusive of coarse textured materials (except when a Histic H horizon is present) and alluvial deposits which show fluvic properties, showing gleyic properties within 50 cm of the surface; having no diagnostic horizons other than an A horizon, a histic H horizon, a cambic B horizon, a sulfuric, a calcic or a gypsic horizon; lacking the characteristics which are diagnostic for Vertisols or Arenosols; lacking salic properties; lacking plinthite within 125 cm of the surface.

[34] Most but not all Fluvisols show gleyic properties. However, on small scale maps it is hardly possible to make a separation between different drainage classes; such a separation may be feasible between different soil subunits at the third level

Eutric Gleysols (GLe) Gleysols having a base saturation (by NH_4OAc) of 50 percent or more at least between 20 and 50 cm from the surface; having no diagnostic horizons other than an ochric A horizon and a cambic B horizon; lacking andic properties; lacking permafrost within 200 cm of the surface.

Calcic Gleysols (GLk) Gleysols which have a calcic or a gypsic horizon, or both, within 125 cm of the surface; having no diagnostic horizons other than an ochric A horizon and a cambic B horizon; lacking andic properties; lacking permafrost within 200 cm of the surface.

Dystric Gleysols (GLd) Gleysols having a base saturation (by NH_4OAc) of less than 50 percent at least between 20 and 50 cm from the surface; having no diagnostic horizons other than an ochric A horizon and a cambic B horizon; lacking andic properties; lacking permafrost within 200 cm of the surface.

Andic Gleysols (GLa) Gleysols having andic properties; lacking permafrost within 200 cm of the surface.

Mollic Gleysols (GLm) Gleysols having a mollic A horizon or a eutric histic H horizon; lacking andic properties; lacking permafrost within 200 cm of the surface.

Umbric Gleysols (GLu) Gleysols having an umbric A horizon or a dystric histic H horizon; lacking andic properties; lacking permafrost within 200 cm of the surface.

Thionic Gleysols (GLt) Gleysols having a sulfuric horizon or sulfidic material at less than 125 cm from the surface; lacking permafrost within 200 cm of the surface.

Gelic Gleysols (GLi) Gleysols having permafrost within 200 cm of the surface.

REGOSOLS (RG)

Soils formed from unconsolidated materials, exclusive of materials that are coarse textured and more than 100 cm deep, or show fluvic properties, having no diagnostic horizons other than an ochric or umbric A horizon; lacking gleyic properties within 50 cm of the surface; lacking the characteristics which are diagnostic for Vertisols or Andosols; lacking salic properties.

Eutric Regosols (RGe) Regosols having a base saturation (by NH_4OAc) of 50 percent or more at least between 20 and 50 cm from the surface but which are not calcareous within this depth; lacking permafrost within 200 cm of the surface.

Calcaric Regosols (RGc) Regosols which are calcareous at least between 20 and 50 cm from the surface; lacking permafrost within 200 cm of the surface.

Gypsiric Regosols (RGy) Regosols which are gypsiferous at least between 20 and 50 cm from the surface; lacking permafrost within 200 cm of the surface.

Dystric Regosols (RGd) Regosols having a base saturation (by NH_4OAc) of less than 50 percent at least between 20 and 50 cm from the surface; lacking permafrost within 200 cm of the surface.

Umbric Regosols (RGu) Regosols having an umbric A horizon; lacking permafrost within 200 cm of the surface.

Gelic Regosols (RGi) Regosols having permafrost within 200 cm of the surface.

LEPTOSOLS (LP)

Soils which are limited in depth by continuous hard rock or highly calcareous material (calcium carbonate equivalent of more than 40 percent) or a continuous cemented layer within 30 cm of the surface, or having less than 20 percent of fine earth over a depth of 75 cm of the surface;

Eutric Leptosols (LPe) Leptosols having an ochric A horizon and a base saturation (by NH_4OAc) of 50 percent or more throughout; lacking hard rock and a continuous cemented layer within 10 cm and permafrost within 200 cm of the surface.

Dystric Leptosols (LPd) Leptosols having an ochric A horizon and a base saturation (by NH_4OAc) of less than 50 percent in at least some part of the soil; lacking hard rock and a continuous cemented layer within 10 cm and permafrost within 200 cm of the surface.

Rendzic Leptosols (LPk) Leptosols having a mollic A horizon[35] which contains or immediately overlies calcareous material with a calcium carbonate equivalent of more than 40 percent; lacking hard rock and a continuous cemented layer within 10 cm and permafrost within 200 cm of the surface.

Mollic Leptosols (LPm) Leptosols having a mollic A horizon which does not contain or immediately overlie calcareous material with a calcium carbonate equivalent of more than 40 percent; lacking hard rock and a continuous cemented layer within 10 cm and permafrost within 200 cm of the surface.

Umbric Leptosols (LPu) Leptosols having an umbric A horizon; lacking hard rock and a continuous cemented layer within 10 cm and permafrost within 200 cm of the surface.

Lithic Leptosols (LPq) Leptosols which are limited in depth by continuous hard rock or a continuously cemented layer within 10 cm of the surface.

Gelic Leptosols (LPi) Leptosols having permafrost within 200 cm of the surface.

ARENOSOLS (AR)

Soils which are coarser than sandy loam to a depth of at least 100 cm of the surface, having less than 35 percent of rock fragments or other coarse fragments in all subhorizons within 100 cm of the surface, exclusive of materials which show fluvic or andic properties; having no diagnostic horizons other than an ochric A horizon or an albic E horizon.

Haplic Arenosols (ARh) Arenosols having no diagnostic horizon other than an ochric A horizon; lacking ferralic properties; lacking gleyic properties within 100 cm of the surface; non-calcaric.

Cambic Arenosols (ARb) Arenosols showing colouring or alteration characteristic of a cambic B horizon immediately below the A horizon; lacking lamellae of clay accumulation; lacking ferralic

[35] When the A horizon contains more than 40 per cent of finely divided calcium carbonate the colour requirements of the mollic A horizon may be waived

properties; lacking an albic E horizon with a minimum thickness of 50 cm; lacking gleyic properties within 100 cm of the surface; non-calcaric.

Luvic Arenosols (ARl) Arenosols showing an increase of 3 percent clay or more or lamellae of clay accumulation within 125 cm of the surface; lacking an albic E horizon with a minimum thickness of 50 cm; lacking gleyic properties within 100 cm of the surface; non-calcaric.

Ferralic Arenosols (ARo) Arenosols showing ferralic properties, and colouring of the horizon immediately underlying the A horizon expressed by chromas of 5 or more or hues redder than 10YR; lacking a clay increase or lamellae of clay accumulation within 125 cm of the surface; lacking an albic E horizon with a minimum thickness of 50 cm; lacking gleyic properties within 100 cm of the surface; non-calcaric.

Albic Arenosols (ARa) Arenosols having an albic E horizon with a minimum thickness of 50 cm within 125 cm from the surface; lacking gleyic properties within 100 cm of the surface; non-calcaric.

Calcaric Arenosols (ARc) Arenosols which are calcaric; lacking gleyic properties within 100 cm of the surface.

Gleyic Arenosols (ARg) Arenosols showing gleyic properties within 100 cm of the surface.

ANDOSOLS (AN)

Soils showing andic properties to a depth of 35 cm or more from the surface and having a mollic or an umbric A horizon possibly overlying a cambic B horizon, or an ochric A horizon and a cambic B horizon; having no other diagnostic horizons; lacking gleyic properties within 50 cm of the surface; lacking the characteristics which are diagnostic for Vertisols; lacking salic properties.

Haplic Andosols (ANh) Andosols having an ochric A horizon and a cambic B horizon; having a smeary consistence and having a texture which is silt loam or finer on the weighted average for all horizons within 100 cm of the surface; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Mollic Andosols (ANm) Andosols having a mollic A horizon; having a smeary consistence, and having a texture which is silt loam or finer on the weighted average for all horizons within 100 cm of the surface; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Umbric Andosols (ANu) Andosols having an umbric A horizon; having a smeary consistence and having a texture which is silt loam or finer on the weighted average for all horizons within 100 cm of the surface; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Vitric Andosols (ANz) Andosols lacking a smeary consistence or having a texture which is coarser than silt loam on the weighted average for all horizons within 100 cm of the surface, or both; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gleyic Andosols (ANg) Andosols showing gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gelic Andosols (ANi) Andosols having permafrost within 200 cm of the surface.

VERTISOLS (VR)

Soils having, after the upper 18 cm have been mixed, 30 percent or more clay in all horizons to a depth of at least 50 cm; developing cracks from the soil surface downward which at some period in most years (unless the soil is irrigated) are at least 1 cm wide to a depth of 50 cm; having intersecting slickensides or wedge-shaped or parallelepiped structural aggregates at some depth between 25 and 100 cm from the surface, with or without gilgai.

Eutric Vertisols (VRe) Vertisols having a base saturation (by NH_4OAc) of 50 percent or more at least between 20 and 50 cm from the surface; lacking a calcic or a gypsic horizon.

Dystric Vertisols (VRd) Vertisols having a base saturation (by NH_4OAc) of less than 50 percent at least between 20 and 50 cm from the surface, lacking a calcic or a gypsic horizon.

Calcic Vertisols (VRk) Vertisols having a calcic horizon or concentrations of soft powdery lime within 125 cm of the surface; lacking a gypsic horizon.

Gypsic Vertisols (VRy) Vertisols having a gypsic horizon within 125 cm of the surface.

CAMBISOLS (CM)

Soils having a cambic B horizon and no diagnostic horizons other than an ochric or an umbric A horizon or a mollic A horizon overlying a cambic B horizon with a base saturation (by NH_4OAc) of less than 50 percent; lacking salic properties; lacking the characteristics diagnostic for Vertisols or Andosols; lacking gleyic properties within 50 cm of the surface.

Eutric Cambisols (CMe) Cambisols having an ochric A horizon and a base saturation (by NH_4OAc) of 50 percent or more at least between 20 and 50 cm from the surface but which are not calcareous within this depth; lacking vertic properties; having a cambic B horizon which is not strong brown to red[36] lacking ferralic properties in the cambic B horizon; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Dystric Cambisols (CMd) Cambisols having an ochric A horizon and a base saturation (by NH_4OAc) of less than 50 percent at least between 20 and 50 cm from the surface; lacking vertic properties; lacking ferralic properties in the cambic B horizon; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Humic Cambisols (CMu) Cambisols having an umbric A horizon or a mollic A horizon overlying a cambic B horizon with a base saturation (by NH_4OAc) of less than 50 percent; lacking vertic properties; lacking ferralic properties in the cambic B horizon; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

[36] Rubbed soil having a hue of 7.5YR and a chroma of more than 4, or a hue redder than 7.5YR.

Calcaric Cambisols (CMc) Cambisols having an ochric A horizon and are calcareous at least between 20 and 50 cm from the surface; lacking vertic properties; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Chromic Cambisols (CMx) Cambisols having an ochric A horizon and a base saturation (by NH4OAc) of 50 percent or more at least between 20 and 50 cm from the surface but which are not calcareous within this same depth; having a strong brown to red cambic B horizon; lacking ferralic properties in the cambic B horizon; lacking vertic properties; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Vertic Cambisols (CMv) Cambisols having an ochric A horizon; showing vertic properties; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Ferralic Cambisols (CMo) Cambisols having an ochric A horizon and a cambic B horizon with ferralic properties; lacking vertic properties; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gleyic Cambisols (CMg) Cambisols showing gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gelic Cambisols (CMi) Cambisols having permafrost within 200 cm of the surface.

CALCISOLS (CL)

Soils having one or more of the following: a calcic horizon, a petrocalcic horizon or concentrations of soft powdery lime within 125 cm of the surface; having no diagnostic horizons other than an ochric A horizon, a cambic B horizon or an argic B horizon which is calcareous; lacking the characteristics which are diagnostic for Vertisols or Planosols; lacking salic properties; lacking gleyic properties within 100 cm of the surface.

Haplic Calcisols (CLh) Calcisols lacking an argic B horizon and a petrocalcic horizon.

Luvic Calcisols (CLI) Calcisols having an argic B horizon; lacking a petrocalcic horizon.

Petrie Calcisols (CLp) Calcisols having a petrocalcic horizon.

GYPSISOLS (GY)

Soils having a gypsic or a petrogypsic horizon, or both, within 125 cm of the surface; having no diagnostic horizons other than an ochric A horizon, a cambic B horizon, an argic B horizon permeated with gypsum or calcium carbonate, a calcic or a petrocalcic horizon; lacking the characteristics which are diagnostic for Vertisols or Planosols; lacking salic properties; lacking gleyic properties within 100 cm of the surface.

Haplic Gypsisols (GYh) Gypsisols lacking an argic B horizon, a calcic horizon and a petrogypsic horizon.

Calcic Gypsisols (GYk) Gypsisols having a calcic or petrocalcic horizon; lacking a petrogypsic horizon.

Luvic Gypsisols (GYl) Gypsisols having an argic B horizon; lacking a calcic horizon and a petrogypsic horizon.

Petric Gypsisols (GYp) Gypsisols having a petrogypsic horizon.

SOLONETZ (SN)

Soils having a natric B horizon.

Haplic Solonetz (SNh) Solonetz having an ochric A horizon; lacking stagnic properties and lacking gleyic properties within 100 cm of the surface.

Mollic Solonetz (SNm) Solonetz having a mollic A horizon; lacking stagnic properties and lacking gleyic properties within 100 cm of the surface.

Calcic Solonetz (SNk) Solonetz having a calcic horizon or concentrations of soft powdery lime within 125 cm of the surface; lacking a gypsic horizon; lacking stagnic properties and lacking gleyic properties within 100 cm of the surface.

Gypsic Solonetz (SNy) Solonetz having a gypsic horizon within 125 cm of the surface overlying or not a calcic horizon; lacking stagnic properties and lacking gleyic properties within 100 cm of the surface.

Stagnic Solonetz (SNj) Solonetz showing stagnic properties; lacking gleyic properties within 100 cm of the surface.

Gleyic Solonetz (SNg) Solonetz showing gleyic properties within 100 cm of the surface.

SOLONCHAKS (SC)

Soils, which do not show fluvic properties, having salic properties and having no diagnostic horizons other than an A horizon, a histic H horizon, a cambic B horizon, a calcic or a gypsic horizon.

Haplic Solonchaks (SCh) Solonchaks having an ochric A horizon; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Mollic Solonchaks (SCm) Solonchaks having a mollic A horizon; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Calcic Solonchaks (SCk) Solonchaks having a calcic horizon or concentrations of soft powdery lime within 125 cm of the surface; lacking a gypsic horizon; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gypsic Solonchaks (SCy) Solonchaks having a gypsic horizon within 125 cm of the surface; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Sodic Solonchaks (SCn) Solonchaks showing sodic properties at least between 20 and 50 cm of the surface; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gleyic Solonchaks (SCg) Solonchaks showing gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gelic Solonchaks (SCi) Solonchaks having permafrost within 200 cm of the surface.

KASTANOZEMS (KS)

Soils having a mollic A horizon with a moist chroma of more than 2 to a depth of at least 15 cm; having one or more of the following: a calcic, a petrocalcic or gypsic horizon or concentrations of soft powdery lime within 125 cm of the surface; lacking a natric B horizon; lacking the characteristics which are diagnostic for Vertisols, Planosols or Andosols; lacking salic properties; lacking gleyic properties within 50 cm of the surface when no argic B horizon is present[37].

Haplic Kastanozems (KSh) Kastanozems lacking an argic B horizon, a calcic horizon and a gypsic horizon.

Luvic Kastanozems (KSl) Kastanozems having an argic B horizon; lacking a gypsic horizon.

Calcic Kastanozems (KSk) Kastanozems having a calcic horizon; lacking an argic B horizon and a gypsic horizon.

Gypsic Kastanozems (KSy) Kastanozems having a gypsic horizon.

CHERNOZEMS (CH)

Soils having a mollic A horizon with a moist chroma of 2 or less to a depth of at least 15 cm; having a calcic or petrocalcic horizon or concentrations of soft powdery lime within 125 cm of the surface; lacking a natric B horizon; lacking the characteristics which are diagnostic for Vertisols, Planosols or Andosols; lacking salic properties; lacking gleyic properties within 50 cm of the surface when no argic B horizon is present; lacking uncoated silt and quartz grains on structural ped surfaces.

Haplic Chernozems (CHh) Chernozems lacking an argic B horizon and a calcic horizon; not showing tonguing of the A horizon into a cambic B or into a C horizon.

Calcic Chernozems (CHk) Chernozems having a calcic or petrocalcic horizon; lacking an argic B horizon overlying the calcic horizon; not showing tonguing of the A horizon into a cambic B or into a C horizon.

Luvic Chernozems (CHl) Chernozems having an argic B horizon; a calcic horizon may be present when underlying the B horizon; lacking gleyic properties within 100 cm of the surface.

Glossic Chernozems (CHw) Chernozems showing tonguing of the A horizon into a cambic B horizon or into a C horizon; lacking an argic B horizon.

Gleyic Chernozems (CHg) Chernozems having an argic B horizon and showing gleyic properties within 100 cm of the surface.

PHAEOZEMS (PH)

Soils having a mollic A horizon; lacking a calcic horizon, a gypsic horizon, concentrations of soft powdery lime; having a base saturation (by NH_4OAc) which is 50 percent or more throughout within 125 cm of the surface; lacking a ferralic B horizon; lacking a natric B horizon; lacking the

[37] Gleyic properties present within 50 cm of the surface in the absence of an argic B horizon meet the definition of the Mollic Gleysols

characteristics which are diagnostic for Vertisols, Nitisols, Planosols or Andosols; lacking salic properties; lacking gleyic properties within 50 cm of the surface when no argic B horizon is presen[4]; lacking uncoated silt and sand grains on structural ped surfaces when the mollic A horizon has a moist chroma of 2 or less to a depth of at least 15 cm.

Haplic Phaeozems (PHh) Phaeozems lacking an argic B horizon and which are not calcareous from 20 to 50 cm of the surface, lacking gleyic properties within 100 cm of the surface, lacking stagnic properties.

Calcaric Phaeozems (PHc) Phaeozems which are calcareous at least from 20 to 50 cm of the surface; lacking an argic B horizon, lacking gleyic properties within 100 cm of the surface, lacking stagnic properties.

Luvic Phaeozems (PHI) Phaeozems having an argic B horizon; lacking gleyic properties within 100 cm of the surface, lacking stagnic properties.

Stagnic Phaeozems (PHj) Phaeozems showing stagnic properties; lacking gleyic properties within 100 cm of the surface.

Gleyic Phaeozems (PHg) Phaeozems showing gleyic properties within 100 cm of the surface.

GREYZEMS (GR)

Soils having a mollic A horizon with a moist chroma of 2 or less to a depth of at least 15 cm and showing uncoated silt and sand grains on structural ped surfaces; having an argic B horizon; lacking the characteristics which are diagnostic for Planosols.

Haplic Greyzems (GRh) Greyzems lacking gleyic properties within 100 cm of the surface.

Gleyic Greyzems (GRg) Greyzems showing gleyic properties within 100 cm of the surface.

LUVISOLS (LV)

Soils having an argic B horizon which has a cation exchange capacity equal to or more than 24 $cmol_{(+)}kg^{-1}$ clay and a base saturation (by NH_4OAc) of 50 percent or more throughout the B horizon; lacking a mollic A horizon; lacking the E horizon abruptly overlying a slowly permeable horizon, the distribution pattern of the clay and the tonguing which are diagnostic for Planosols, Nitisols and Podzoluvisols respectively.

Haplic Luvisols (LVh) Luvisols having an argic B horizon which is not strong brown to red[38]lacking an albic E horizon; lacking a calcic horizon and concentrations of soft powdery lime within 125 cm of the surface; lacking vertic properties; lacking ferric properties; lacking gleyic and stagnic properties within 100 cm of the surface.

Ferric Luvisols (LVf) Luvisols showing ferric properties within 125 cm of the surface; lacking an albic E horizon; lacking plinthite within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface.

[38] Rubbed soil has a hue of 7.5YR and a chroma of more than 4, or a hue redder than 7.5 YR

Chromic Luvisols (LVx) Luvisols having a strong brown to red argic B horizon; lacking vertic properties; lacking an albic E horizon; lacking a calcic horizon, or concentrations of soft powdery lime within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface.

Calcic Luvisols (LVk) Luvisols having a calcic horizon or concentrations of soft powdery lime, or both, within 125 cm of the surface; lacking vertic properties; lacking an albic E horizon; lacking gleyic and stagnic properties within 100 cm of the surface.

Vertic Luvisols (LVv) Luvisols showing vertic properties; lacking an albic E horizon; lacking gleyic and stagnic properties within 100 cm of the surface.

Albic Luvisols (LVa) Luvisols having an albic E horizon; lacking gleyic and stagnic properties within 100 cm of the surface.

Stagnic Luvisols (LVj) Luvisols showing stagnic properties within 50 cm of the surface; lacking gleyic properties within 100 cm of the surface.

Gleyic Luvisols (LVg) Luvisols showing gleyic properties within 100 cm of the surface.

PLANOSOLS (PL)

Soils having an E horizon showing stagnic properties at least in part of the horizon, and abruptly overlying a slowly permeable horizon within 125 cm of the surface, and lacking a natric or a spodic B horizon.

Eutric Planosols (PLe) Planosols having an ochric A horizon and having a base saturation (by NH_4OAc) of 50 percent or more throughout the slowly permeable horizon within 125 cm of the surface; lacking permafrost within 200 cm of the surface.

Dystric Planosols (PLd) Planosols having an ochric A horizon and having a base saturation (by NH4OAc) of less than 50 percent in at least a part of the slowly permeable horizon within 125 cm of the surface; lacking permafrost within 200 cm of the surface.

Mollic Planosols (PLm) Planosols having a mollic A horizon or a eutric histic H horizon; lacking permafrost within 200 cm of the surface.

Umbric Planosols (PLu) Planosols having an umbric A horizon or a dystric histic H horizon; lacking permafrost within 200 cm of the surface.

Gelic Planosols (PLi) Planosols having permafrost within 200 cm of the surface.

PODZOLUVISOLS (PD)

Soils having an argic B horizon showing an irregular or broken upper boundary resulting from deep tonguing of the E into the B horizon, or from the formation of discrete nodules larger than 2 cm, the exteriors of which are enriched and weakly cemented or indurated with iron and having redder hues and stronger chromas than the interiors; lacking a mollic A horizon.

Eutric Podzoluvisols (PDe) Podzoluvisols having a base saturation (by NH_4OAc) of 50 percent or more throughout the argic B horizon within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Dystric Podzoluvisols (PDd) Podzoluvisols having a base saturation (by NH_4OAc) of less than 50 percent in at least a part of the argic B horizon within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Stagnic Podzoluvisols (PDj) Podzoluvisols showing stagnic properties within 50 cm of the surface; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gleyic Podzoluvisols (PDg) Podzoluvisols showing gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gelic Podzoluvisols (PDi) Podzoluvisols having permafrost within 200 cm of the surface.

PODZOLS (PZ)

Soils having a spodic B horizon.

Haplic Podzols (PZh) Podzols having a spodic B horizon which in all subhorizons has a ratio of free iron to organic carbon of less than 6, but which contains sufficient free iron to turn redder on ignition; having a continuous albic E horizon that is thicker than 2 cm or a distinct separation within the spodic B horizon of a subhorizon which is visibly more enriched with organic carbon, or both; lacking gleyic properties with 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Cambic Podzols (PZb) Podzols having a spodic B horizon which in all subhorizons has a ratio of free iron to of organic carbon of less than 6, but which contains sufficient iron to turn redder on ignition; lacking or having only a thin (2 cm or less) or discontinuous albic E horizon; lacking a subhorizon within the spodic B horizon which is visibly more enriched with organic carbon; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Ferric Podzols (PZf) Podzols having a spodic B horizon in which in all subhorizons the ratio of free iron of organic carbon is 6 or more; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Carbic Podzols (PZc) Podzols having a spodic B horizon in which a subhorizon[39] contains dispersed organic matter and lacks sufficient free iron to turn redder on ignition[40]; lacking gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gleyic Podzols (PZg) Podzols showing gleyic properties within 100 cm of the surface; lacking permafrost within 200 cm of the surface.

Gelic Podzols (PZi) Podzols having permafrost within 200 cm of the surface.

[39] If this subhorizon is discontinuous, it should be present in at least half of a soil section large enough to study a full cycle of recurring horizon variations

[40] Normally corresponding to less than 0.5 percent Fe in the fine earth fraction

LIXISOLS (LX)

Soils having an argic B horizon which has a cation exchange capacity of less than 24 $cmol_{(+)}kg^{-1}$ clay at least in some part of the B horizon and a base saturation (by NH_4OAc) of 50 percent or more throughout the B horizon; lacking a mollic A horizon; lacking the E horizon abruptly overlying a slowly permeable horizon, the distribution pattern of the clay and the tonguing which are diagnostic for Planosols, Nitisols and Podzoluvisols respectively.

Haplic Lixisols (LXh) Lixisols lacking an albic E horizon; lacking ferric properties and plinthite within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface.

Ferric Lixisols (LXt) Lixisols showing ferric properties within 125 cm of the surface; lacking an albic E horizon; lacking plinthite within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface.

Plinthic Lixisols (LXp) Lixisols having plinthite within 125 cm of the surface; lacking an albic E horizon; lacking gleyic and stagnic properties within 100 cm of the surface.

Albic Lixisols (LXa) Lixisols having an albic E horizon; lacking gleyic and stagnic properties within 100 cm of the surface; lacking plinthite within 125 cm of the surface.

Stagnic Lixisols (LXj) Lixisols having stagnic properties within 50 cm of the surface; lacking gleyic properties within 100 cm of the surface; lacking plinthite within 125 cm of the surface.

Gleyic Lixisols (LXg) Lixisols showing gleyic properties within 100 cm of the surface.

ACRISOLS (AC)

Soils having an argic B horizon which has a cation exchange capacity of less than 24 $cmol_{(+)}kg^{-1}$ clay and a base saturation (by NH_4OAc) of less than 50 percent in at least some part of the B horizon within 125 cm of the surface; lacking the E horizon abruptly overlying a slowly permeable horizon, the distribution pattern of the clay and the tonguing which are diagnostic for Planosols, Nitisols and Podzoluvisols respectively.

Haplic Acrisols (ACh) Acrisols which are not strongly humic; lacking ferric properties; lacking plinthite within 125 cm of the surface; lacking gleyic properties within 100 cm of the surface.

Ferric Acrisols (ACt) Acrisols which are not strongly humic; showing ferric properties within 125 cm of the surface; lacking plinthite within 125 cm of the surface; lacking gleyic properties within 100 cm of the surface.

Humic Acrisols (ACu) Acrisols having an umbric or a mollic A horizon and which are strongly humic; lacking plinthite within 125 cm of the surface; lacking gleyic properties within 100 cm of the surface.

Plinthic Acrisols (ACp) Acrisols having plinthite within 125 cm of the surface.

Gleyic Acrisols (ACg) Acrisols showing gleyic properties within 100 cm of the surface; lacking plinthite within 125 cm of the surface.

ALISOLS (AL)

Soils having an argic B horizon which has a cation exchange capacity equal to or more than 24 $cmol_{(+)}$ kg^{-1} clay and a base saturation (by NH4OAc) of less than 50 percent in at least some part of the B horizon within 125 cm of the surface; lacking the E horizon abruptly overlying a slowly permeable horizon, the distribution pattern of the clay and the tonguing which are diagnostic for Planosols, Nitisols and Podzoluvisols respectively.

Haplic Alisols (ALh) Alisols which are not strongly humic; lacking ferric properties; lacking plinthite within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface.

Ferric Alisols (ALf) Alisols which are not strongly humic; showing ferric properties within 125 cm of the surface; lacking plinthite within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface.

Humic Alisols (ALu) Alisols having an umbric or a mollic A horizon and which are strongly humic; lacking plinthite within 125 cm of the surface; lacking gleyic and stagnic properties within 100 cm of the surface.

Plinthic Alisols (ALp) Alisols having plinthite within 125 cm of the surface.

Stagnic Alisols (ALj) Alisols showing stagnic properties within 50 cm of the surface; lacking gleyic properties within 100 cm of the surface; lacking plinthite within 125 cm of the surface.

Gleyic Alisols (ALg) Alisols showing gleyic properties within 100 cm of the surface; lacking plinthite within 125 cm of the surface.

NITISOLS (NT)

Soils having an argic B horizon showing a clay distribution which does not show a relative decrease from its maximum of more than 20 percent within 150 cm of the surface; showing gradual to diffuse horizon boundaries between A and B horizons; having nitic properties in some subhorizon within 125 cm of the surface; lacking the tonguing which is diagnostic for Podzoluvisols; lacking ferric or vertic properties; lacking plinthite within 125 cm of the surface.

Haplic Nitisols (NTh) Nitisols which are not strongly humic and have an argic B horizon that is not red to dusky red[41]

Rhodic Nitisols (NTr) Nitisols which are not strongly humic and have a red to dusky red argic B horizon.

Humic Nitisols (NTu) Nitisols having an umbric or a mollic A horizon, and which are strongly humic.

FERRALSOLS (FR)

Soils having a ferralic B horizon.

[41] Rubbed soil has hues redder than 5YR with a moist value of less than 4 and a dry value not more than one unit higher than the moist value

Haplic Ferralsols (FRh) Ferralsols having a ferralic B horizon that is neither red to dusky red nor yellow to pale yellow[42]; which are not strongly humic; lacking geric properties throughout the ferralic B horizon within 125 cm of the surface; lacking plinthite within 125 cm of the surface.

Xanthic Ferralsols (FRx) Ferralsols having a yellow to pale yellow ferralic B horizon; which are not strongly humic; lacking geric properties throughout the ferralic B horizon within 125 cm of the surface; lacking plinthite within 125 cm of the surface.

Rhodic Ferralsols (FRr) Ferralsols having a red to dusky red ferralic B horizon; which are not strongly humic; lacking geric properties throughout the ferralic B horizon within 125 cm of the surface; lacking plinthite within 125 cm of the surface.

Humic Ferralsols (FRu) Ferralsols having an umbric or a mollic A horizon and which are strongly humic; lacking geric properties throughout the ferralic B horizon within 125 cm of the surface; lacking plinthite within 125 cm of the surface.

Geric Ferralsols (FRg) Ferralsols having geric properties in at least some part of the ferralic B horizon within 125 cm of the surface; lacking plinthite within 125 cm of the surface.

Plinthic Ferralsols (FRp) Ferralsols having plinthite within 125 cm of the surface; lacking an albic E horizon or stagnic and gleyic properties within 100 cm of the surface.

PLINTHOSOLS (PT)

Soils having 25 percent or more plinthite by volume in a horizon which is at least 15 cm thick within 50 cm of the surface or within a depth of 125 cm when underlying an albic E horizon or a horizon which shows gleyic or stagnic properties within 100 cm of the surface.

Eutric Plinthosols (PTe) Plinthosols having an ochric A horizon and a base saturation (by NH4OAc) of 50 percent or more in the plinthite horizon; lacking an albic E.

Dystric Plinthosols (PTd) Plinthosols having an ochric A horizon and a base saturation (by NH4OAc) of less than 50 percent in the plinthite horizon.

Humic Plinthosols (PTu) Plinthosols having an umbric or mollic A horizon or a dystric histic H horizon, and which are strongly humic.

Albic Plinthosols (PTa) Plinthosols having an albic E horizon.

HISTOSOLS (HS)

Soils having 40 cm or more of organic soil materials (60 cm or more if the organic material consists mainly of sphagnum or moss or has a bulk density of less than 0.1 Mg m^{-3}) either extending down from the surface or taken cumulatively within the upper 80 cm of the soil; the thickness of the H horizon may be less when it rests on rock or on fragmental material in which the interstices are filled with organic matter.

[42] Rubbed soil has hues of 7.5YR or yellower with a moist value of 4 or more and a moist chroma of *5* or more

Folic Histosols (HSl) Histosols that are well drained and are never saturated with water for more than a few days; lacking a sulfuric horizon or sulfidic materials within 125 cm of the surface; lacking permafrost within 200 cm of the surface.

Terric Histosols (HSs) Histosols having highly decomposed organic materials with strongly reduced amounts of visible plant fibres and a very dark grew to black colour to a depth of 35 cm or more from the surface; having an imperfect to very poor drainage; lacking a sulfuric horizon or sulfidic materials within 125 cm of the surface; lacking permafrost within 200 cm of the surface.

Fibric Histosols (HSt) Histosols having raw or weakly decomposed organic materials, the fibre content of which is dominant to a depth of 35 cm or more from the surface; having a very poor drainage or being undrained; lacking a sulfuric horizon or sulfidic materials within 125 cm of the surface; lacking permafrost within 200 cm of the surface.

Thionic Histosols (HSt) Histosols having a sulfuric horizon or sulfidic materials within 125 cm of the surface; lacking permafrost within 200 cm of the surface.

Gelic Histosols (HSi) Histosols having permafrost within 200 cm of the surface.

ANTHROSOLS (AT)

Soils in which human activities have resulted in a profound modification or burial of the original soil horizons through removal or disturbance of surface horizons, cuts and fills, secular additions of organic materials, long-continued irrigation, etc.

Aric Anthrosols (ATa) Anthrosols showing remnants of diagnostic horizons due to deep cultivation.

Cumulic Anthrosols (ATe) Anthrosols showing an accumulation of sediments with a texture which is sandy loam or finer, thicker than 50 cm, resulting from long-continued irrigation or man made raising of the soil surface.

Fimic Anthrosols (ATt) Anthrosols having a fimic A horizon.

Urbic Anthrosols (ATu) Anthrosols having to a depth of more than 50 cm an accumulation of wastes from mines, town refuse, fills from urban developments, etc.

APPENDIX 4: BIOCHAR SUITABILITY BASED ON SOIL TYPE

A-Table 8: Numerical values of biochar suitability of soils in the Greater Mekong Sub-region.

FAO group	Legend	Biochar suitability index
Acrisols	AC - Acrisols	9.5
	ACf - Ferric Acrisols	11.2
	ACg - Gleyic Acrisols	6.9
	ACh - Haplic Acrisols	11.2
	ACp - Plinthic Acrisols	5.0
	ACu - Humic Acrisols	11.2
Alisols	AL - Alisols	9.5
	ALh - Haplic Alisols	11.2
Andosols	AN - Andosols	11.2
Anthrosols	ATc - Cumulic Anthrosols	5.2
Arenosols	AR - Arenosols	7.0
	ARb - Cambic Arenosols	8.0
	ARh - Haplic Arenosols	8.0
	ARl - Luvic Arenosols	8.0
	ARo - Ferralic Arenosols	8.0
Calcisols	CL - Calcisols	1.0
	CLh - Haplic Calcisols	1.0
Cambisols	CM - Cambisols	7.0
	CMd - Dystric Cambisols	8.0
	CMe - Eutric Cambisols	7.0
	CMg - Gleyic Cambisols	5.3
	CMi - Gelic Cambisols	7.0
	CMo - Ferralic Cambisols	8.0
Ferralsols	FR - Ferralsols	9.5
	FRh - Haplic Ferralsols	11.2
	FRp - Plinthic Ferralsols	5.0
	FRr - Rhodic Ferralsols	11.2
	FRu - Humic Ferralsols	11.2
	FRx - Xanthic Ferralsols	11.2
Fluvisols	FL - Fluvisols	4.7
	FLd - Dystric Fluvisols	5.2
	FLdg - Gleyi-dystric Fluvisols	3.7
	FLe - Eutric Fluvisols	4.7
	FLt - Thionic Fluvisols	5.8
	FLu - Umbric Fluvisols	5.2
	FLc- Calcic Fluvisols	3.0
Gleysols	GL - Gleysols	2.7
	GLd - Dystric Gleysols	4.2
	GLe - Eutric Gleysols	3.3
	GLk - Calcic Gleysols	2.2
	GLm - Mollic Gleysols	4.2
	GLt - Thionic Gleysols	5.8
	GLu - Umbric Gleysols	5.2

Histosols	HS - Histosols	1.0
	HSf - Fibric Histosols	1.0
Leptosols	LP - Leptosols	1.0
	LPd - Dystric Leptosols	1.0
	LPe - Eutric Leptosols	1.0
	LPq - Lithic Leptosols	1.0
Lixisols	LX - Lixisols	4.7
	LXf - Ferric Lixisols	5.2
	LXg - Gleyic Lixisols	3.7
	LXh - Haplic Lixisols	5.2
	LXj - Stagnic Lixisols	3.7
Luvisols	LV - Luvisols	4.7
	LVf - Ferric Luvisols	5.2
	LVg - Gleyic Luvisols	3.7
	LVh - Haplic Luvisols	5.2
	LVj - Stagnic Luvisols	3.7
	LVk - Calcic Luvisols	3.0
Nitisols	NT - Nitisols	8.0
Planosols	PL - Planosols	2.6
Plinthosols	PT - Plinthosols	4.7
	PTa - Albic Plinthosols	5.2
	PTd - Dystric Plinthosols	5.2
Podzols	PZh - Haplic Podzols	2.8
Regosols	RGe - Eutric Regosols	6.1
Solonchaks	SC - Solonchaks	1.0
	SCg - Gleyic Solonchaks	1.0
	SCh - Haplic Solonchaks	1.0
Solonetz	SNg - Gleyic Solonetzs	1.0
	SNh - Haplic Solonetzs	1.0
Vertisols	VR - Vertisols	1.0
	VRd - Dystric Vertisols	1.0
	VRe - Eutric Vertisols	1.0

APPENDIX 5: BIOCHAR SUITABILITY BASED ON SLOPE

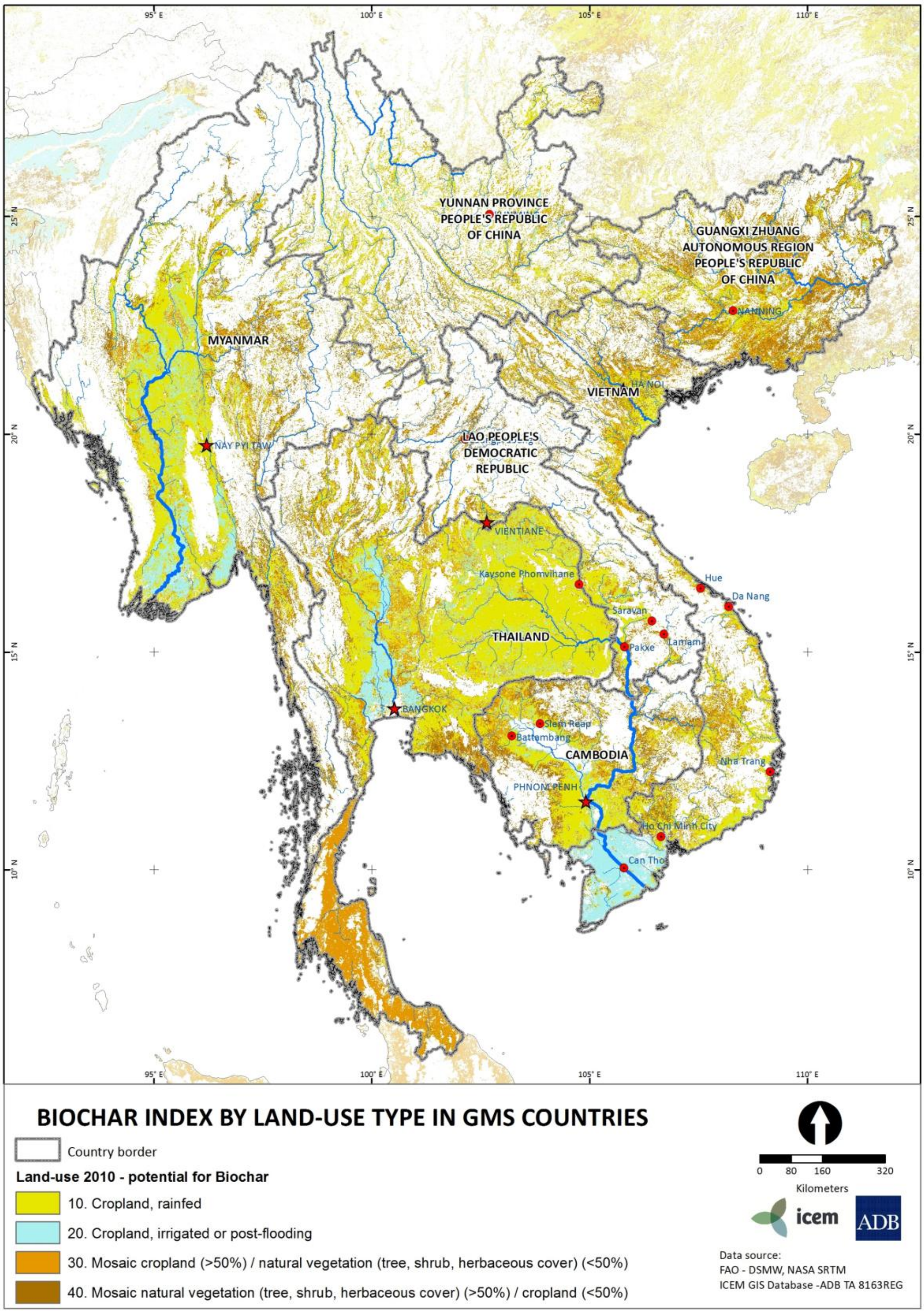
A-Table 9: Numerical values of biochar suitability for soils with different degree of slopes in the Greater Mekong Sub-region.

Slope (%)	Biochar suitability index based on soil loss based on the equation given in the footnote	Inverse of the soil loss numerical values	Now constraining the highest value to 11.2 (equal to the maximum value for soil based numerical value)
3.0	5.08	0.1968	11.2
7.0	15.95	0.0627	3.57
15.0	44.62	0.0224	1.28
25.0	88.92	0.0112	0.64
35.0	140.04	0.0071	0.41
70.0	356.99	0.0028	0.16

Soil loss = $(S/0.9)^{1.35}$, where S is percent slope.

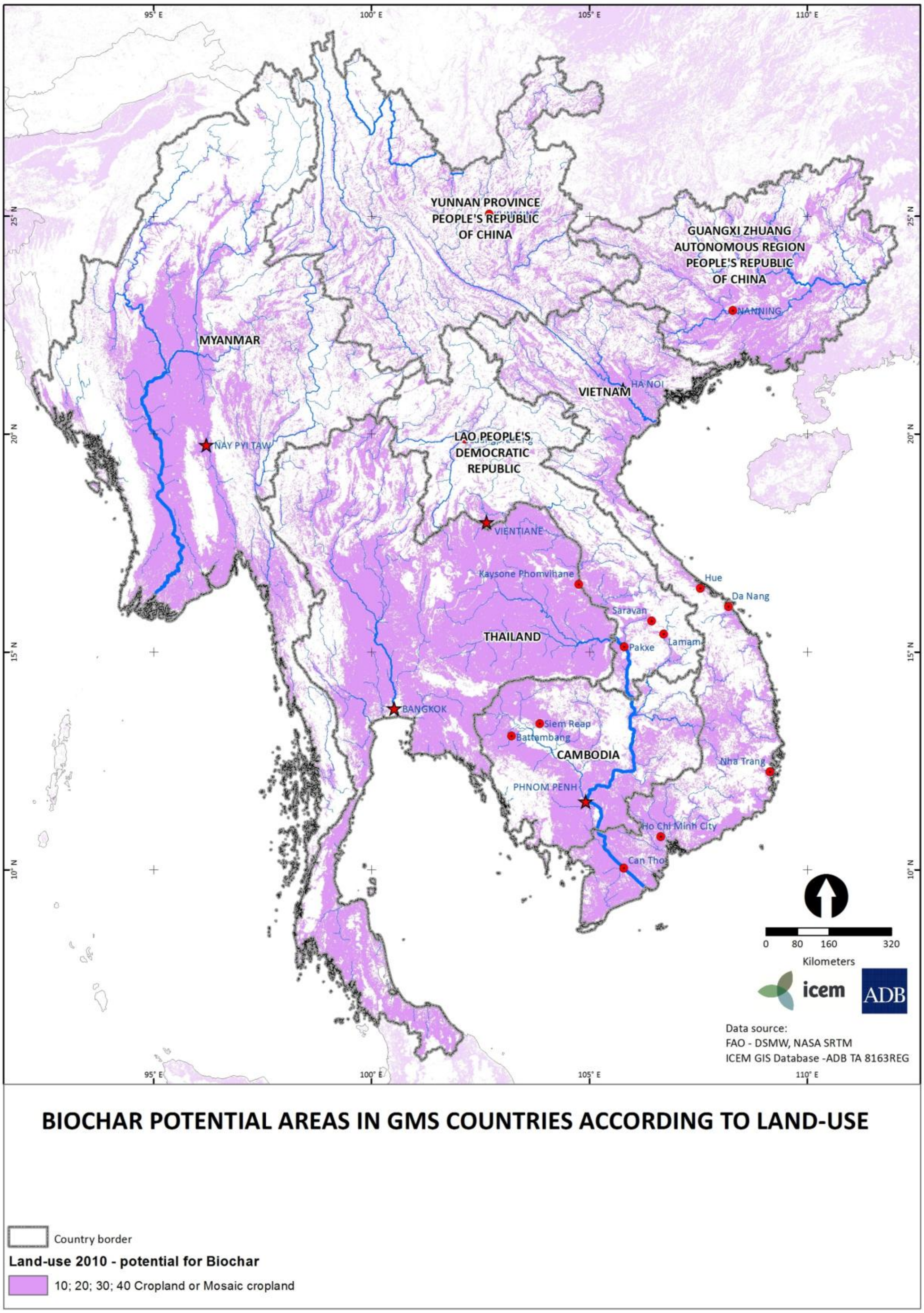
APPENDIX 6: LAND-USE SUITABLE FOR BIOCHAR

A-Figure 31: Biochar suitability of the GMS based on the land-use type. The areas under different land use are indicated in the figure legend.



APPENDIX 7: BIOCHAR POTENTIAL AREAS IN THE GMS

A-Figure 32: Biochar potential areas in the GMS based on land-uses. The three suitability classes for biochar and cropped land-use are highlighted in purple.



APPENDIX 8: DATA SOURCES

Data sources:

Myanmar: Soil types – shape file from Digital Agriculture Atlas of the Union of Myanmar . The soil types use the local soil classification system.

Lao PDR: Lao soil type data is extracted from MRC Soil Types (this data covers only Mekong river basins accounting 85,3% Lao area. MRC soil type data was created based on Field survey and reinterpretation of older 1:250,000 soil maps. Interpretation of 1:1m geology maps, satellite imagery, forestry and land cover mapping (1989) and 1:30,000 aerial photos. Data can be referred at http://www.mrcmekong.org/ The soil type system of MRC is followed the FAO/UNESCO classification system

Thailand: General Soil Map was done the geometric correction and then digitized based on 3 files in JPG format (TH2005_1SO.jpg, TH2005_2SO.jpg, TH2005_3SO.jpg). Three JPG files were downloaded from http://eusoils.jrc.ec.europa.eu/esdb_archive/eudasm/asia/maps/TH2005_3SO.htm

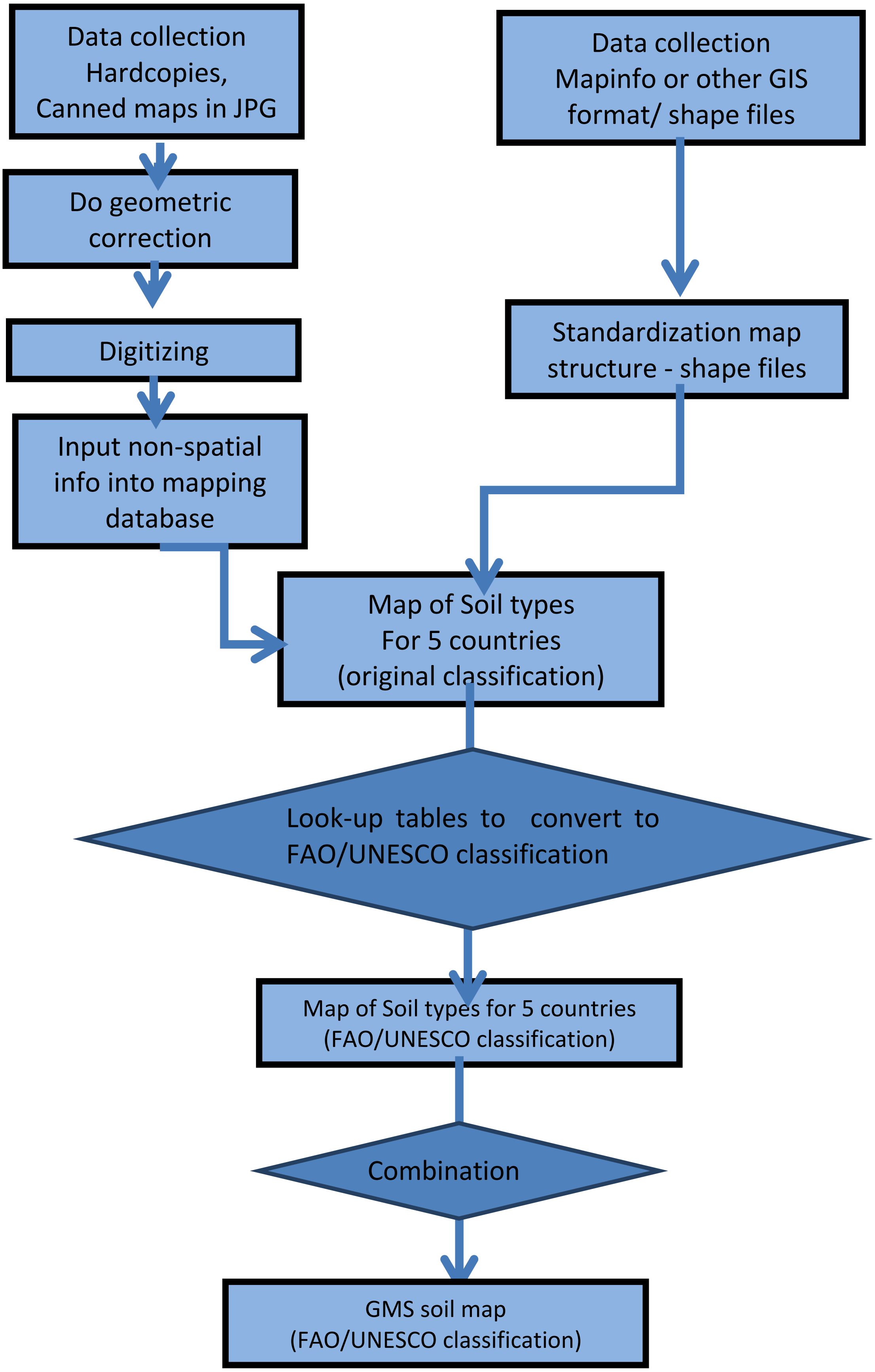
Source of hardcopy maps: Soil survey Division – Department of Land Development – Ministry of Agriculture and Cooperatives – Thailand.

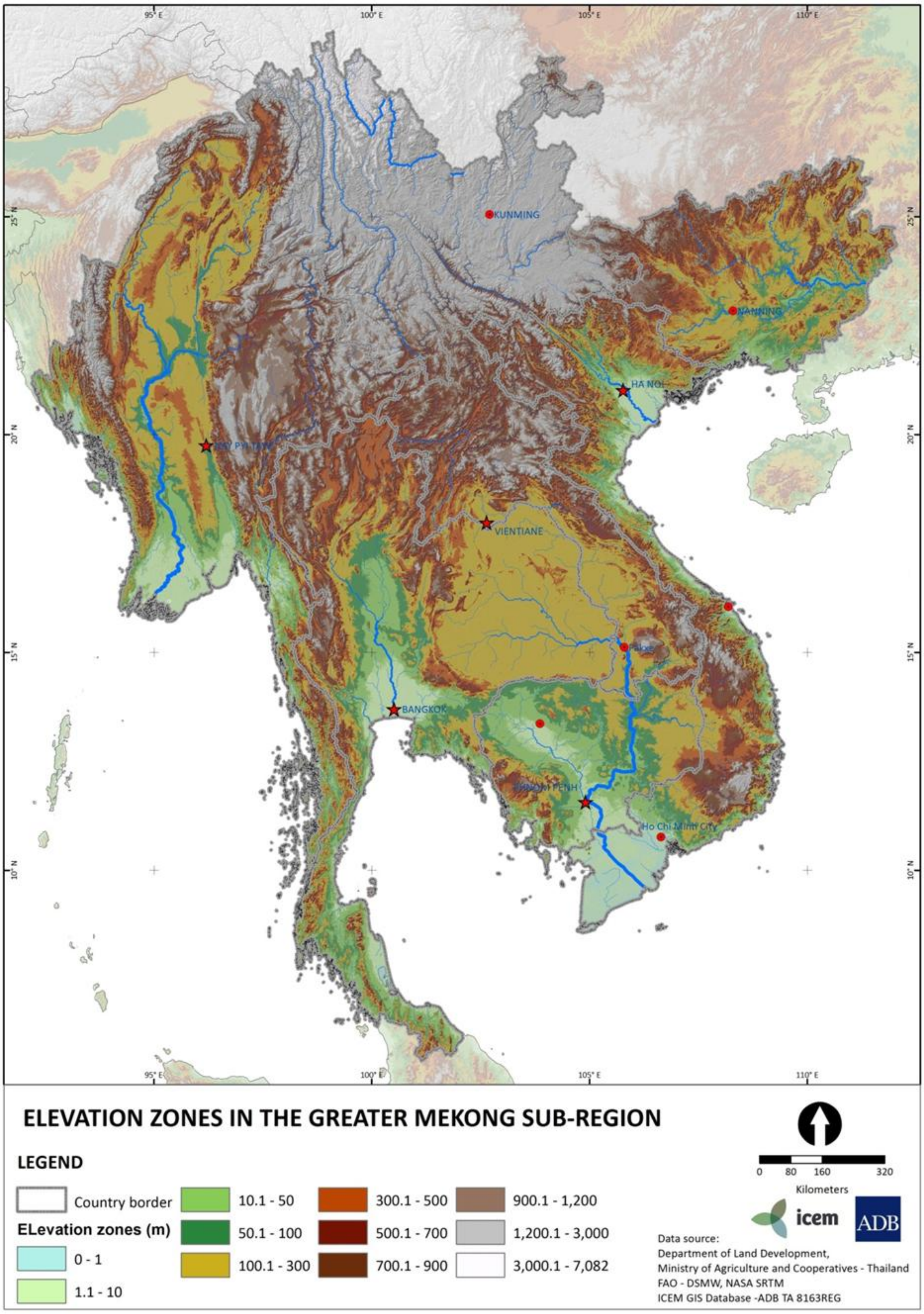
The map of soil types of Thailand has 89 soil names belong to 9 orders and 30 suborders/ and following the local name/ description

Cambodia: Soil map was downloaded at www.opendevelopmentcambodia.net in shape file format. The soil type in local classification

Vietnam: Soil map was collected from Nation Atlas 1990 in Mapinfo format (Dr Vinh is asking for this data source – we are waiting). This data is converted into shape file format (ArcGIS). It has xxx classes with local name.

Methodology to establish the GMS soil map:





A-Figure 33: The elevation map of the Greater Mekong Sub-region.

APPENDIX 9: POTENTIAL AVAILABLE WASTE IN HOTSPOTS

A-Table 10: Potential amount (tonnes per annum) of agricultural wastes potentially available in selected areas (hotspots) of the Greater Mekong Subregion countries.

Country	Province/State/ Hotspot	Rice	Maize	Sugar Cane	Cassava	Peanut	Total residue
Viet Nam	Tay Ninh (V1)	401,720	8,042	84,677	33,076	8,185	535,701
	Vinh Phuc (V2)	166,179	18,931	517		1,811	187,437
	Binh Thuan (V3)	327,501	33,558	6,468	90,701	2,128	460,356
	Binh Dinh (V4)	335,755	13,576	7,775	55,018	7,476	419,600
Cambodia	Svay Rieng (C1)	284699	24	1539	67,768	-	354,029
	Kâmpóng Chhnang (C2)	204,156	1,348	269	731	-	206,504
Lao PDR	Savannakhet (L2)	260,429	7,557	37,323	-	622	305,930
	Vientiane (L1)	174,545	4,097	309	-	30	178,981
Thailand	Rayong (T1)	5,973	-	972	31,752	-	38,697
	Kalasin (T2)	369,717	23	205,889	118,817	-	694,445
	Nakhon Pathom (T3)	257,421	-	43,357	-	-	300,778
-	Nakhon Ratchasima (T4)	631,698	127,802	334,325	1,025,477	-	2,119,302
Myanmar	Nay Pwi Taw (M1)	-	-	-	-	-	-
	Shwebo (M2)	-	-	-	-	-	-

A-Table 11: Dry matter waste (tonnes per annum) potentially available from livestocks and poultry animals available in the selected areas (hotspots) of the Greater Mekong Subregion countries.

Country	Province/State/ Hotspot	Cattle	Buffalo	Pig	Sheep & Goat	Poultry	Total residue
Viet Nam	Tay Ninh (V1)	63,875	24,100	42,675	-	-	130,650
	Vinh Phuc (V2)	71,037	22,416	111,585	-	-	205,038
	Binh Thuan (V3)	119,950	9,631	52,344	-	-	181,925
	Binh Dinh (V4)	184,282	22,937	153,504	-	-	360,723
Cambodia	Svay Rieng (C1)	195,193	8,214	25,051	48	26,546	255,052
	Kâmpóng Chhnang (C2)	154,754	46,749	22,381	168	17,797	241,849
Lao PDR	Vientiane (L1)	77,015	20,805	25,514	5,338	30,801	159,473
	Savannakhet (L2)	292,365	318,645	59,568	16,726	31,661	718,965
Thailand	Rayong (T1)	14,730	2,003	15,764	-	141,487	176,932
	Kalasin (T2)	67,047	56,037	10,383	-	12,952	151,419
	Nakhon Pathom (T3)	39,016	569	206,705	-	49,046	302,805
	Nakhon Ratchasima (T4)	234,778	59,339	66,627	-	160,584	529,573
Myanmar	Nay Pwi Taw (M1)	177,875	76,472	3,657	71,210	464,270	793,484
	Shwebo (M2)	666,316	94,679	32,592	69,677	563,441	1,426,705

APPENDIX 10. HOTSPOTS: SOIL PROPERTIES AND AND OTHER RELEVANT INFROMATION

1. VIET NAM

V1 - Tay Ninh Province

Soils in Tay Ninh have been classified under four soil groups and with 12 soil units (A-Table 12; A-Figure 35) according to the Vietnamese soil classification system and three soil groups based on the FAO classification system.

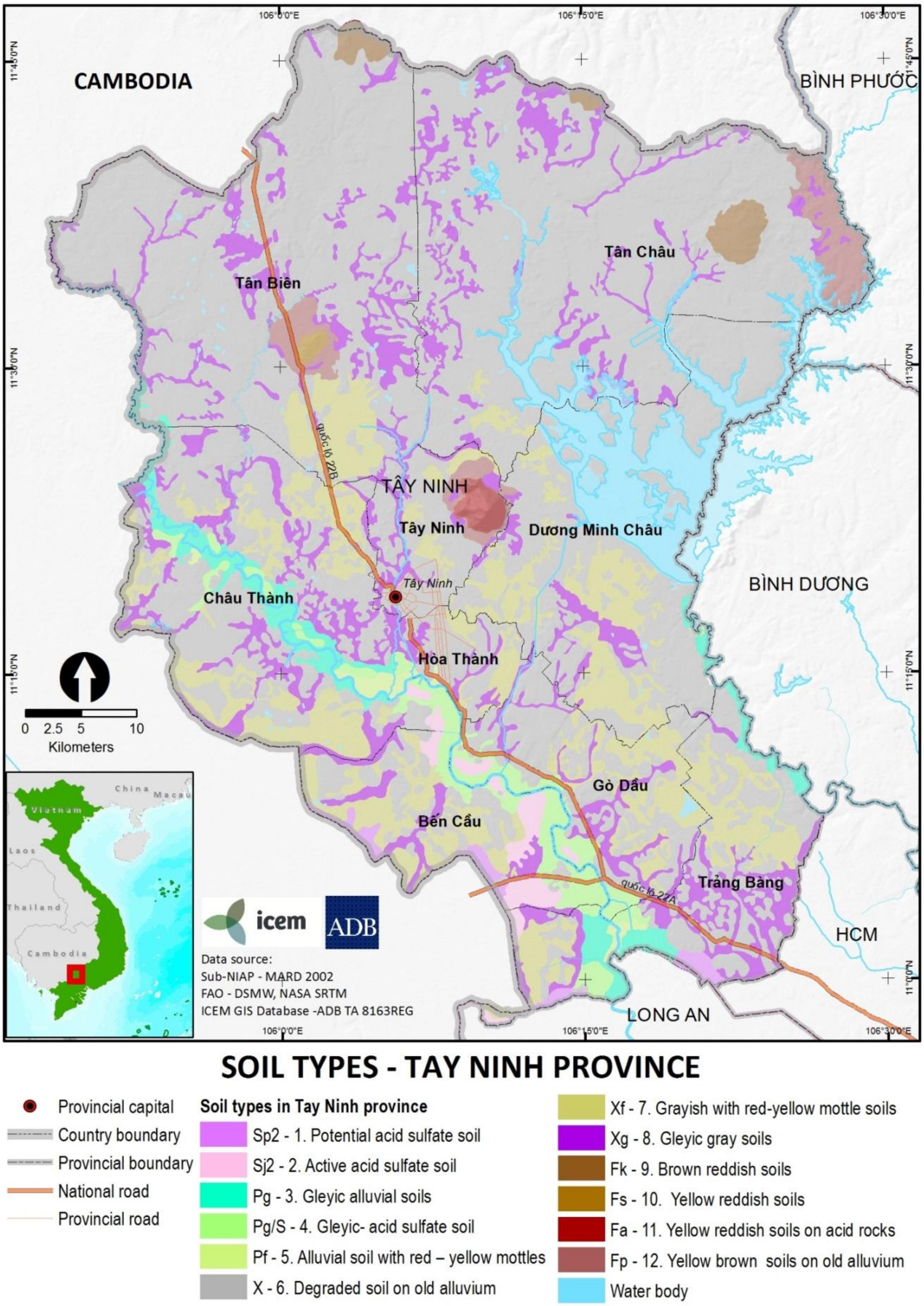
A-Table 12: The distribution and soil types in Tay Ninh province of Viet Nam.

Vietnam classification system		FAO classification system		Area	
Soil name	Symbol	Soil name	Symbol	ha	%
I. Acid sulfate soils		**Thionic Fluvisols**	**FLt**	**6,822**	**1.69**
1. Potential acid sulfate soils	Sp2	Proto-thionic Gleysols	GLtp	2,633	0.65
2. Active acid sulfate soils	Sj2	Orthi-thionic Fluvisols	FLto	4,189	1.04
II. Alluvial soils		**Fluvisols**	**FL**	**21,867**	**5.43**
3. Gleyic alluvial soils	Pg	Gleyi-Umbric Fluvisols	Flug	9,799	2.43
4. Gleyic alluvial soils on acid sulfate soil layers	Pg/S	Thionic Gleyic Fluvisols	FLg	10,237	2.54
5. Alluvial sols with mottle layer	Pf	Cambic Fluvisols	CMg	1,831	0.45
III. Degraded gray soils		**Acrisols**	**AC**	**330,033**	**81.9**
6. Degraded gray soils on old alluvium	X	Haplic Acrisols	ACh	230,323	57.16
7. Grayish soil with mottle	Xf	Plinthic Acrisols	ACp	50,526	12.54
8. Gleyic gray soils	Xg	Gleyic Acrisols	ACg	49,184	12.21
IV. Red yellowish soils		**Ferralsols/Acrisols**		**14,468**	**3.59**
9. Brownish yellow soils on basaltic rock	Fk	Rhodic Ferralsols	FRr	3,812	0.95
10. Yellowish red soils on shale and metamorphic rocks	Fs	Ferric Acrisols	ACf	546	0.14
11. Yellowish red soils on acid ingenuous rocks	Fa	Haplic Acrisols	Ach	1,553	0.39
12. Brownish yellow soils on old alluvial stone	Fp	Haplic Acrisols	ACh	8,557	2.12
V. Rivers and lakes				29,770	7.39

Source: National Institute of Agriculture planning and Projection (NIAPP) 2005.

Degraded gray soils are most wide spread in the Province, occupying an area of 330,033 ha (81.9%). These soils are distributed in Tay Ninh town (10.442 ha), Go Dau (20.447 ha), Tan Bien (79.789 ha), Bien Cau (14.828 ha), Tan Chau (83.428 ha), Trang Bang (25.486 ha), DM Chau District (42.294 ha), Hoa Thanh (7.114 ha) and Chau Thanh (46.203 ha) districts.

Alluvial soils cover an area of 21,867 ha (5.43%) in the Province. These soils are derived from alluvium deposited by Vam Co Dong and Sai Gon rivers. Alluvial soils are present in Tan Bien (483 ha), Ben Cau (3,446 ha), DM. Chau (606 ha), Trang Bang (4,938 ha), Chau Thanh (8,478 ha), Hoa Thanh (710 ha) and Go Dau (3,206 ha) districts.



A-Figure 34: The soil (local classification system) map of Tay Ninh province, Viet Nam.

Acid sulfate soils exist over an area of 6,822 ha (1.69%) and these soils occur in Chau Thanh (453 ha); Ben Cau (4,106 ha); Go Dau (463 ha) and Trang Bang (1,800 ha) districts.

Red yellowish soils exist over an area of 14,468 ha (3.59%). These soils are present in Tay Ninh town (2,770 ha) and Tan Chau (7,426 ha), Tan Bien district (4,104 ha) and DM Chau (168 ha) districts.

A-Table 13: A summary of main soil properties of common soils in Tay Ninh province

Soil group	pH (water)	Clay (%)	O.M. (%)	CEC ($cmol_c$/kg)	Total N (%)	Total P_2O_5 (%)	Total K_2O (%)
	Range						
Degraded gray soils	4.4-4.7	<35	1.4-2.5	3.91- 4.05	0.06-0.10	0.02-0.05	0.03-0.04
Red yellowish soils	4.7-4.8	50-60	2.3-4.1	6.74- 9.84	0.15-0.22	0.09-0.10	0.021-0.024
Alluvial soils	4.2-4.8	56-64	4.8-8.9	16.8-17.9	0.16-0.33	0.05-0.08	0.34-0.38
Acid sulphate soils	3.5-4.3	53-63	10.0-11.0	16.9-18.8	0.40-0.50	0.12-0.16	0.16-0.41

Degraded gray soils have highly acidic pH, low clay content and poor fertility as indicated by the low levels of organic matter, total N, total P and total K contents (A-Table 13). All other soils in the Province also have highly acidic pH, with pH < 4.0 for most acid sulfate soils. Based on the pH alone, all soils in the province will benefit from biochar application. However, most benefits from biochar application would be expected in degraded gray soils and acid sulfate soils.

V2 - Vinh Phuc Province

The northeast of the province is mountainous and topography becomes flatter from the northeast to the southeast in the province. Soils of the Vinh Phuc province can be distinguished based the three distinct topographic regions: plain or low land, midland or hilly topography, and mountainous with low to medium mountains. The plains are dominated by alluvial soils (Fluvisols and Gleysols) whereas Degraded gray, Red yellowish and Skeletal eroded soils (Acrisols, Plinthosols and Leptosols) are common in the hilly and hill slopes areas. The distribution and extent of various soil types in Vinh Phuc province are given in A-Figure 36 and A-Table 14.

Alluvial soils are 45,415 ha (26.8%) are distributed in Vinh Tuong (10,819 ha), Yen lac (8,127 ha), Me Linh (9,134 ha), Lap Thach (5,688 ha), Binh Xuyen (4,820 ha), Tam Duong (1,500 ha) and Vinh Yen (2,187 ha). These soils are mostly formed on sediments deposited by Red river, Lo rivers and some other streams or rivers. There are 8 soil units of alluvial soils as shown in A-Table 14.

Deposited alluvial soils on Red river system are slightly to moderately alkaline reaction with pH_{KCl}> 7,0), CEC = 10-15 , low organic matter (OM%: 0.5-0.6%); very low total N (0.02-0.05%), high total P (P_2O_5 >0.08%), moderate total K (K_2O%: 0,8-1,5). Deposited alluvial soils on other rivers are more acidic than in Red river system with pHKCl=4.0-5.0, CEC: 5-7 cmolc/kg, low organic matter (OM% <1.0%); low total N (<0.08%), moderate total P and total K (P_2O_5%: 0.04-0.08; K_2O%: 0.8-0.9).

Annual deposited alluvial soils covers an area of 1037 ha (0.9%) and these are distributed in Lap Thach (836 ha) and Tam Duong (201 ha). Annual sedimentation is deposited by Lo, Ca Lo and Pho Day rivers. These soils are characterized by acidic pH (pH_{KCl} = 4.0-5.0), low base saturation (50-60%), low CEC (5-7 $cmol_c$/kg), low OM and total N (OM = <1.0%; N = <0.08%) and moderate total P and total K (P_2O_5 = 0.04-0.08%; K_2O% = 0.8-0.9%).

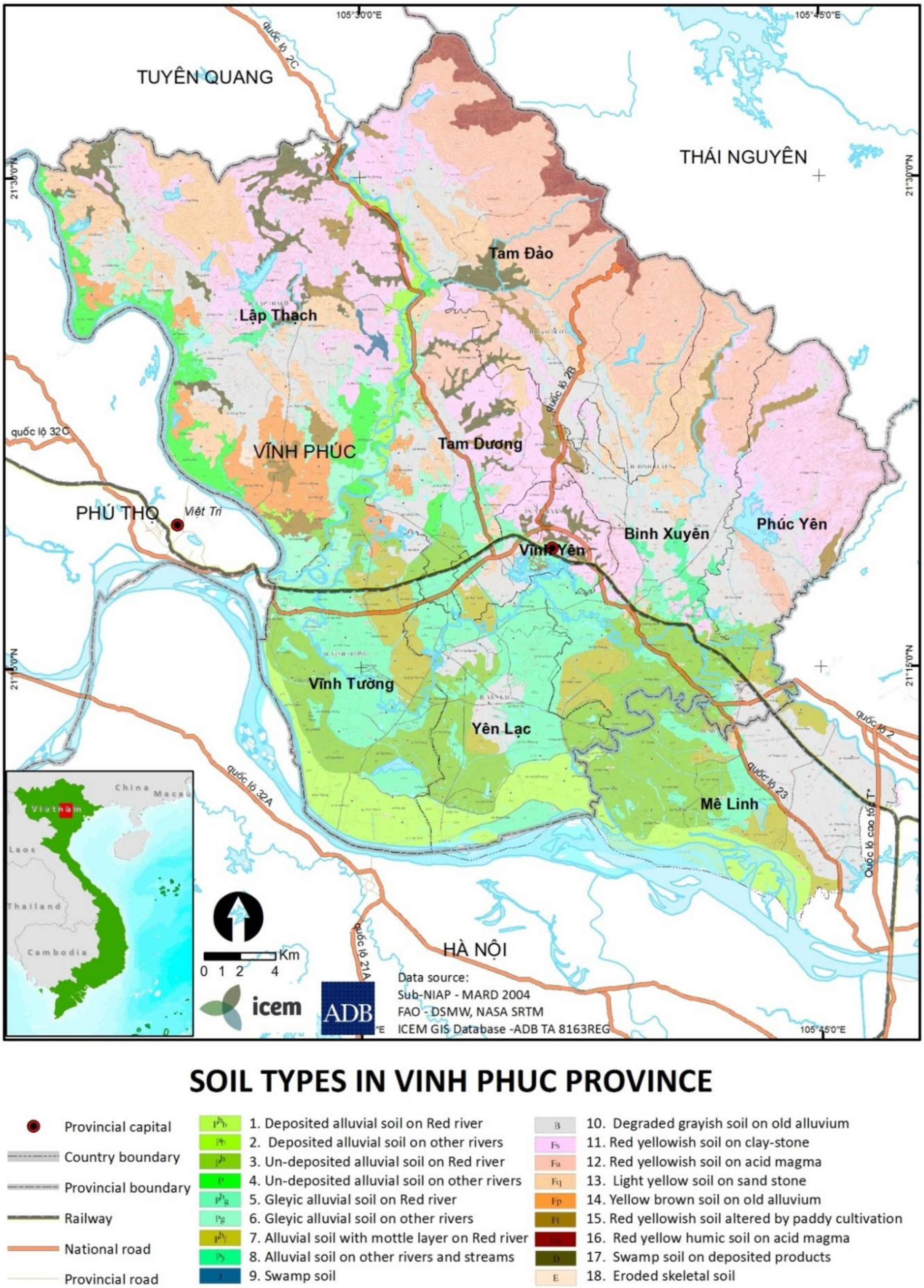
Gray soils cover 21,927 ha (18.1%) area in the province and these are distributed Me Linh (6,584 ha), Lap Thach (6,027 ha), Binh Xuyen (3,748 ha) and Tam Duong (3,606 ha) districts. Soils are acidic (pH_{KCl} = < 5.5), low base saturation (<50%), low CEC (3-9 $cmol_c$/kg), low OM and nitrogen (OM = <1%; N = <0.08%) and low level of total P and K (P_2O_5 < 0.04%; K_2O <0.8%).

Degraded gray soils (Acrisols) occur over 51,013 ha (42.2%) area in the province. These soils are highly acidic (pH_{KCl} = 4.0-4.5) , low base saturation (< 50%), low CEC (5-10 $cmol_c$/kg), low OM and nitrogen (OM = <2%; N = <0.1%) and moderate levels of total P and K (P_2O_5 < 0.06-0.08%; K_2O <1.0-1.5%).

A-Table 14: The distribution and soil types in Vinh Phuc province of Vietnam.

Vietnam classification system		FAO classification system		Area	
Soil name	Symbol	Soil name	Symbol	ha	%
Alluvial soils		Fluvisols		45,415	26.8
1. Deposited alluvial soil on Red rivers	Pbh	Eutric Fluvisols	FLe	7,405	6.1
2. Deposited alluvial soils on other rivers	Pb	Eutric Fluvisols	FLe	1,037	0.9
3. Un-deposited alluvial soils on Red river	Ph	Haplic Fluvisols	FLh	11,402	9.4
4. Un-deposited alluvial soils on other rivers	P	Haplic Fluvisols	FLh	3,140	2.5
5. Gleyic alluvial soils on Red river	Pgh	Gleyic Fluvisols	FLg	11,641	9.6
6. Gleyic alluvial soils on other rivers	Pg	Gleyic Fluvisols	FLg	5,681	4.7
7. Alluvial soil with mottle layer on Red river	Pfh	Plinthosols	PT	4,177	3.5
8. Alluvial soil on other rivers and streams,	Py	Eutric Fluvisols	FLe	932	0.8
Swamp and Peat soils		Histosols	HS	159	0.1
9. Swamp soils	J	Histosols	HS	159	0.1
Degraded gray soils		Acrisols		21,927	18.1
10. Degraded grayish soils on old alluvium	B	Haplic Acrisols	ACh	21,927	18.1
Red yellowish soils		Ferrasols	FR	51,013	42.2
11. Red yellowish soils on clay stone	Fs	Ferralic Acrisols	FRf	19,323	16.0
12. Red yellowish soil on acid magma rocks	Fa	Arenic Acrisols	AC	14,430	11.9
13. Light yellow soils on sandstones	Fq	Arenic Acrisols	AC	11,319	9.4
14. Yellow brown soil on old alluvium	Fp	Haplic Acrisols	ACh	3,443	2.8
15. Red yellowish soil altered by paddy cultivation	FL	Stagni- Albic Acrisols	ACa/s	2,498	2.1
Red yellow humic soils on mountains		Humic Ferrasols	FRh	2,246	1.9
16. Red yellow humic soil on acid magma rocks	Ha	Humic Ferrasols	FRh	2,246	1.9
Swamp soils		Gleysols	GL	3,186	2.6
17. Swamp soils on deposited products	D	Umbic Gleysols	GLu	3,186	2.6
Skeletal eroded soils		Leptosols	LP	102	0.1
18. Skeletal eroded soils	E	Leptosols	LP	102	0.1
Rivers and lakes		**Water body**		**16,238**	

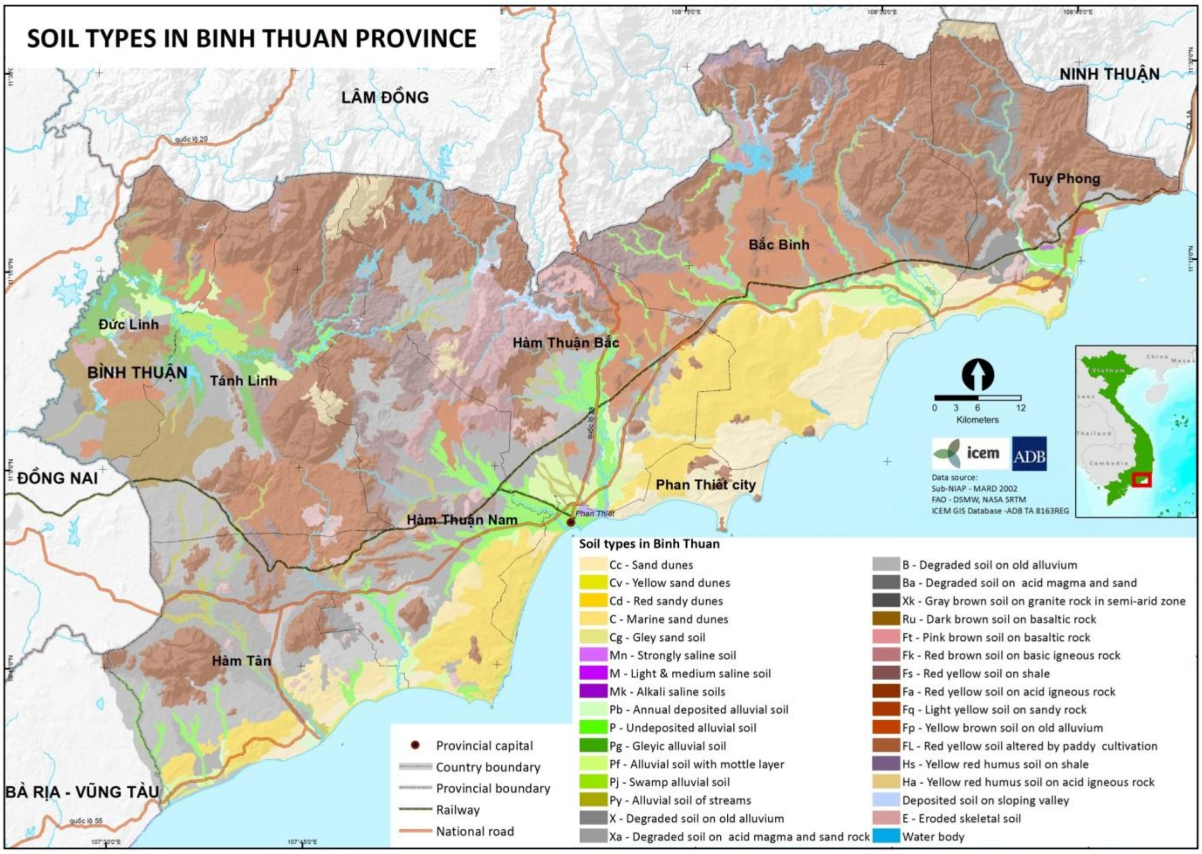
Source: National Institute of Agriculture planning and Projection (NIAPP), 2004.



A-Figure 35: The soil (Local classification system) map of Vinh Phuc Province, Viet Nam.

V3 – Binh Thuan Province

There are 10 soil groups with 32 soil units in province (A-Table 15; A-Figure 37). The largest area is covered by reddish yellow soils (366,130 ha, 46.77%), followed by degraded gray soils (137,349 ha, 17.54%), sandy soils (117,486 ha, 15.01%) and alluvial soils (87,376 ha, 14.16%). Black soils (21,240 ha, 2.71%), Red and brownish gray soils in semi-arid regions (11,708 ha), Yellow red humus soil on mountains (Andosols), 10.325 ha (1.32%), skeletal soils 8,299 ha (1.06%), saline soils 5,102 ha (5.02%) are the other soil groups in the Province.



A-Figure 36: The soil (local classification system) map of Binh Thuan Province, Viet Nam.

The summary of soil properties data for main soil types in Binh Thuan is presented in A-Table 15. A large majority of the soils in the province are highly to extremely acidic (pH < 5.5), with low contents of organic matter, and total nitrogen, phosphorus and potassium. The cation exchange capacity of most soils is also low to very low. It is expected that biochar application in these soil will produce some beneficial effects from the liming effect and addition of nutrients. The application of biochar is also likely to increase the nutrient and water holding capacity of the soils in the Province.

A-Table 15: The distribution and soil types in Binh Thuan province of Vietnam.

Vietnam classification system		FAO classification system		Area	
Soil name	Symbol	Soil name	Symbol	ha	%
I. Sandy soils, sand dunes and marine sandy soils	**C**	**Arenosols**		**117,486**	**15.01**
1.White sandy dune	Cc	Luvic Arenosols	ARl	37,449	4.78
2. Yellowish sand dune	Cv	Luvic Arenosols	ARl	4,014	0.51
3. Reddish sandy dune	Cd	Ferralic Arensols	ARf	65,538	8.37
4. Marine sandy soils	C	Haplic Arenosols	ARh	7,231	0.92
5. Gleyic sandy soils	Cg	Gleyic Arenosols	ARg	3,255	0.42
II. Saline soils	**M**	**Solonchaks**	**SC**	**853**	**0.11**
6. Strongly saline soils	Mi	Haplic Solonchaks	SCh	586	0.07
7. Moderate saline soils	M	Molic Solonchaks	SCm	144	0.02
8. Alkaline saline soils	Mk	Haplic Solonchaks	SCh	122	0.02
III. Alluvial soils		**Fluvisols**	**FL**	**87,374**	**11.6**
9. Deposited alluvial soils	Pb	Eutric Fluvisols	FLe	3,203	0.41
10. Un-deposited alluvial soils	P	Dystric Fluvisols	FLd	34,242	4.37
11. Gleyic alluvial soils	Pg	Umbric Fluvisols	Flu	11,598	1.48
12. Alluvial soils with mottle layer	Pf	Cambic Fluvisols	FLc	18,209	2.33
13. Swamp alluvial soils	P	Umbric Fluvisols	Flu	2,511	0.32
14. Alluvial soils on stream sedimentation	Py	Haplic Fluvisols	FLh	17,611	2.25
IV. Degraded gray soils	**X**	**Acrisols/Lixisols/Luvisols**		**137,349**	**17.54**
15. Gray soil on old alluvial	X	Haplic Acrisols	ACh	63,125	8.06
16. Gray soils on acidic and sandstones	Xa	Haplic Acrisols	ACh	62,277	7.96
17. Gleyic gray soils	Xg	Gleyic Acrisols	ACg	511	0.07
18. Gray soils on old alluvial	B	Haplic Lixisols	LXh	9,748	1.25
19. Degraded gray soils on granite rocks and sandstones	Ba	Chromic Luvisols	LVc	1,687	0.22
V. Red and brownish gray soils in semi-arid regions		**Chromic Lixisols**	**LXc**	**11,708**	**1.50**
20. Brownish gray soils in semi-arid regions	Xk	Chromic Luvisols	LVc	11,708	1.50
VI. Black soils		**Luvisols**	**LV**	**21,240**	**2.71**
21. Dark brown soil on basaltic rock	Ru	Chromic Luvisols	LVl	21,240	2.71
VII. Reddish yellow soils	**Ft**	**Ferralsols/Acrisols**		**366,130**	**46.77**
22. Red brown soil on basic igneous rock	Fk	Rhodic Ferralsols	FRr	1,812	0.23
23. Red yellow soil on shale	Fk	Haplic Ferralsols	FRd	24,999	3.19
24. Red yellow soil on acid igneous rock	Fs	Plinthic Acrisols	ACp	41,872	5.35
25. Light yellow soil on sandy rock	Fa	Arenic Acrisols	ACr	202,852	25.91
26. Yellow brown soil on old alluvial	Fq	Hyper-Dystric Acrisols	ACd	35,446	4.53
27. Red yellow soil altered by paddy cultivation	Fp	Cambic Fluvisols	FLc	49,658	6.34
28. Reddish yellow alternative by paddy cultivation	Xpb	Stagni- Albic Acrisols	ACs	9,491	1.21
VIII. Yellow red humus soil on mountains		**Andosols**	**AN**	**10,325**	**1.32**
29. Yellow red humus soil on shale	Hs	Andosols	AN	1,202	0.15
30. Yellow red humus soil on acid igneous rock	Ha	Andosols	AN	9,123	1.17
IX. Swamp soils		**Gleysols**	**GL**	**5,102**	**0.65**
31. Deposited soil on sloping valley	D	Umbric Gleysols	GLu	5,102	0.65
X. Eroded skeletal soil	**E**	**Leptosols**	**LP**	**8,299**	**1.06**
32. Eroded skeletal soil	E	Lithic Leptosols	LPl	8,299	1.06
Others				16,981	2.17
Rivers and Lakes		Water body		8,394	1.07

Source: National Institute of Agriculture Planning and Projection (NIAPP) 2005.

A-Table 16: A summary of main soil properties of soils in Binh Thuan province.

Soil group	pH (KCl)	Clay (%)	O.M. (%)	Total N (%)	Total P_2O_5 (%)	Total K_2O (%)	CEC ($cmol_c$/kg)
	Range						
Arenosols	4.20- 4.67	10-30	0.67- 2.55	0.03- 0.08	0.01- 0.015	0.03-0.72	2.0-3.0
Solonchaks	4.50- 4.70	-	0.79-1.55	0.06-0.08	-	-	No data
Acrisols	4.25- 4.95	25-30	0.81- 0.93	0.05- 0.06	0.06- 0.12	0.01-0.02	3.2-4.0
Ferralsols	4.89- 6.04	45-55	3.0-4.0	0.10-0.15	0.01-0.026	0.47- 5.36	No data
Fluvisols	4.00- 5.70	30-45	1.52-1.81	0.09-0.13	0.06-0.15	0.16-0.65	11.6-14.2

Source: NIAPP, 2005

V4 – Binh Dinh Province

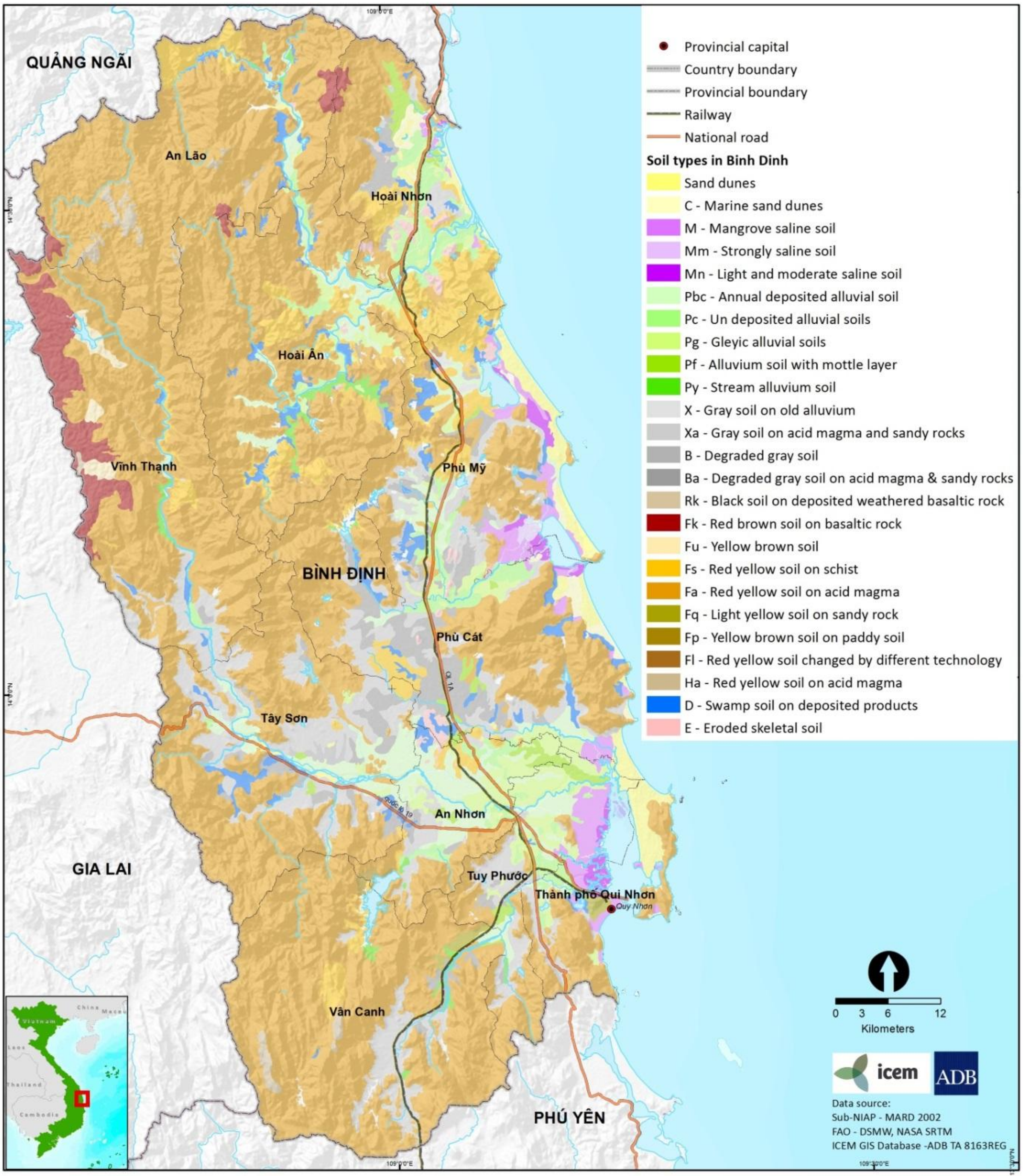
The distribution of soil according to the local and FAO classification systems is presented in A-Table 17 and A-Figure 38. Reddish yellow soils 401,811 ha (68.97%) are the most dominant soil type in Binh Dinh Province. Degraded gray soils (70,809 ha), Alluvial soils (63,756 ha), sandy soils (13,283 ha), saline soils (12,710 ha) and swamp soils (12,875 ha) are other important soils in the Province (A-Table 17 and A-Figure 38).

A-Table 17: The distribution and soil types in Binh Dinh province of Vietnam.

Vietnam soil classification	Symbol	FAO soil classification	Symbol	Area	
				ha	%
I. Sandy soils, sand dune & marine sandy soils, C		**Arenosols**		**13,283**	**2.28**
1.White sandy dune	Cc	Luvic Arenosols	ARl	10,494	1.80
2. Marine sandy soils	C	Haplic Arenosols	ARh	2,789	0.48
II. Saline soils	**M**	**Solonchaks**	**SC**	**12,710**	**2.18**
3. Mangrove saline soils	Mm	Gleyic Solonchaks	SCg	438	0.08
4. Strong saline soils	Mn	Haplic Solonchaks	SCh	2,654	0.46
5. Moderate and slightly saline soils	M	Molic Solonchaks	SCm	9,618	1.65
III. Acid sulfate soils	**S**	**Thionic Fluvisols**	**FLt**	**456**	**0.08**
6. Deep potential acid sulfate, saline soils	Sp2M	Proto-thionic Gleysols	GLtp	49	0.01
7. Deep potential acid sulfate soils	Sp2	Proto-thionic Gleysols	GLtp	407	0.07
IV. Alluvial soils	**P**	**Fluvisols**	**FL**	**63,756**	**10.94**
8. Annual deposited alluvial soils	Pbc	Stagnic dystric Fluvisols	FLd	24,371	4.18
9. Un-deposited acidic alluvial soils	Pc	Gleyic dystric Fluvisols	FLd	15,783	2.71
10. Gleyic alluvial soils	Pg	Gleyic Fluvisols	FLg	15,549	2.67
11. Alluvial soils with mottle layer (*)	Pf	Cambic Fluvisols	FLb	4,840	0.83
12. Alluvial soils of other rivers	Py	Dystric Fluvisols	FLd	3,213	0.55
VI. Degraded gray soils	**X/B**	**Acrisols**	**AC**	**70,809**	**12.15**
13. Gray soils on old alluvial	X	Plinthic Acrisols	ACh	353	0.06
14. Gray soils on acidic igneous rocks	Xa	Ferralic Acrisols	ACx	49,639	8.52
15.Degraded grayic soils on old alluvium	B	Haplic Acrisols	ACh	836	0.14
16. Degraded gray soils on acidic igneous and sandy rocks	Ba	Haplic Acrisols	ACp	19,981	3.43
VII. Black soils	**R**	**Luvisols**	**LV**	**160**	**0.03**
17. Black soils on basaltic deposited products	Rk	Chronic Luvisols	LVc	160	0.03
VIII. Reddish yellow soil	**F**	**Ferralsols/Acrisols**		**401,811**	**68.97**
18. Red brown soils on basic and neutral igneous rocks	Fk	Rhodic Ferralsols	FRr	12,596	2.16
19. Brown yellowish soils on basic and neutral igneous rocks	Fu	Rhodic Ferralsols	FRx	1,034	0.18

20. Reddish yellow soils on schist and metamorphic rocks	Fs	Plinthic Acrisols		33,408	5.73
21. Reddish yellow soil on acidic igneous rocks	Fa	Rhodic Acrisols	AC	351,302	60.30
22. Lightly yellow soil on sandstone	Fq	Haplic Acrisols	ACh	1,362	0.23
23. Brown yellow soils on old alluvium	Fp	Haplic Acrisols	ACh	730	0.13
24. Reddish yellow soil altered by paddy cultivation	Fl	Stagnic Acrisols	ACs	1,379	0.23
IX. Reddish yellow humic soils on mountains	**H**	**Alisols**	**AL**	**3,461**	**0.59**
25. Red yellow humic soils on acidic igneous rocks	Ha	Humic Alisols	AL	3,461	0.59
X. Swamp soils	**D**	**Gleysols**	**GL**	**12,875**	**2.21**
26. Swamp soils of deposited products		Stagnic Gleysols	GLs		
XI. Eroded skeletal soils	**E**	**Leptosols**	**LP**	**3,292**	**0.57**
27. Eroded skeletal soils	E	Lithic Leptosols	LPl	3,292	0.57
Water surface and rivers				19,942	3.31

SOIL TYPES IN BINH DINH PROVINCE



A-Figure 37: The soil (local classification system) map of Binh Dinh Province, Viet Nam.

Most soils including the most predominant soil (Reddish yellow soil) have highly acidic pH. The organic matter content in the soils is highly varied from very low to high; however in the dominant soil the SOM is low. The CEC, Total N, total P and total K contents in the most common soils are low (A-Table 18). Based on the pH alone, all soils in the province will benefit from biochar application. However, most benefits from biochar application would be expected in acid sulfate soils, degraded gray soils and Reddish yellow soils.

A-Table 18: A summary of soil properties of the soils in Binh Dinh province.

Soil group	pH (KCl)	O.M. (%)	Total N (%)	Total P_2O_5 (%)	Total K_2O (%)	CEC ($cmol_c$/kg)
	Range					
Saline soils	3.0-6.0	2.5-6.0	0.13-0.20	0.02-0.09	0.25-0.80	4.3
Acid sulfate soils	2.9-4.0	3.0-4.5	0.20-0.35	0.07-0.10	0.34	8-25
Alluvial soils	4.5-5.5	2.0-3.5	0.10-0.20	0.05-015	0.15-0.35	10-13
Degraded gray soils	3.9-5.0	0.8-2.0	0.05-0.10	0.03-0.16	0.10-0.20	3.5-13
Reddish yellow soils	4.0-5.5	0.1-3.5	0.01-0.30	0.05-0.12	0.20-0.40	6.8-8.5
Reddish yellow humic soils	3.8-4.1	6.4-7.4	0.27-0.28	0.22-0.58	0.02-0.04	-
Swamp soils	4.0-4.5	<1.36	0.05-0.10	-	-	2.2-3.5

2. CAMBODIA

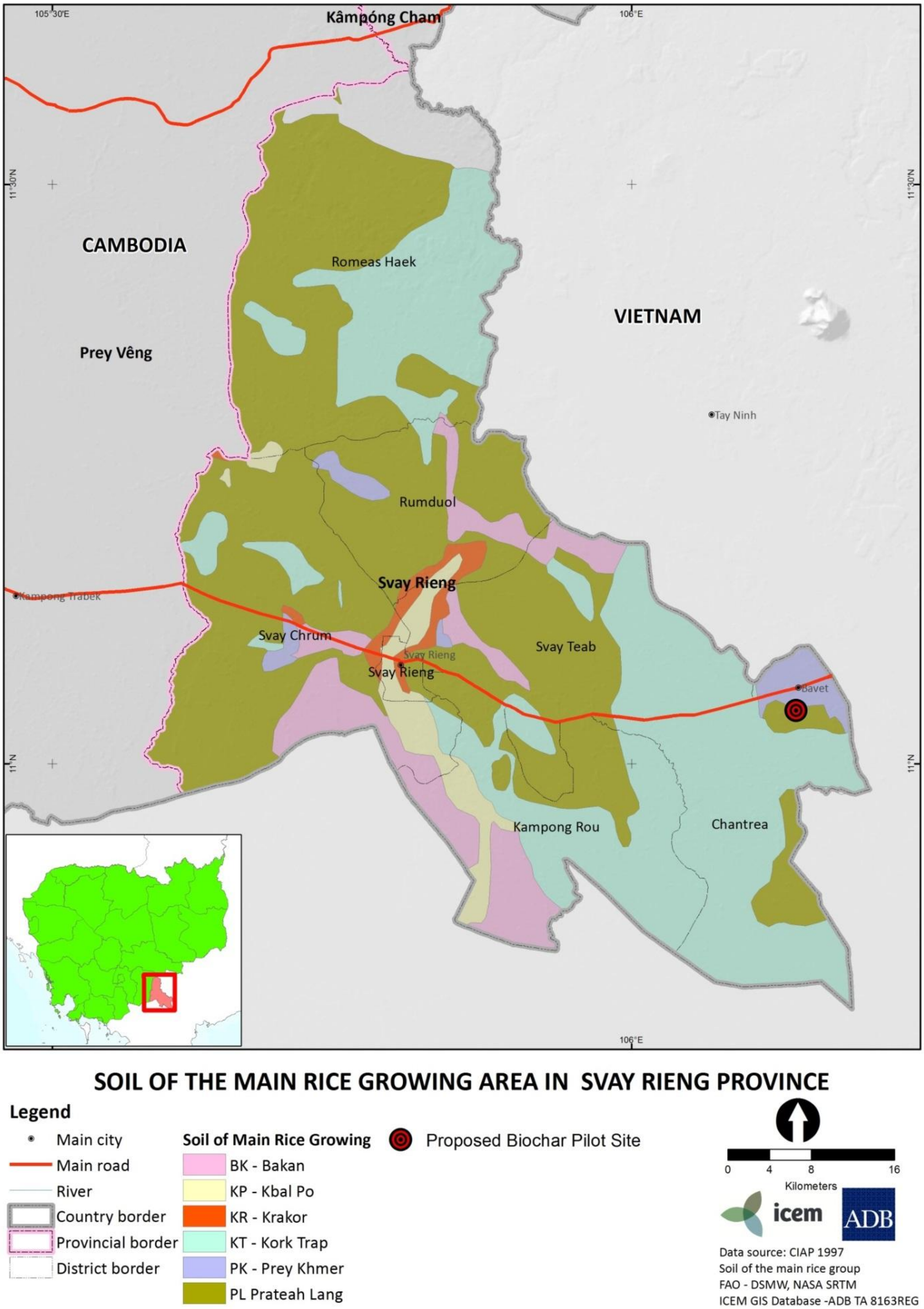
C1 - Svay Rieng Province

The detailed soil map of Svay Rieng Province according to the Cambodian Agronomic Soil Classification System (CASC) is given in A-Figure 39 (White et al., 1997). Soil fertility potential, land use and FAO soil classification of the soils in the province are presented in A-Table 19.

A-Table 19: Soil types in Svay Rieng province and their fertility potential.

Map Symbol	CASC Soil Group	Possible FAO Classification	Soil fertility potential
BK	Bakan	Luvisols, Acrisols, Planosols	High
KP	Kbal Po	Fluvisols, Gleysols	Medium
KR	Krakor	Fluvisols, Gleysols	High
KT	Koktrap	Acrisols	Medium
PK	Prey Khmer	Fluvisols, occasionally Arenosols	Low
PL	Prateah Lang	Luvisols, Acrisols, Planosols	Low

Prateah Lang and Koktrap soil groups cover most of the province where soils have formed on the old alluvium. Bakan, Krakor and Koktrap soil groups are more common on the recent alluvium close to the river. Soil fertility potential of main soil types is low to medium and thus will benefit from biochar application. The province has 6,000-7,000 ha of acid sulfate soils and biochar application to these soils will be beneficial for cropping to increase the pH of highly acidic soils. Approximately 100, 000 t of rice husk can be potentially used for biochar production in the province. Other agricultural wastes are not be available for biochar production, for example sugarcane waste is generally sold or used for another purposes, cassava waste is used for fuel.

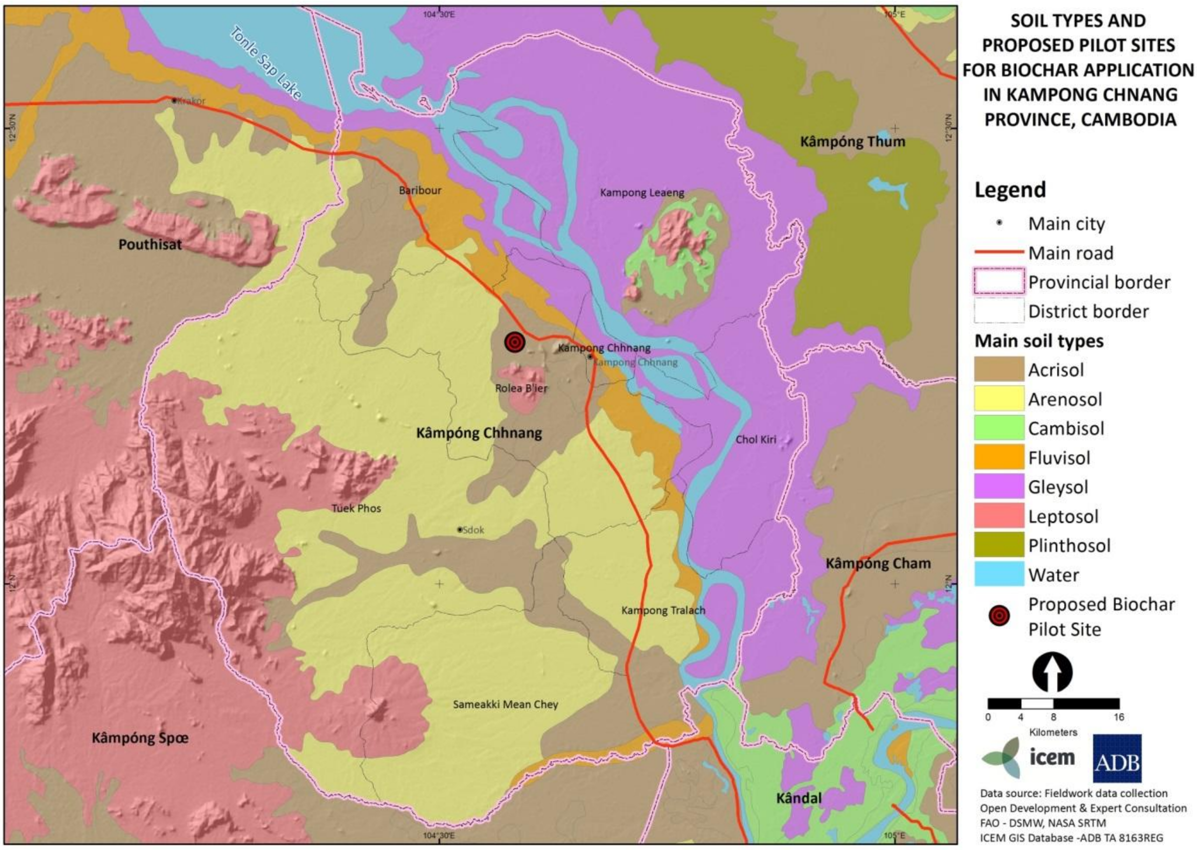


A-Figure 38: Detailed soil map of Svay Rieng Province. The selected pilot site is indicated by the Red/black circle on the map.

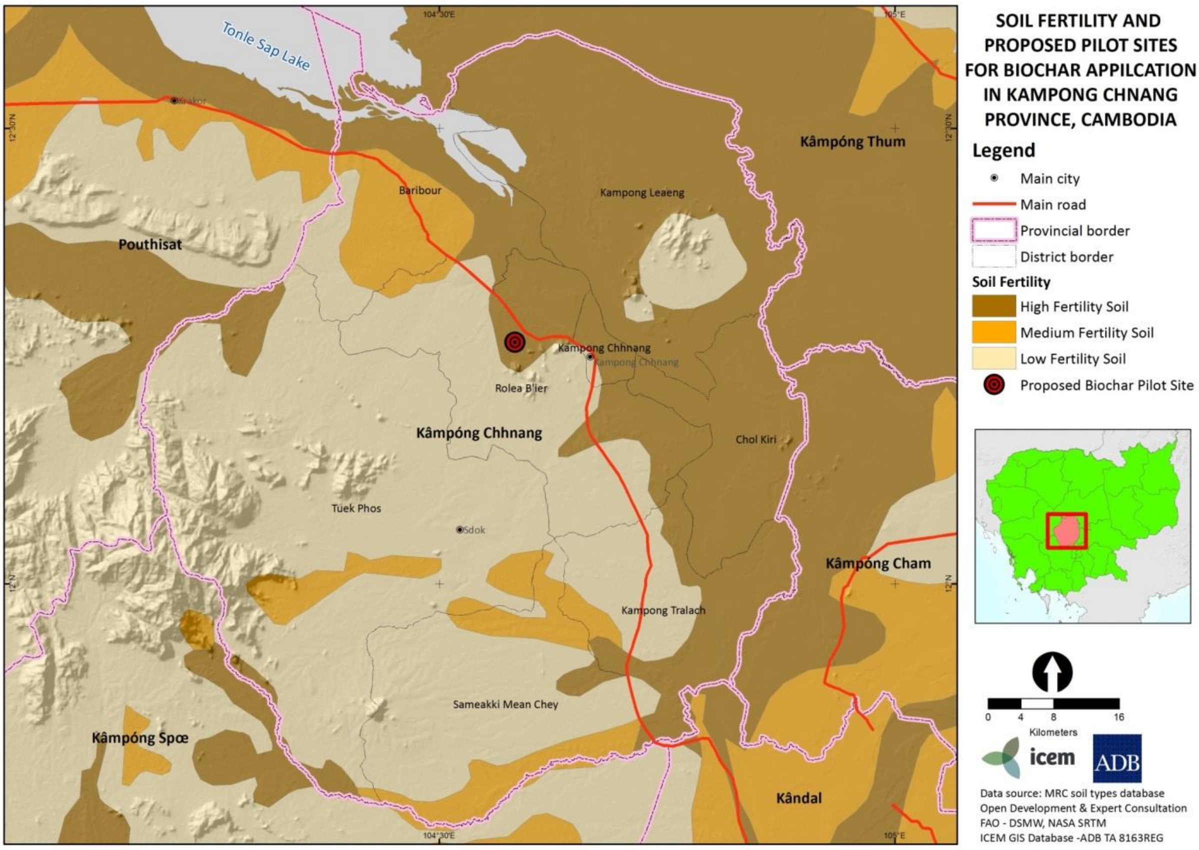
C2 – Kampong Chhnang Province

The detailed soil map of Kampong Chnang province according to the FAO Soil Classification System is given in A-Figure 40. The fertility status of the soils in the province is presented in A-Figure 41. On the south and south-west side of the lake, Leptosols, Acrisols and Arenosols are the main soil types, whereas closer to the Tonle River Fluvisols and Gleysols are most common. On the north and north-east of the province, Acrisols and Plinthosols occur. Cambisols are found along the river intermingled with Gleysols and Fluvisols in the south-east corner of the province. Soil fertility is generally high for Gleysols, Fluvisols and Plinthosols, and low for Arenosols and Leptosols.

The two sites selected for potential biochar trials occur in the region occupied by Acrisols and Arenosols with low fertility status.



A-Figure 39: Detailed soil map of Kampong Channang Province. The selected pilot site is indicated by the Red/black circle on the map.

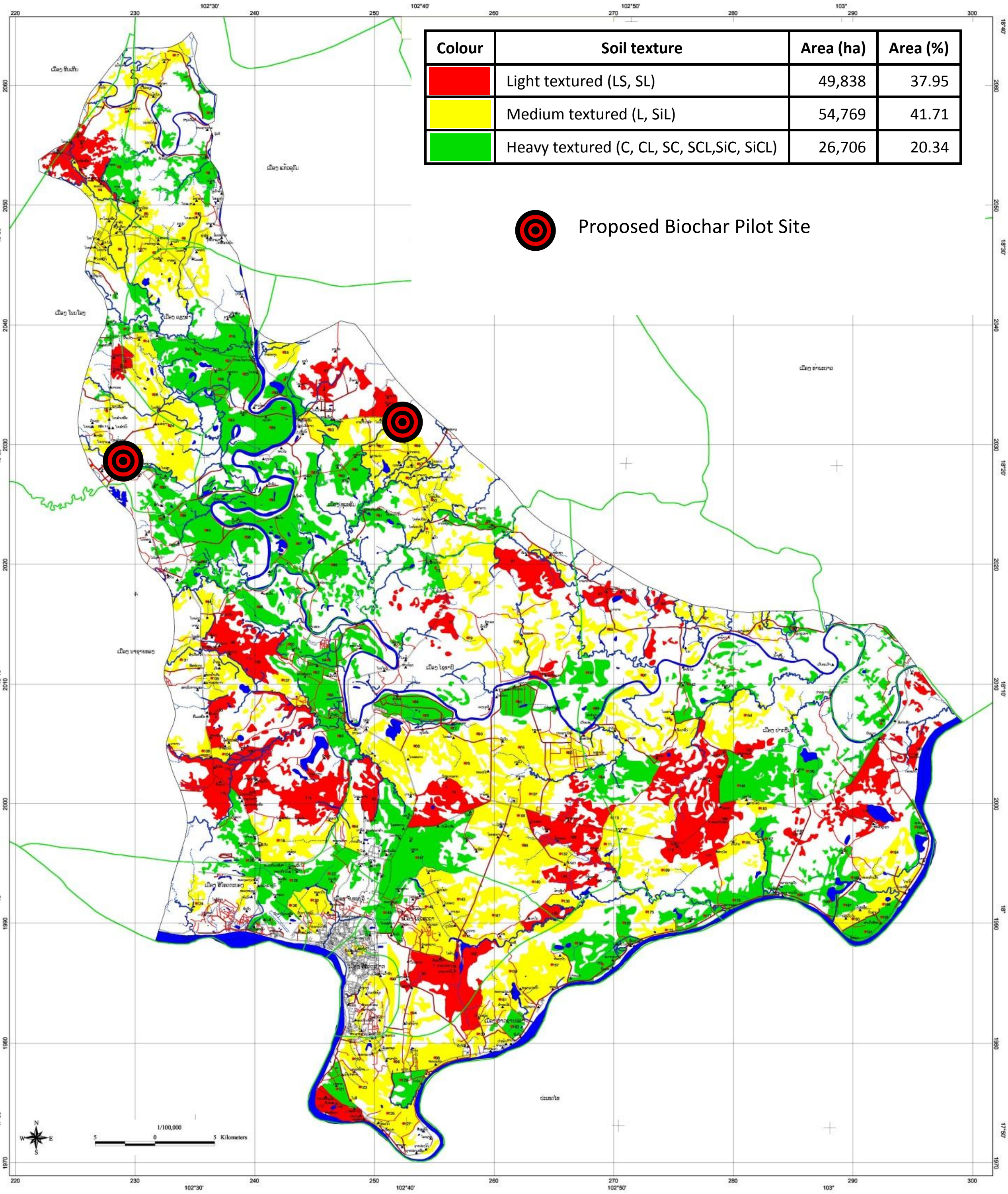


A-Figure 40: Generalised soil fertility map of Kampong Channang Province. The selected pilot site is indicated by the Red/black circle on the map.

3. LAO PDR

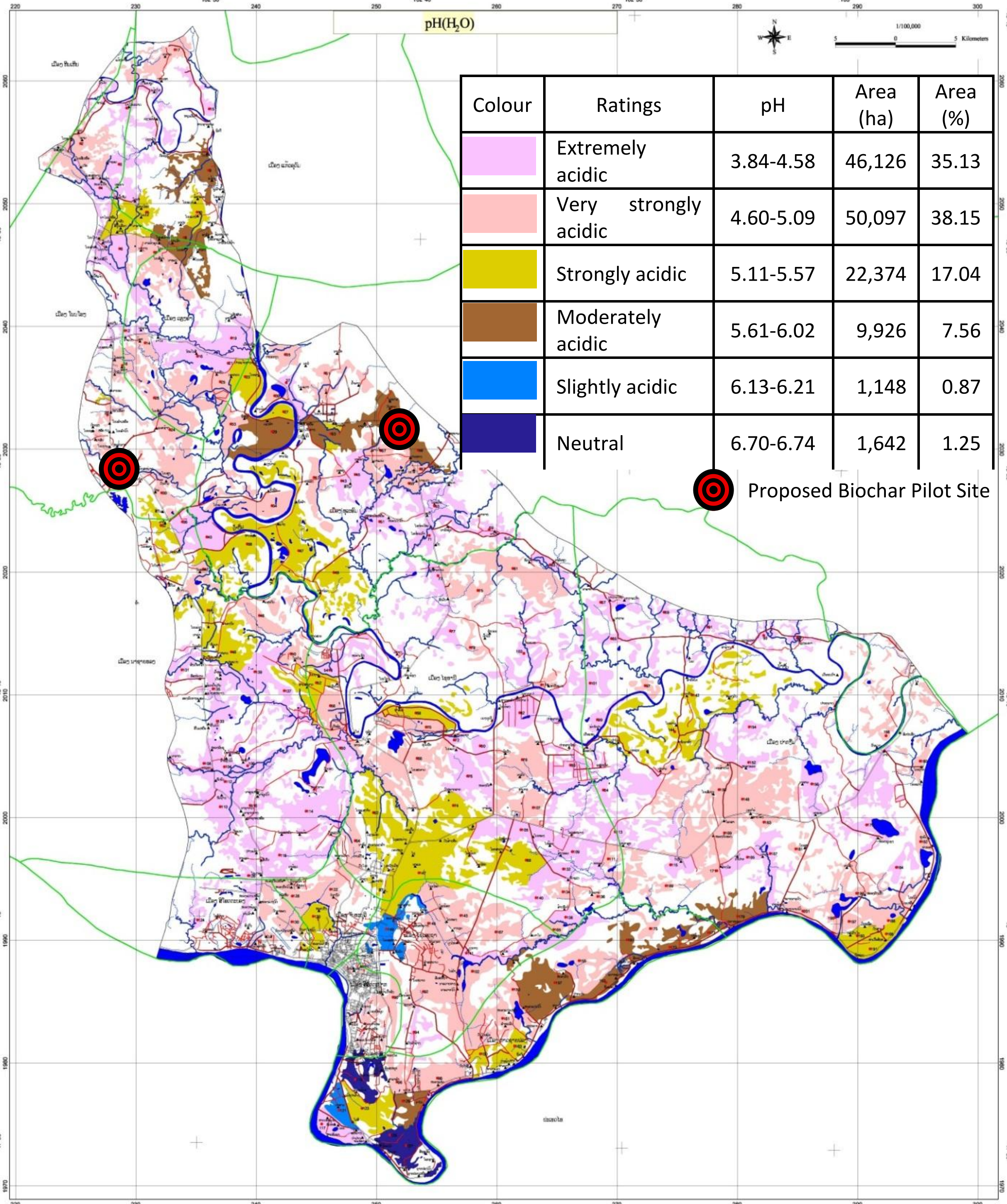
L1 - Vientiane Province

There is no detailed soil map of Vientiane province, however, soil texture, pH and fertility maps are available for the province, which are given in A-Figures 42-44. Nearly 80% of the soils in the province are light to medium textured (A-Figure 42), and both the hotspot sites have light-medium textured soil. The distribution of soil pH in Vientiane province is shown in A-Figure 43, with extremely acidic and moderately acidic pH at the two hotspots sites. About 70% of the soils in Vientiane province have low to moderate amount of organic matter (A-Figure 44). Both the selected sites have low contents of organic matter. Based on the soil pH, texture and organic matter contents of the soils at the chosen sites, it is expected that biochar application to soil will produce beneficial effects on crop productivity.



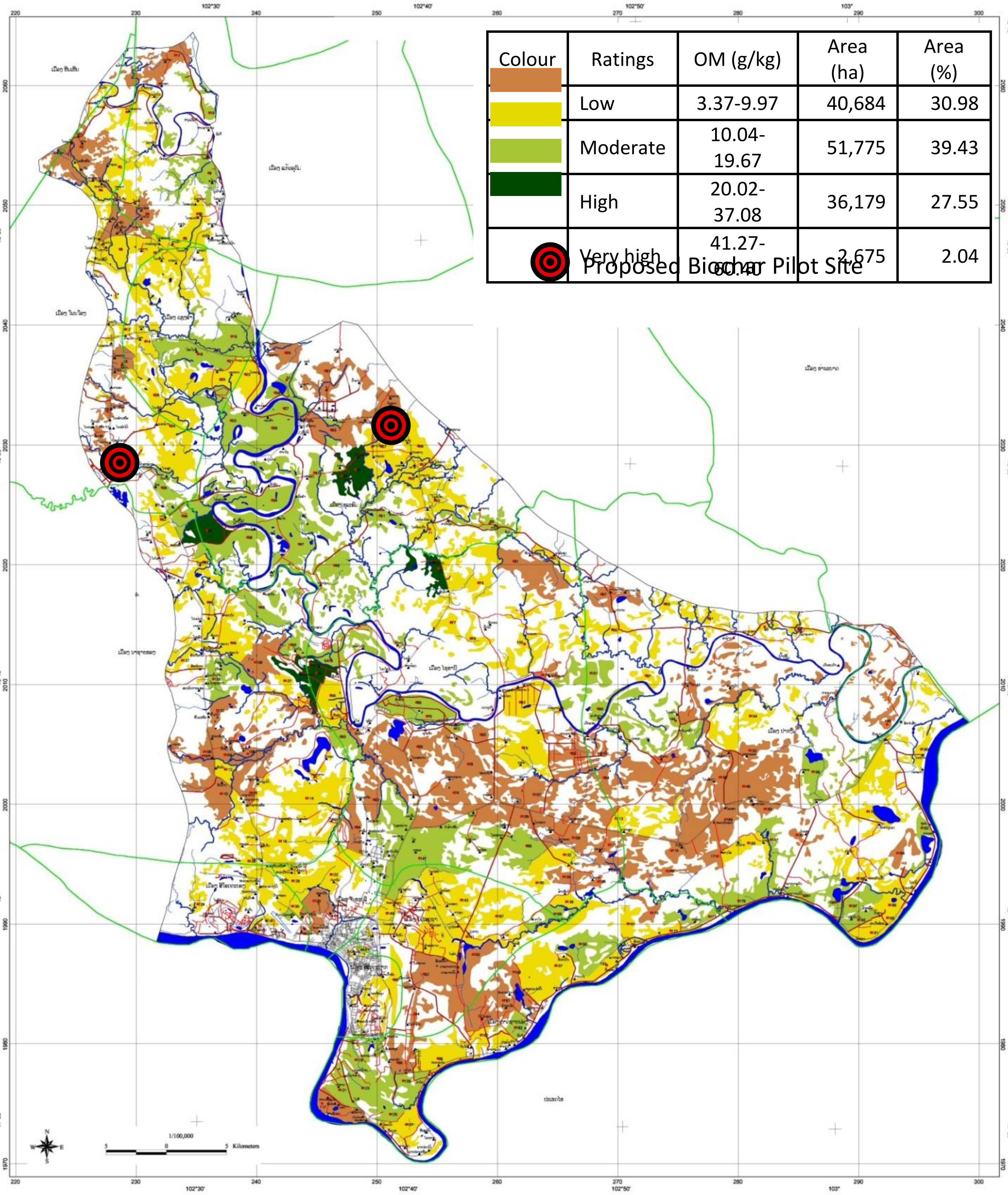
Colour	Soil texture	Area (ha)	Area (%)
Red	Light textured (LS, SL)	49,838	37.95
Yellow	Medium textured (L, SiL)	54,769	41.71
Green	Heavy textured (C, CL, SC, SCL,SiC, SiCL)	26,706	20.34

A-Figure 41: Soil map of Vientiane Province based on soil textural classes. The selected pilot sites are indicated by the Red/black circle on the map.



Colour	Ratings	pH	Area (ha)	Area (%)
	Extremely acidic	3.84-4.58	46,126	35.13
	Very strongly acidic	4.60-5.09	50,097	38.15
	Strongly acidic	5.11-5.57	22,374	17.04
	Moderately acidic	5.61-6.02	9,926	7.56
	Slightly acidic	6.13-6.21	1,148	0.87
	Neutral	6.70-6.74	1,642	1.25

A-Figure 42: The map showing the distribution of pH of the surface soils of Vientiane Province in Lao PDR. The selected pilot sites are indicated by the Red/black circle on the map.

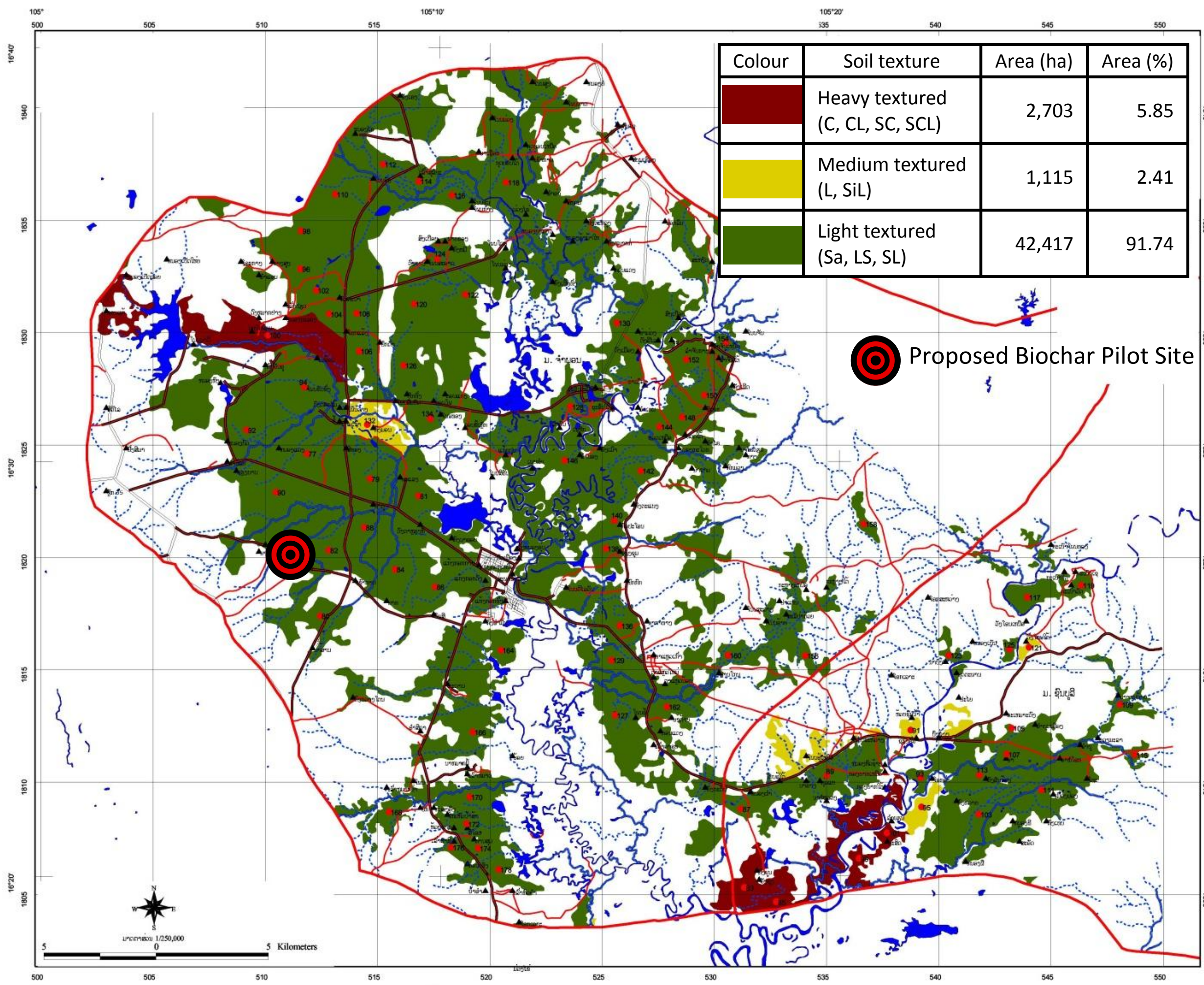


Colour	Ratings	OM (g/kg)	Area (ha)	Area (%)
	Low	3.37-9.97	40,684	30.98
	Moderate	10.04-19.67	51,775	39.43
	High	20.02-37.08	36,179	27.55
	Very high	41.27-60.40	2,675	2.04

A-Figure 43: The map showing the distribution of organic matter in the surface soils of Vientiane Province in Lao PDR. The selected pilot sites are indicated by the Red/black circle on the map.

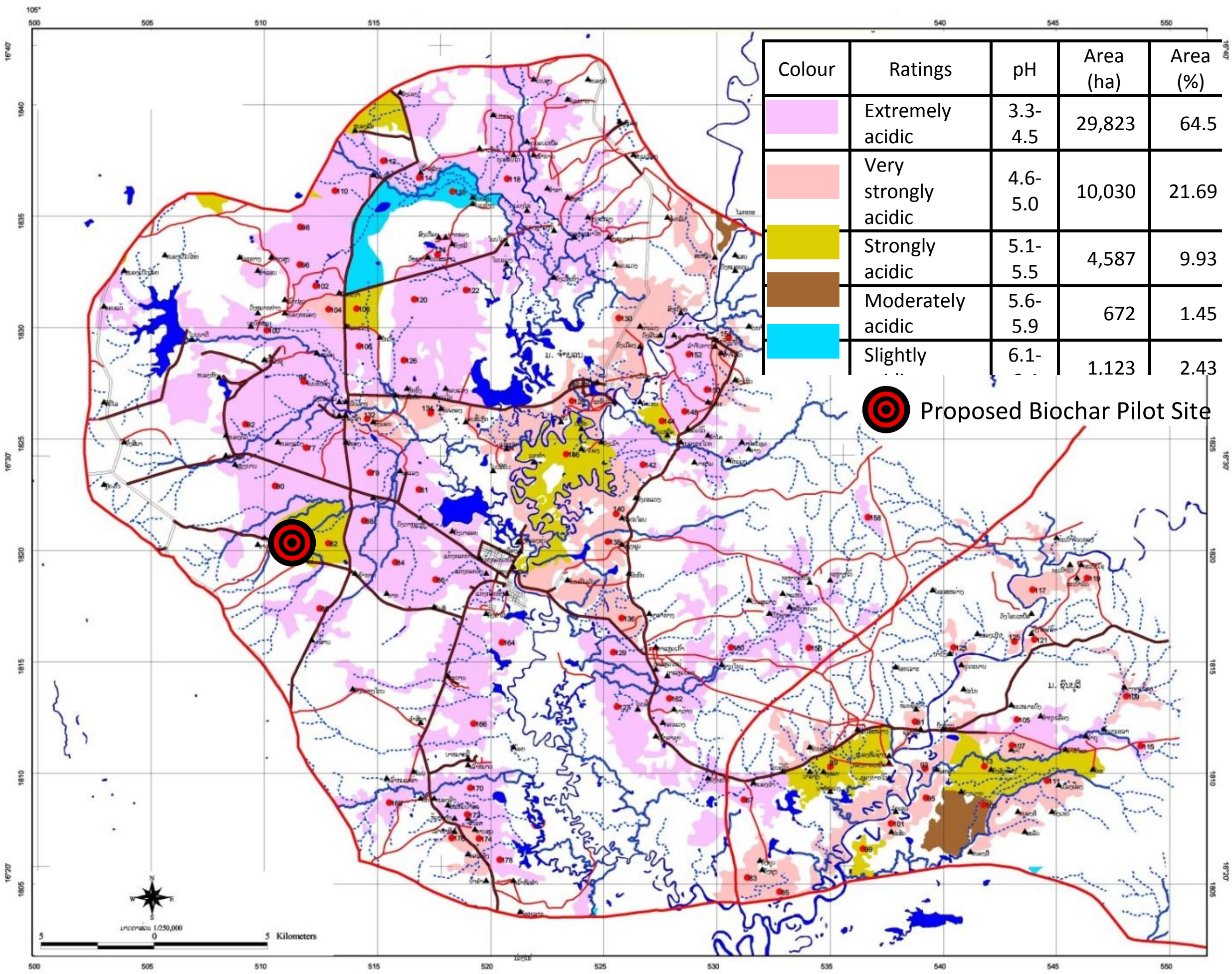
L2 - Savannakhet Province

There is no detailed soil map of Savannakhet, however, soil texture, pH and soil carbon maps are available for the district, which are given in A-Figures 45-47. Nearly 92% of the soils in the province are light textured (A-Figure 45), and the soil at hotspot site also has a light texture. More than 86% of the soils are extremely to very strongly acidic, the detailed distribution of soil pH in Vientiane province is shown in A-Figure 46. The soil pH at the chosen field site is strongly acidic. About 80% of the soils in Savannakhet province have low organic matter content (A-Figure 47) and the selected site also falls in this category. Based on the soil pH, texture and organic matter contents of the soils at the chosen sites, it is expected that biochar application to soil will produce beneficial effects on crop productivity.

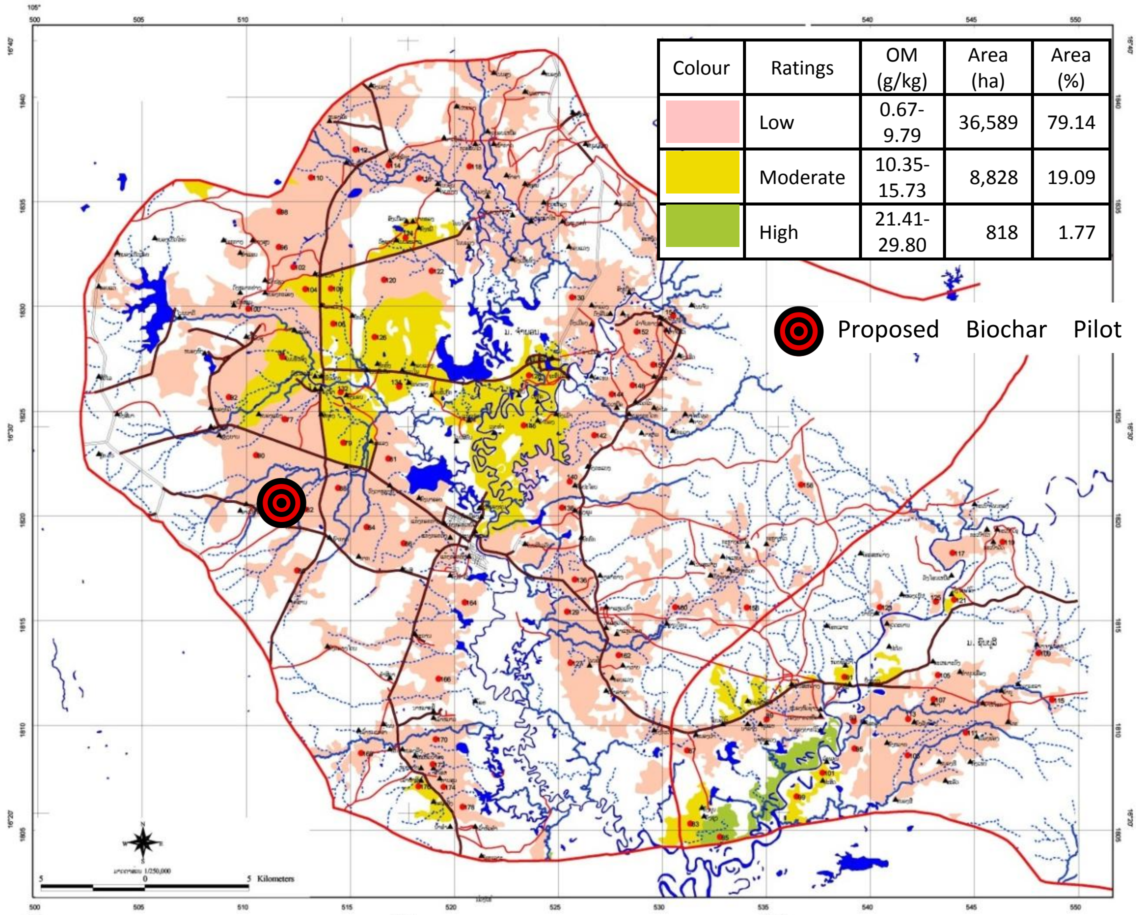


Colour	Soil texture	Area (ha)	Area (%)
	Heavy textured (C, CL, SC, SCL)	2,703	5.85
	Medium textured (L, SiL)	1,115	2.41
	Light textured (Sa, LS, SL)	42,417	91.74

A-Figure 44: Soil map (based on soil textural classes) of Champhone district in Savannakhet Province of Lao PDR. The selected pilot sites are indicated by the Red/black circle on the map.



A-Figure 45: The map showing the distribution of surface soil pH in Champhone District of Savannakhet Province in Lao PDR. The selected pilot sites are indicated by the Red/black circle on the map.



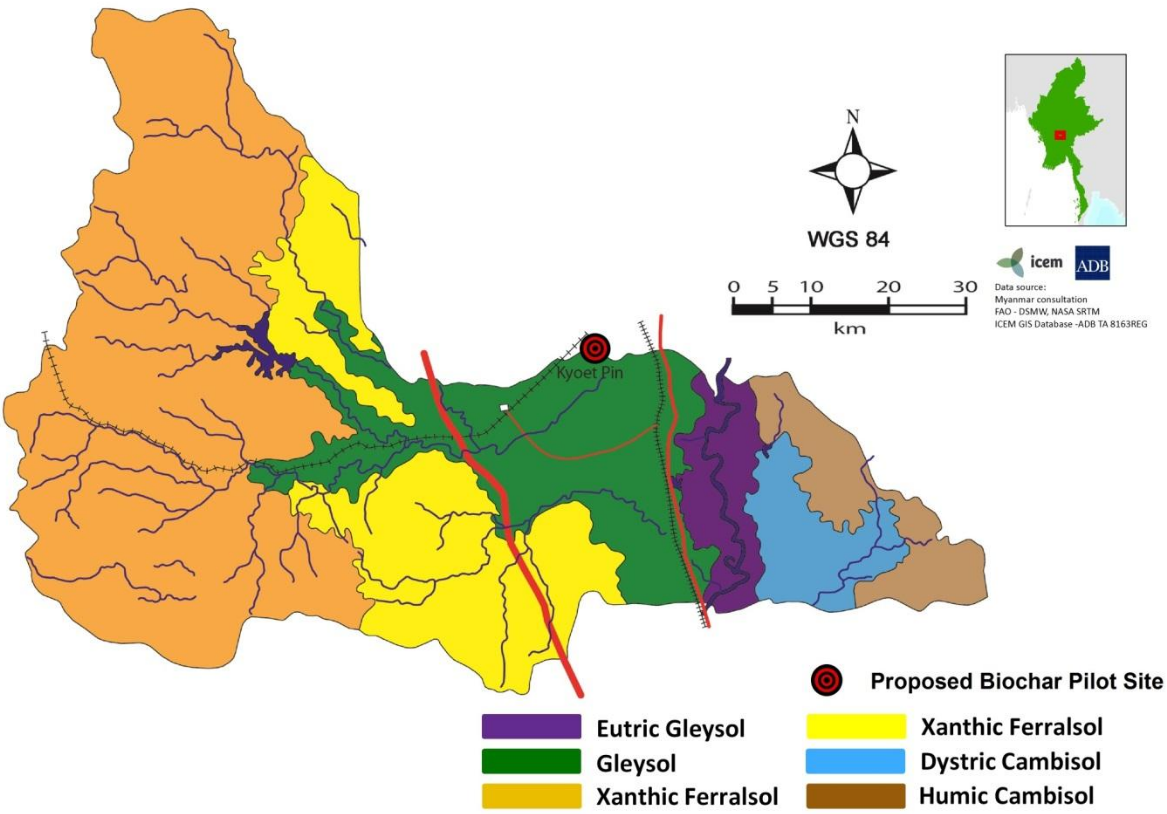
A-Figure 46: The map showing the distribution of organic matter in the surface soils in Champhone district of Savannakhet Province in Lao PDR. The selected pilot sites are indicated by the Red/black circle on the map.

4. MYANMAR

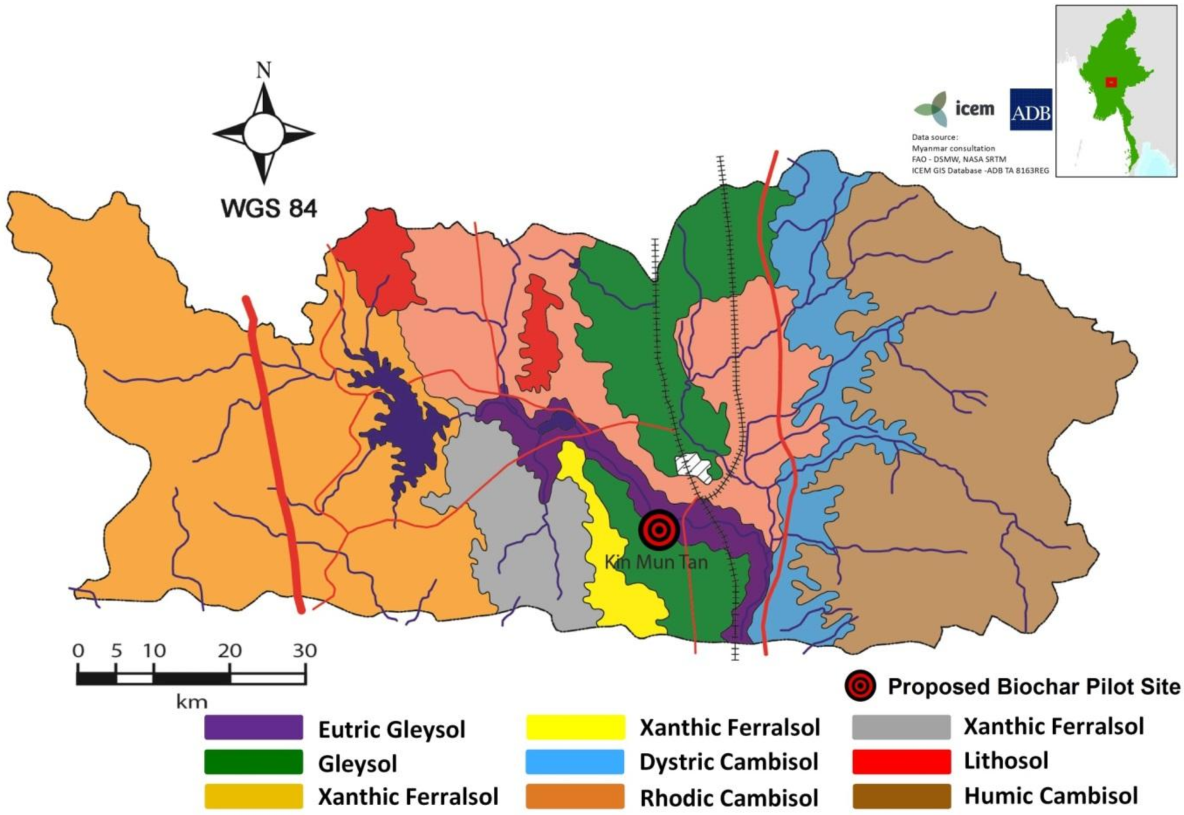
M1 –Nay Pyi Taw Council

Three FAO soil groups have identified in Le Way Township (A-Figure 48). Ferralsols are the dominant soils covering 58% of the area, followed by Gleysols with 27% area and Cambisols occupy 15% of the area in Le Way Township (A-Figure 48). In Tat Kone Township four soil groups, i.e. Ferralsols, Cambisols, Gleysols and Lithosols, are present (A-Figure 49). Ferralsols covers 52% of the area and are the most common soil, followed Cambisols (29%) and Gleysols (17%). Lithosols are present over only 2% of the area.

Detailed soil analysis data are not available for the area; however, in general Ferralsols have acidic pH, and low to medium level of nitrogen, phosphorus and potassium. Gleysols and Cambisols are expected to have medium fertility status, and pH could be varied from acid to slightly alkaline range.



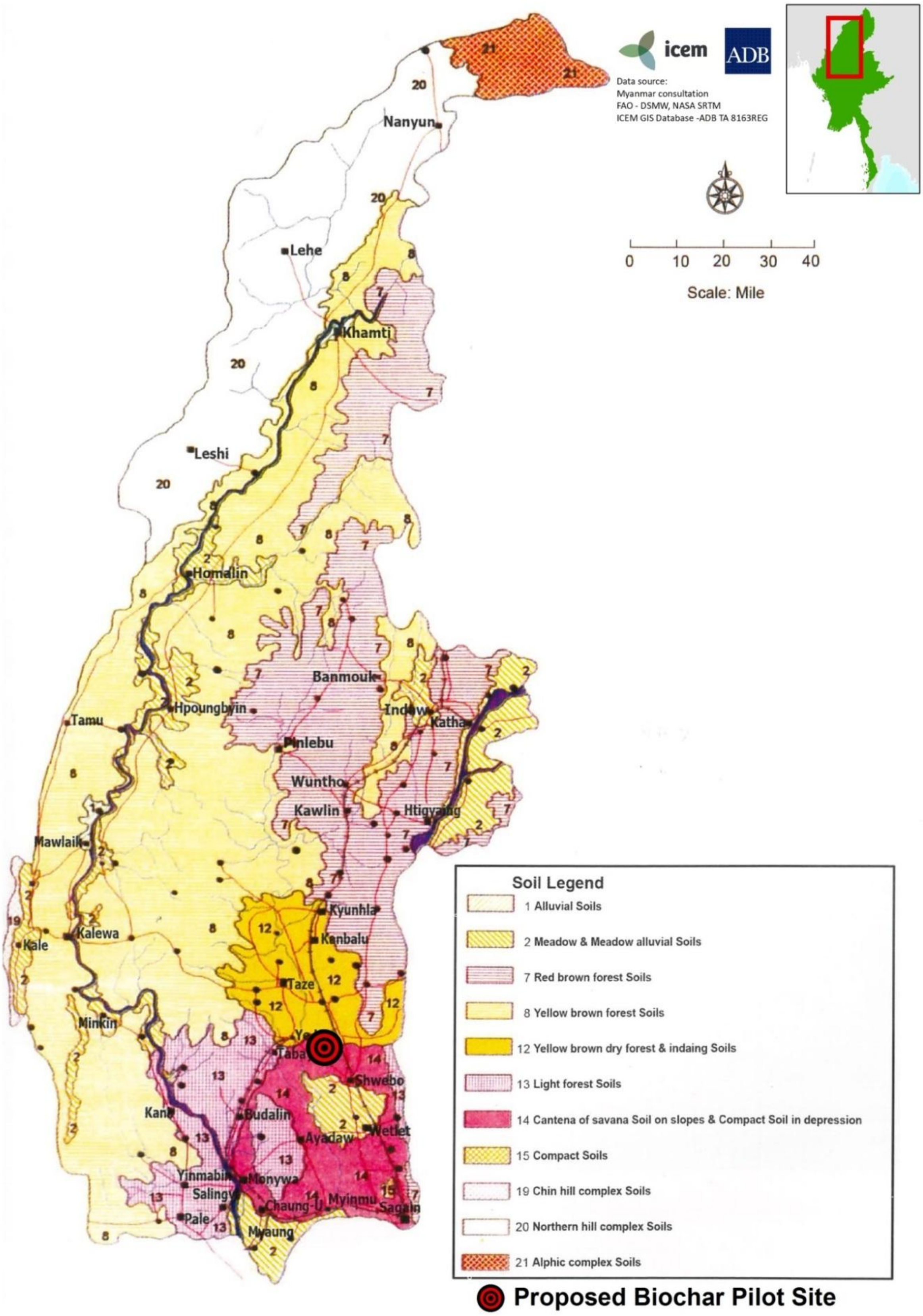
A-Figure 47: Detailed soil map of Le Way Township Province. The selected pilot site is indicated by the Red/black circle on the map.



A-Figure 48: Detailed soil map of Tat Kone Township. The selected pilot site is indicated by the Red/black circle on the map.

M2 –Shwe Bo District (Sagaing Division)

The soil map of Sagaing division according to the local classification system is given in A-Figure 50. Eleven different soil shave identified in the division. Yellow brown forest soils (Xanthic Ferralsols) and Red brown forest soils (Rhodic Ferralsols) are the most predominant soils; these soils are mostly used for forest plantations. Soil at the site chosen for the biochar trial belongs to 'Catena of Savanna soils on Slopes and Compact soils in depressions' soil type. These soils are light textured (sandy loam) with low to medium total nitrogen, phosphorus and potassium. Detailed soil analysis data are not available for the soils in the dividsion.



A-Figure 49: The soil map of Sagaing Division in Myanmar. The pilot site in the Shwe Bo district is indicated by the Red/black circle on the map.