Managing sands of the Lower Mekong Basin to limit land degradation: a review of properties and limitations for crop and forage production

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Highlights

- Rapid agricultural development of sandy terrains is occurring in the Lower Mekong Basin
- Acidity, erosion, nutrient deficiencies and decline in soil organic matter are major risks
- Knowledge about distribution and properties of sands in the LMB is limited
- Cost effective technologies are needed to overcome multiple limitations on sands

Abstract

Land development is rapidly occurring on sand–dominant soils that cover substantial areas of the Lower Mekong Basin. Sands are at risk of degradation on sloping uplands where agriculture is expanding and on lowland landscapes where intensification of cropping is occurring. Sandstone and granitic geology explain the prevalence of sand-dominant texture in profiles. The sand terrains in uplands of Cambodia and southern Laos mostly have not been comprehensively mapped and their diversity and edaphic properties are poorly understood. On high permeability sands, lowland rainfed rice crops are drought-prone, while nutrient losses from leaching are also a risk. Furthermore, waterlogging, inundation and subsoil hardpans are significant water-related hazards that influence the choice of field crops and forages for lowland soils. Land use change in the lowlands to alternative field crops and forages on sands is contingent on their profitability relative to rice, the amounts and reliability of early wet season rainfall and amounts of stored water available after harvesting rice. Soil acidity, low nutrient status, hard-setting and shallow rooting depth are significant constraints for crops and forages on sands in the lowlands. Low soil fertility and soil acidity are limitations to the productivity of farming systems on the sand profiles in uplands, while erosion, low soil organic

matter levels and water balance are concerns for their sustainable use. There is a need for widespread land suitability assessment and the development of sustainable farming systems before uncontrolled expansion of agriculture causes degradation of sandy terrain of the Lower Mekong Basin.

1. Introduction

Forest clearing and land use change expose soils in the Lower Mekong Basin (LMB) to degradation risks (Phompilla et al., 2017; Liao et al., 2020). A large proportion of soils at risk of degradation in the LMB are sands and attention is increasingly being turned to the potential for diversification of cropping systems and the prospects for more intensive land uses in sandy lowland terrain (Bell et al., 2007b; Seng et al., 2009; Philp et al., 2019). In light of the mounting pressure from the expansion of agriculture into poorly-described sandy upland soils, there is a need to hasten the pace of research so that sustainable farming systems are developed to alleviate land development limitations and to avoid land degradation. In addition, there is a need for research on the suitability of sands in the lowlands for cropping system intensification, particularly on those soils where rice productivity is low, the period of continuous soil water saturation is short, or the risk of drought is high (Vial et al., 2020). Earlier papers reviewed some of the properties of sands of Cambodia (Seng et al., 2007) and the rice soils of Cambodia, Laos and North East Thailand (NET) (Bell and Seng, 2004). Here, we review the broader geological setting of Cambodia and Southern Laos to explain the prevalence, distribution and diversity of sands in the LMB. While regional assessments of land degradation status and risk in Southeast Asia have been reported (Nachergale et al., 2010; Yagi et al., 2015), for the LMB these are lacking detailed knowledge of the soil resources, their properties and response to management.

The area of lowland rainfed rice has remained fairly static over the past decade, but yields of rice have increased. In addition, irrigated lowland rice in the dry season is expanding but not substantially on sands. In Cambodia, national average rice yield has increased from 1.79 t/ ha in 1995 to 3.30 t/ha in 2017 (MAFF, 2018). It is not known whether the increases in yield on the sand-dominant Prateah Lang and Prey Khmer Soil groups (see Table 1) have occurred at the same rate as on the loamy and clay textured lowland soils.

The area of non-rice crops expanded markedly in Cambodia from 2002 to 2017: this has mostly occurred in upland soils (Fig. 1). Prior to 2002, maize in western Cambodia was the main non-rice field crop. Most of the increase from 2002 to 2005 came from soybean and sesame expansion. From 2005 to 2009, both maize and cassava accounted for most of the increase. From 2010 to 2017, the production area of cassava doubled, while the area of maize declined by 25 % and the areas of other crops were stable. Much of the increase in field crop area has been in the western districts of Cambodia, driven by market demand in Thailand, while areas of basaltic soils in Kampong Cham and Tbung Khmum provinces have also contributed significantly. It is not clear how much of the increase can be attributed to production on sands in the upland areas but the regions of greatest expansion have limited areas of sands.

In southern Laos, there has been decrease in forest cover between 2006 and 2012 (Phompilla et al., 2017), especially in hilly areas, but much of the cleared forest was converted to rubber plantations. Again, it is unclear how much of the increase can be attributed to production on sands in the upland areas in southern Laos.

As lowland rainfed rice production remains the dominant form of agriculture in both Cambodia and southern Laos, we review the nature and properties of the sands in the lowlands for rice production and for cropping systems intensification with alternative field crops and forages. Finally, we discuss the limited knowledge-base of sands in the upland areas that are already experiencing development pressure that is likely to accelerate over the next two decades. Where there are gaps in knowledge from Cambodia and southern Laos, findings from NET are used to illustrate principles, likely constraints, relevant technologies and emerging opportunities.

2. Distribution of sands in the LMB

2.1 Extent and distribution of sand

In Cambodia, the mapped Arenosols (deep sands featuring very weak or no soil development) cover only 1.6 % of the land area (Bell and Seng, 2004). However, there are more extensive areas of profiles with surface horizons of sand texture and underlying clay-rich subsoil horizons (Table 2). Amongst the more prevalent Soil Groups with sand textured profiles are Acrisols and Leptosols (MRC, 2002).

Of the mapped rice soils in Cambodia (Oberthur et al., 2000b), Prey Khmer and Prateah Lang Soil Groups, which comprise 11 and 28 %, respectively, of the rice-growing soils, have sand-textured surface horizons. Prey Khmer soils have sand or loamy sand texture in both the surface and sub-soil horizons and will be the focus of the present paper (Table 1 and 2). The Soil Groups have been defined using the Cambodian Agronomic Soil Classification (CASC) which categorizes soils according to their effects on lowland rice production (White et al., 1997). The CASC, that was adapted from the Fertility Capability Classification (Buol et al., 1973), is not a soil classification based on concepts of soil genesis that emphasize sub-soil properties. Instead, the CASC emphasizes 0-20 cm soil properties, since rice roots are relatively shallow. Even Prey Khmer Soil Group when used for lowland rice is defined based on the 0-50 cm layers in CASC (White et al., 1997). There is no equivalent of the CASC in Laos and NET.

Soils classified as Prey Khmer, have < 180 g clay/kg and > 650 g sand/kg in surface layers (Table 1), but in uplands often do not classify as Arenosols because the rice soil classification in Cambodia only considers properties to 50 cm, whereas Arenosols should contain < 180 g clay/kg to 100 cm depth or more (Table 1, 2).

Arenosols are more common in central and southern Laos than in Cambodia, comprising 10 % of the area (Linquist et al. 1998). In central Laos, Alisols are the major soil, comprising 50 % of the soils of the main plains. By contrast, Alisols only comprise 34 % of soils in southern Laos. Collectively, approximately 50 % of the soils in central and southern Laos are Alisols and Luvisols. Other significant soil groups are: Cambisols (8-12 %), Leptosls (5-8 %) and Acrisols (5-8 %). The Acrisols that are common in Cambodia are not common in southern Laos. However, due to the scarcity of detailed soil profile descriptions and mapping in central and southern Laos, as well as in Cambodia, these conclusions must be treated with caution.

In southern Laos, 75 % of soils have sand, loamy sand or sandy loam textures, by contrast with only 41 % in central Laos (Linquist et al., 1998). According to Lathvilayvong et al. (1996), lowland rice soils typically have a topsoil sand content exceeding 650 g/kg, ranging as high as 850 g/kg, with a minimum clay content of 50 g/kg. Low organic matter content, cation exchange capacities (CEC) and percent base saturation are also common in these soils. Extractable acidity is generally high in the Acrisols and Alisols.

2.2 Geology

Extensive sedimentary formations underlie much of Cambodia and the neighbouring Khorat Plateau in NET, which also extends into southern and central Laos on the eastern side of the Mekong River. Mesozoic sandstone underlies most of the basement geology in Cambodia (Workman, 1972, see Fig. 2) whereas Cretaceous sandstone forms the Khorat Plateau (Carter and Bristow, 2003). Therefore, sandstone and its weathering products has a dominating influence on the properties of upland soils in the region. While lowland soils are mainly derived from deposits of alluvial, colluvial and lacustrine sediments, these too are often sandy materials (Lathvilayvong et al., 1996; White et al., 1997). In Cambodia, nearly 40 % of the lowland rice soils have sandy surface horizons because the soil parent materials are substantially derived from the weathering and erosional products of sandstone (White et al. ,1997).

Outcrops of felsic igneous intrusions (mostly granite) on low hills and mountains (e.g., Aoral Mountains), particularly in south and south-east Cambodia, have also supplied siliceous sediments for the recent and older alluvial/ colluvial terraces. By contrast in eastern Cambodia, basaltic lava flows from the Pleistocene cover significant areas of older alluvial terraces, while extensive areas of basalt flows occur in Mondulkiri and Ratanakiri Provinces in northeast Cambodia as well as the Boloven Plateau of south-east Laos (Barr and McDonald, 1981) and to a very limited extent in NET (Tawornpruek et al., 2005). The soils formed on the weathered basalt and their alluvial/colluvial sediments have very different properties, particularly related to nutrient and water availability, to those formed from the siliceous parent materials (White et al., 1997). In the west of Cambodia bordering Thailand, substantial areas of non-siliceous siltstone, limestone and marl occur (Fig. 2) in areas that are increasingly utilized for upland crop production. Finally, the sediments deposited by the Mekong River along its flood plain and in the basin of the Tonle Sap have resulted in a large areas of recent alluvial/ lacustrine sediments in central Cambodia (Oberthur et al., 2000b). The alluvial soils on the Mekong flood plain includes sandy loam textured soils on the recent alluvial terraces (White et al., 1997).

The central and southern regions of Laos that are dominated by fine-grained red sandstone (JICA and Department of Geology of the Lao DPR, 2008) include formations of siltstone and claystones as well as evaporite (halite and gypsum). Older sedimentary rocks from the Jurassic and Triassic periods include light-colored sandstones, conglomerates, siltstone, claystone and limestone. Hence throughout southern Laos, soils are predominantly composed of fine grained sands, but sometimes mixed with silt and clay from weathered formations of siltstone and claystone. Finally, soils on the Mekong floodplain in southern Laos are mainly derived from mixed alluvial deposits that reflect the Mekong Basin geology as well as more local sources of sediments.

2.3 Regional soil resource maps

The sands in Cambodia or southern Laos have not been specifically mapped on a national scale. A regional soil resources map for the LMB (1: 250,000) covering most of Cambodia and Laos was completed, based on the FAO World Soils Map (1988) (MRC, 2002). The rice-growing soils of Cambodia have been mapped using the Cambodia rice soils classification (White et al., 1997) based in part on an old small-scale national map (1:900,000) of soils (Oberthur et al., 2000b). However, the upland regions, where sandy soils are predominantly developed on sandstones and related siliceous formations, are poorly described (Seng and White, 2005).

Laos is covered by the Soil map of Southeast Asia (FAO, 1979) at 1:5,000,000 scale. Soil unit delineation was by interpretation of the geological map of Indochina at 1:2,000,000 and the 1:1,000,000 USAF K-10 Operational Navigational Chart published in 1965. Second, the Soil survey of Laos was conducted during 1990-1995 (SSLCC, 1996) at a scale of 1:1,000,000. The outputs are a map and GIS dataset of 2405 soil profiles with descriptions and soil physical and chemical data attributes (Nyi et al., 2017). The soil data produced by the SLCC (1996) has been used to produce digital soil maps (DSM) of the northern uplands of Laos but not central and southern Laos. Maps of a range of soil physical and chemical properties have been produced with associated land suitability maps for upland rice and rubber (Field and Odgers, 2016).

2.4 District-scale soil mapping

District-scale soil mapping has been conducted in Cambodia in Tboung Khmum Province, Takeo Province and Kampong Speu Province on sandy terrain (Hin et al., 2006, 2007a,b). The soil maps are supported by detailed profile descriptions, and profile chemical and physical properties, and the data are accessible in the Cambodia Soil Database at the Cambodia Agricultural Research and Development Institute (CARDI). However, these surveys only cover about 10,000 ha each. Other small areas have been mapped including social concession areas and small-scale irrigation projects (e.g., Stung Chinit soil survey- Sanyo Corporation, 1971), but generally the profile descriptions are not accessible and there is no known chemical and physical analysis to support the soil classifications. Other than these, there is little detailed mapping or archived point source information on soil properties for upland sand profiles of Cambodia. A soil survey programme at the District and Province-level by the Cambodia Department of Agricultural and Land Resource Management will progressively identifying upland soils and contributing to digital soil maps of soil characteristics (Seng Vang, personal communication).

3. Limitations for agricultural production on sands in Cambodia and southern Laos

Rainfall is a key constraint for the use of sands for agriculture in Cambodia and southern Laos due to variability in the amount and reliability of rainfall during the wet season (April to October). In addition, the amounts of stored water after harvesting rice and the availability of surface or groundwater for irrigation are major limitations for dry season cropping. In addition, soil acidity and low nutrient status are significant constraints for crop production on sand in Cambodia (Seng et al. 2009; Hin et al., 2017) and in Laos (Phengsavanh and Phimphachanvongsod, 1998; Schiller et al., 2001).

3.1 Rainfall

Mean annual rainfall ranges from 1250-1750 mm for most of Cambodia (e.g., Fig. 3) but it increases up to 2500 mm in the south (e.g., Kampot; Figs 3, 4), and in the east of the country (Nesbitt, 1997). The variations in average annual rainfall, the average start and end date of the rainy season, and its reliability, have consequences for cropping patterns, and define options for pre-rice and post-rice cropping choices, especially on sands with limited soil water storage. While detailed modeling of the rice growing season start and end dates have been conducted for central Laos (Inthavone et al., 2011), little analysis of climatic variability has been conducted to determine the reliability of pre-monsoon or post-monsoon season cropping, apart from Vance and Bell (2004) who predicted sowing rules for early wet season cropping in southeast Cambodia. The high-rainfall south of Cambodia (Kampot) has higher early wet season rainfall (April) and may therefore be a more prospective area for expanding field crops on upland sands as well as on lowland sands in the pre-rice season (Fig. 3, 4). In general, the annual rainfall in the lowlands of southern Laos exceeds that of the lowlands of Cambodia. This is clear from the comparison of Pakse with Siem Reap or Takeo (Fig. 3, 4). The implications of these differences for pre-rice and post-rice cropping have not been explored. The rainfall patterns in northern Cambodia at Stung Treng more closely resembles that in Ubon Rathchatani, NET, which may have implications for the transfer of upland cropping patterns and soil management technologies on sands that have been developed in NET.

3.2 Cropping seasons

Cropping in the LMB revolves around three seasons: in Cambodia, the early wet season (EWS) lasts from April to July; the main wet season (MWS) from July to October; and the dry season (DS) from November to March (Nesbitt, 1997). For southern Laos, the MWS starts in May and ends in October (Phengsavanh and Phimphachanvongsod, 1998). Rice is the dominant crop on lowlands in the MWS. The growing season for lowland rice ends approximately one month earlier in southern Laos than the main rainfed lowlands of Cambodia (Fukai and Ouk, 2012). Traditionally, transplanting occurs as soon as sufficient rain falls allow cultivation of soils and then for the accumulation of standing water in the fields, so that puddling and transplanting can proceed.

In recent years, due to labor shortages in Cambodia (UNESCO, 2018), direct seeding of lowland rice in the MWS has replaced transplanting in up to 90 % of the planted area (Makara Ouk and Vang Seng, personal communication). Rice establishment dates vary from June to late August, depending on the season and landscape position of the field. Harvesting coincides with the early part of the dry season. Dry season crops can only be planted where there is sufficient stored soil water or where irrigation water is available. The amount of stored soil profile water available for post-monsoon crops will vary with soil texture, landform element (lower, middle or upper landform position), the presence of compact sub-soil layers, and the preceding rainfall (Vial et al., 2020). Throughout Cambodia and southern Laos, substantial year-to-year variation in total rainfall and rainfall distribution patterns is apparent (e.g., Fig. 5). The degree of annual rainfall variability means that reducing the risk of pre-monsoon and post-monsoon crop failure is an important factor in farmer adoption of new technologies.

4. Lowland sands: chemical and physical characteristics and degradation risks

Within the lowlands of the LMB, there are deep sands and higher elevation land neither of which are highly suitable for rice because of the difficulty of maintaining ponded water in the paddy fields. These areas have potential for alternative land uses such as forages (Philp et al. 2019), field crops and vegetables (Vial et al. 2020). Some of the soil constraints for field crops and forages will differ from those affecting wetland rice and so too will management strategies to avoid soil degradation.

4.1 Nutrient deficiency and depletion

In the deep sands of the lowlands (i.e. the Prey Khmer Soil Group), low fertility is associated with a combination of very low CEC, organic C, total N, exchangeable K and Olsen P (Table 1). Lowland rice in Cambodia generally responds strongly to N in sandy soils (Seng et al., 2001b), but often on these soils rice did not respond to N alone (White et al., 1997, Seng et al., 2001b). Rice yield responses to P alone have been reported, but the strongest responses generally require both N and P. On sands, K and S fertilizers often further improve rice yields. Low levels of Mg and B have also been identified as potential limiting nutrients for crops on the Prey Khmer soils, but have not been demonstrated to limit rice or other crop yields in the field (Lor et al., 1996). Leaching of N and other nutrients may also limit productivity of these soils even when water is not limiting. The Prey Khmer soil in Cambodia has low potential productivity for wetland rice even following recommended rates of fertilizer application (White et al., 1997; Kong et al., 2019).

The responses of lowland rice to nutrients was similar in central and southern Laos (Linquist et al., 1998), so no distinction is made between those regions in their review. Nitrogen was the most limiting nutrient, with 86 % of experimental sites responding to N in the central and southern regions. On average, the yield increase with N fertilizer additions in the central and southern regions was 1.2 t ha^{-1}. For rice, P deficiency was acute. Indeed, 30 % of sites where rice was tested did not respond to N application unless P was applied first. This is similar to findings in Cambodia. However, given that these results relate to a period before P fertilizer application was widespread, they may no longer reflect the responses of rice to P fertilizer. Linquist et al. (1998) reported that 40-50% of the P applied was taken up by rice. In NET, the mean partial P balance (i.e., fertilizer P input minus outputs in harvested grain) on 12 typical farms was +7.7 kg P/ha/year from a mean input of 11 kg P/ha/year (Lefroy and Konboon, 1998). On rainfed lowland Prateah Lang soil, with added P fertilizer, there was a net P gain in the soil of 5.6 or 9.5 kg ha^{-1} per crop when straw was removed or returned to the soil, respectively (Pheav et al., 2005). Hence unless there is significant P leaching, which is possible on sands (Sharma et al., 2015), soil P levels should have increased over the last 20 years and P deficiency is probably less prevalent or less severe on rice fields than indicated in earlier reports. Nevertheless, acute P deficiency may remain a limiting factor for crops grown on soils where P fertilizer application at recommended rates has not been a regular practice. Moreover, anoxia in wetland soils increases P availability to rice roots (Kirk, 2004), and soil P availability to dryland field crops and forages may be more limiting (Seng et al., 2006).

In central and southern Laos, rice yield responded to K fertilizer at 27 % of sites (Linquist et al., 1998). However, over time, responses to K and a need for K inputs are expected to increase as production has increased through double cropping (wet-season and dry-season cropping) and as rice yields increase as a result of improved varieties combined with increased N and P fertilizer management and improved agronomic practices. Removal of rice straw from fields greatly increases the depletion of soil K (Linquist et al., 1998). The removal of residues of other crops such as peanut on deep sands can also cause large negative partial K balances (e.g., Hoang et al., 2019).

Sulfur deficiency was identified in 25 % of 43 on-farm omission experiments at lowland sites in central and southern Laos but responses were generally small (Haefele et al., 2006). However, on sands, with the same geology and land use history, S deficiency was diagnosed by plant analysis in 35 % of 633 peanut crops in NET (Bell et al., 1990). There has been no investigation of the occurrence or prevalence of other nutrient deficiencies. However, given the similar geology and land use to NET, where deficiencies of boron, copper and molybdenum are common in legume crops (Bell et al., 1990), similar limitations may occur in southern Laos.

4.2 Effect of hydrology and water balance on physical and chemical characteristics of soils

The hydrology of lowland rice soils has a major bearing on soil chemical and physical properties (Wade et al., 1999). The shallow, drought- and submergence-prone sub-ecosystems make up 66-86 % of the rice sub-ecosystems in Cambodia, Laos and NET, in part due to the erratic rainfall, topography and the prevalence of sand textures in the root zone of the rice crop. In Laos, 33 % of lowland soils have neither drought nor submergence stress compared with only 10 % in Cambodia or NET (Wade et al., 1999).

While the sub-ecosystem concept is useful in regional classifications of lowland rice growing areas, in practice, local surface hydrology varies to such an extent that it can override the influence of rainfall. Within a single farm or among adjacent fields, the upper terraces, which are commonly sandy, may be classified in the drought-prone sub-ecosystem while the lower terraces that commonly have higher clay content (Table 3) may belong to the submergence-prone or drought- and submergence-prone sub-ecosystem. Fields in the high or upper terraces of the lowlands lose large amounts of water, particularly after heavy rainfall, through surface runoff, subsurface lateral water movement and deep drainage, while those in the lower terraces may intercept the lateral flows from the upper paddies (Fukai et al., 2000). The location of farm infrastructure such as drains and bunds, and road embankments and drains under roads can markedly affect where the runoff is directed and result in localized areas of inundation risk.

Toposequences in NET with elevation differences of 1.5-6 m have revealed further patterns of variation in soil properties across distances of 150-500 m. Homma (2002) studied an area of 9.3 ha on 10 farms in the southwest of Ubon Ratchathani, and found significant variation in yield across the toposequences that correlated with variation in clay and organic matter content, flooding regimes and rice biomass. During the wet season, the duration of flooding was inversely related to elevation, while days of flooding was positively related to yield (Table 3). The lower elevation sites had higher organic matter and clay content, suggesting that the lower elevations may benefit not only from run-off water from higher elevations (Fukai et al., 2000), but also have soil properties that aid soil water retention and make it easier to form a plough pan. Oberthur and Kam (2000) also report that soils in NET are typically much higher in clay and organic matter content in the lower terraces than mid and upper terraces. These patterns of variation in hydrology and soil properties are likely to exist in the lowlands of Cambodia and southern Laos in sandy terrain.

Water balance models are particularly useful for identifying key aspects of the surface hydrology experienced by rainfed rice. Fukai et al. (1995) developed a water balance model for sandy soils in NET and this model has been applied to the sands of central Laos and Cambodia. Maintaining standing water in the root zone for rice is hindered on sand by the high percolation rates in lowland rice soils of Cambodia (White et al., 1997), NET (Fukai et al., 2000) and central Laos (Inthavong et al., 2011). Water balance modeling showed that increasing deep percolation rate from 1 to 6 mm/day could depress rice yield from 2.5 to 1.8 t/ha (Fig. 6; Fukai et al., 2000). The effects of deep percolation in rice yields are exacerbated when fields also lose water by run-off (Fig. 6).

In the rainfed lowlands, loss of soil-water saturation occurs intermittently for various lengths of time during the growing season for wetland rice (e.g., Seng et al., 1996; Fukai et al., 2000). Based on the loss of soil water saturation and variable rainfall distribution, it is often assumed that drought is the main soil water-related constraint for rice in the region. However, low soil water also limits nutrient availability and uptake because variations in soil water saturation interact with nutrient availability and accessibility (Bell et al., 2001). Fluctuating soil water regimes will have major effects on the forms and availability of N and P (Seng, 2000; Seng et al., 1999) and on Fe and Al toxicities (Seng et al., 2004b). The implications of the temporary periods of loss of soil-water saturation for nutrient availability are not fully understood (Fukai et al., 1999). Intermittent loss of soil water saturation may also decrease the incidence and severity of Fe toxicity, which is reported to occur in Cambodia (Seng et al., 2004b) and Laos (Haefele et al., 2006). In addition, loss of soil water saturation increases the risk of Al toxicity for lowland rice on acid soils (Seng et al., 2004b). By contrast, rice roots grown under oxic (aerobic) root zone conditions experience a rapid drop in P uptake when transferred to anoxic conditions (Insalud et al., 2006). This has implications for crop nutrition when paddy fields undergo intermittent transitions between flooded and drained conditions.

Conversion of paddy fields to the production of non-rice crops and forages will have a number of implications for water balance and crop water availability. Firstly, constraints such as Al and Mn toxicity that are ameliorated by flooding of soils (Kirk, 2004) remain as significant constraints for dryland and irrigated crops. Secondly, the repeated puddling of sandy soils for rice production produced a dense plough pan with low macroporosity (Bruand et al., 2004). Tillage to alleviate the subsoil compaction at 20-40 cm depth has only short-term benefits for increasing root growth and yield because reconsolidation of the sand occurs (Hartmann et al. 2002). The pasture legume, *Stylosanthes hamata*, has roots that were able to penetrate the compacted layer and after 2 years to create biopores that enhanced the root growth and yield of a subsequent maize crop (Lesturgez et al., 2004). Both of these examples illustrate the importance of addressing subsoil constraints on sands when converting land use from wetland rice to dryland or irrigated crops and pastures.

4.3 Land suitability

Sands are characterized by multiple limiting factors, as demonstrated in studies in NET and South-Central Coastal Vietnam (Bell et al., 1990; Bell et al., 2015). For Cambodian rice soils, White et al. (1997) summarized the main limitations for each of the rice Soil groups. Of particular relevance here are the main constraints of Prey Khmer and Prateah Lang Soil groups for wetland rice production (Table 4). Nutrient deficiencies are prevalent in both soils, as discussed above. For non-rice crops grown on the same soils when aerated, some of the same constraints apply but others change due to altered soil chemistry and the greater importance of subsoil constraints (Table 5). For non-rice crops, Seng et al. (2009) developed a land suitability assessment scheme as a means of highlighting the key limitations and their relative severity for non-rice crop production. Since both Prey Khmer and Prateah Lang soils are characterized by multiple limiting factors, correct diagnosis of all the limiting factors is critical for successful management of such soils (Bell et al., 1990; Bell et al., 2015). Some factors such as low supply of nutrients can be alleviated through the use of fertilizers. Constraints such as compact subsoil may severely limit the growth of some crops, while others may be able to penetrate these layers (e.g., Lesturgez et al., 2004). Other limitations are more intractable and downgrade the land suitability for crops. There has been no equivalent land suitability assessment scheme developed for southern Laos.

5. Upland sands: physical and chemical characteristics and degradation risks

Only generalized comments can be made about the diversity and properties of upland soils, and these are mostly based on what is known about rice soils with similar properties in Cambodia (White et al., 1997) and Laos (SSLCC, 1996), and on recent studies carried out in the west of Takeo province (Bell et al., 2005; Hin et al., 2006; Hin, 2018), eastern Kampong Speu province (Hin et al., 2007b), Tbung Khmum province (previously Kampong Cham province) (Hin et al., 2007a; Hin, 2018), Kampot (Hin, 2018) and Kampong Chhnang (Hin, 2018) where sandy soils are prevalent. On upland soils, the main crops in Cambodia are cassava, maize, rubber, soybean, mung bean, sesame, peanut and sugar cane (FAOSTAT, 2018). There is very limited information on the specific mix of crops grown on sandy upland soils of Cambodia and southern Laos.

5.1 Soil types

Sands similar to the Prey Khmer Soil Group are encountered in the uplands of Cambodia, with sand layers at up to 80 cm depth. A typical soil profile from upland Kampot is shown in Table 2 (Hin, 2018). These soils are suitable for non-rice field crops and forages. The surface soil properties are similar to those reported above (Table 2), with low amounts of organic C, total N, Olsen extractable P, and exchangeable K are commonly found in surface layers. In addition, KCl_{40} extractable S levels, DTPA extractable Cu, and Zn, and hot $CaCl_2$ extractable B levels were low (Table 5). Other sands up to 185 cm deep have been reported by Hin (2018) on granitic uplands in Kampong Chhnang province. The sand grains in these deep sand profiles vary from predominantly coarse sand to predominantly fine sand, depending on the parent material.

Presently, there is no systematic description or classification of upland soils in Cambodia. Variations on Rice Soil Groups have been proposed to accommodate additional Soil Groups (e.g., Seng et al., 2007a) such as deep phases of the Prey Khmer Soil Group (White et al., 1997)(see Table 1). As discussed above, the major factor likely to account for variations in upland soils in Cambodia is geology. For southeast Cambodia, Hin (2018) examined the origin of sands and concluded that *in situ* weathering of sandstone, granite and sedimentary soil parent materials was the major factor explaining differences in sand-dominated profiles. Some evidence of colluvial movement of weathered materials was evident based on changes in particle size distribution and sand grain roundness along toposequences from the base of emergent hills. Sand profiles on granite parent rock in Kampong Chhnang province had > 300 g of coarse sand (600-2000 um) / kg. By contrast, sand profiles based on sandstone (Kampot province) and old alluvium (Tbung Khmum) had a greater dominance of fine sand (63-200 um). More detailed surveying may identify further variations among granitic sand profiles, based on particle size of the quartz grains in the rock. Similarly, sandstone varies in composition due to shale, siltstone or conglomerate layers, which will alter the particle size distribution of the profile. Hin (2018) found that some sand profiles in old alluvium parent material contained higher silt and clay contents than nearby profiles which presumably reflects the variation in sediment deposition in alluvium. Investigations of the sandy upland soils of southern Laos may reveal additional variation in profile types and properties since the sandstone of the eastern Khorat basin is older than that in Cambodia (Carter and Bristow, 2003).

Among sand profiles, variations of only a few percent in clay content can have quite profound effects on water and nutrient availability for crops (Scanlan et al., 2021). Moreover, even small increases in clay content with depth on sands can have large effects on the amounts of plant available stored soil water in the root zone, provided that root access is not hampered by Al toxicity or compaction (Bell et al., 2015). Finally, gravel content in sands can greatly decrease plant available water storage in the root zone (Scanlan et al., 2021). Further research on the upland sands of the LMB should provide insight to subsoil properties that constrain crop and forage production in a rainfed environment where intermittent drought is common and root access to subsoil water and nutrient reserves is likely to be significant (Bell and Oliveira, 2021).

5.2 Acidity and acidification

Soil acidity appears to be a significant factor limiting field crops in a range of upland sands in southeast Cambodia (Hin et al., 2010). In deep sands of the Prey Khmer Soil Group in uplands of western Takeo province, sub-soil Al saturation values were 50-80 % (Table 6), which is above the threshold of 20 % that is commonly regarded as a toxic level of Al for sensitive crops (e.g. mung bean). By contrast, in very tolerant crops (e.g. cassava), > 80 % Al saturation impairs crop growth (Dierolf et al., 2001). Seng et al. (2004) showed strong responses by upland rice to lime application on the acid Prateah Lang soils (pH $CaCl_2$ 4.0; Al saturation 80 %) when maintained in an aerated state, whereas no response was found when those soils were flooded. Hin (2018) examined lime responses of mung bean on three contrasting acid sands from Kampong Chhnang (KC: coarse sand formed on granite with 2 % clay), Ponhea Krek (PK: fine sand formed on old alluvium with 9 % clay), and Tramkak (TK: fine sand formed on quartzite/sandstone with 2 % clay). In pots, near maximum growth of mung bean (90-95 % of maximum) was achieved at 0.8-0.9 t of lime /ha in PK and 0.6-0.7 t of lime /ha in KC. The soil pH ($CaCl_2$) (0-15 cm) associated with near maximum growth was 5.3 in PK and 6.0 in KC. In unlimed sands, leaf Mn concentrations suggested severe Mn toxicity, especially in TK. Lime at 1 t/ha reduced Mn concentrations to values suitable for mung bean growth. Lime also strongly stimulated nodule formation in mung bean. Dry topsoil suppressed a response to lime and increased the severity of subsoil acidity effects on mung bean. In the field, incorporation of lime to at least 10 cm (TK) or 15 cm (PK) was superior to shallow incorporation for mung bean yield. In summary, strong growth responses were obtained with relatively low lime rates (0.8-1.1 t/ha) in well-watered sands. However, multiple limitations were evident in these sands, suggesting that, in addition to lime treatments, further research on optimum fertilizer types and rates would be required to achieve high crop yields. More research is needed to distinguish between the sands that induce Mn toxicity and those that induce Al toxicity, and the relative tolerances of common crop species to these two constraints.

The prevalence of Mo deficiency for legumes also needs to be assessed in Cambodia and southern Laos, as legumes grown in NET on similar deep sands have previously responded to Mo application (Bell et al., 1990). In the studies by Hin (2018) on acid sands, there was no indication that Ca alone was deficient, since the responses to low rates of lime could be attributed primarily to the pH change and the alleviation of either Mn or Al toxicity. Nevertheless, further assessment for Ca deficiency on acid sands is warranted.

In addition to establishing the extent of soil acidity in the LMB, the rates of acidification on sands needs to be assessed under different land use types. Sands in NET have low pH buffering capacity and are prone to rapid increases in acidity following the clearing of forests due to the loss of soil organic matter (Noble et al., 2000)

5.3 Water availability

Water supply is a key limiting factor for most upland areas of the LMB because of the monsoonal rainfall pattern and the erratic rainfall distribution during the EWS and MWS (Figs 2-3). Most of the crops grown in the EWS and MWS receive less than optimal water supply (Bell et al., 2005).

While standing water is a key requirement for wetland rice growth to suppress weeds and ensure an adequate water supply to rice, for non-rice rainfed crops the plant available water content (PAWC) is a critical determinant of crop productivity. The PAWC also varies markedly with soil texture (Inthavong et al., 2011). On loamy sand and sand textures with < 7 % clay, PAWC is only 4-5 mm/10 cm of soil depth for soils of central Laos (Table 7). At crop water use rates of 5 mm/day, the 0-20 cm topsoil only supplies enough water for about 2 days growth. The PAWC stored within 0-100 cm depth was only sufficient for about 8-11 days of crop water use. Hence, the sand profiles can dry quite rapidly and in the absence of frequent rainfall or a persistent shallow water table, dry matter production will be limited by drought, due to limited stored soil moisture. In addition, any limitation to deep root penetration such as subsoil Al toxicity or compaction will severely limit the PAWC available for crop growth. The water storage capacity of the soil would have a large bearing on the regulation of water availability to crops, especially on sandy soils. Deep sands are generally considered unsuitable or of low productivity for paddy rice because water is not retained in the shallow root zone of rice, and because a plough pan does not readily form to assist with water storage (White et al., 1997). Deep sands (75-100 cm) will therefore have a higher potential for production of deep-rooted crops and forages than for rice (Vial et al., 2019). Subsoil Al may, however, impede root growth and limit access to stored sub-soil water (Table 6).

5.4 Erosion

Water erosion is predicted to be a major degradation risk for upland soils in Cambodia (Land Development Neutrality-Target Setting Program, 2018). Based on national estimates, approximately two-thirds of the Cambodian land mass is rated as moderately susceptible to erosion, especially in the higher rainfall southwest of the Kingdom. The areas of moderate susceptibility comprise most of the sandy terrains of the uplands. Comparable estimates for southern Laos have not been located. Across the LMB, there has been limited study involving direct measurement of erosion. The study by Chapalot et al. (2005) in northern Laos is an exception, but since the average land slope was 56 % and the average clay content of the soils studied was 28 %, the results may not be relevant to sandy uplands of the LMB.

5.4 Land suitability

Multiple constraints can limit crop production (e.g., acidity, salinity, water holding capacity, waterlogging), soil management (e.g., stones, erosion risk) or cause off-site environmental impacts (e.g., loss of soluble P to surface or ground water) on sands. A land suitability assessment scheme was developed for Cambodia to assess and rank limitations (Table 8; Bell et al., 2007). For upland crops in Cambodia, the limits for crop tolerance were aligned with those of the Fertility Capability Classification (Sanchez et al., 2003) which was also used for the CASC (White et al., 1997). The rating of the land qualities has been modified for the soils and environments of Cambodia, based on descriptions of soil properties and limiting factors in White et al. (1997), recent soil surveys (e.g., Hin et al., 2005a,b,c), field experiments (Seng et al., 2009) and published information for the field crops of interest (Sys et al., 1993).

The suitability of Prey Khmer and Prateah Lang Soil Groups were compared in Cambodia for peanut, mung bean, maize and soybean and compared with the suitability of crops on other Soil Groups (White et al., 1997) for EWS and MWS planting (Seng et al., 2009). Well-managed mung bean crops with adequate fertilizer application yielded better on Prey Khmer soils than the mean yield for all soils tested (Table 9). Peanut pod yield and maize cob yield was 10-20 % lower on Prey Khmer than the mean of all soils. By contrast, soybean was depressed by 40 % on Prey Khmer relative to the mean on other soils. On Prateah Lang soil, all mung bean crops failed while crop failure was common for maize and soybean. The vulnerability of crops to failure on Prateah Lang is likely related to waterlogging and inundation risk from the slow drainage of subsoil clay after heavy rain but could also be due to acidity or low soil water storage in the root zone (Table 8). Even for peanut crops which only failed in 25 % of cases, the mean yield on Prateah Lang soil was only 56 % of the mean for all soils.

6. Management options for improving productivity and avoiding degradation of sands

With multiple constraints, the key to productive agricultural use of sands is to diagnose the limiting constraints and develop profitable technologies to alleviate these limitations. At the same time, sands are poorly buffered and their properties can degrade quickly in response to forest clearing and intensive use (e.g., Noble et al. 2000). Sustainable technologies need to maintain soil organic matter levels, avoid nutrient depletion, erosion and acidification and correct nutrient limitations to allow high water use efficiency on land use systems.

6.1 Crop management and nutrition:

Multiple nutrient deficiencies are common on upland sands of NET (Bell et al., 1990). Apart from N, P and K, deficiency of S and deficiencies of the micronutrients B, Cu and Mo, have been reported. For southern Laos and Cambodia, there has been no systematic study to identify the nutrient deficiencies on upland soils. Sulfur deficiency symptoms have been observed on forages in southern Laos and southeast Cambodia (Philp et al. 2020). Sulfur deficiency is common on deep sands in south-central coastal Vietnam, along with B and Cu deficiency (Hoang et al., 2015, 2020). Hence, while there is limited evidence of multiple deficiencies on sands in uplands of southern Laos and Cambodia, given the evidence from comparable sands in the region, such deficiencies should be anticipated. The double pot approach used in Vietnam is a promising method to quickly survey for nutrient deficiencies of a diverse range of sands, even when laboratory facilities for soil and plant testing are limited (Hoang et al., 2015). With multiple nutrient deficiencies, a complete fertilizer is needed to correct all the limiting nutrients. Reliance on N and P fertilizer, which is common practice by farmers, will not achieve yield potential on sands with multiple nutrient deficiencies (Bell et al., 1990; Hoang et al., 2015).

There have been few studies to define optimum or economic rates of fertilizers for crops on sands of Cambodia or southern Laos, apart from rice. Interim recommendations for Cambodia have been derived from Dierolf et al. (2001). However, responses to fertilizer alone were often poor on sands in NET unless an organic amendment is applied (Ragland and Boonpukdee, 1987). In Vietnam also, addition of an organic amendment, biochar or cattle manure), boosted yield of peanut regardless of whether inorganic fertilizer was applied. Hence, for the sands of the LMB, integrated nutrient management (INM) approaches are required to develop fertilizer application packages. However, more importantly, the most profitable packages of fertilizer and organic amendments need to be developed for the smallholder farmers. On acid sands it is probably essential to include lime application for upland crops as part of the package (Hin, 2018).

The major shift towards direct seeding for rice establishment has occurred in Cambodia in recent years has the potential to alter soil properties. Firstly, the absence of annual soil puddling in paddy fields may alter properties such as the plough pan and soil structure. In addition, the more common use of combine harvesters for rice retains more and taller straw in paddy fields. This may be advantageous for rice soil properties (soil structure, soil organic matter) and nutrient balance (especially K). However, there has also been an increase in demand for beef cattle which increases the demand for rice straw as feed source. Hence there is a need to assess how both of these trends are being expressed on farms and to measure the medium to long term implications for properties of sands in Cambodia. Similar trends may emerge in Laos also since in both countries a shortage of farm labor is driving practice change towards labor-saving operations on farms.

6.2 Maintaining organic matter levels

There are a number of approaches to maintaining or enhancing soil organic matter levels in sands, including retention of crop residues, addition of organic maters (manure, mulch, biochar) or growing green manure crops. Retention of rice straw at 2 t/ha boosts lowland rainfed rice yields in central and southern Laos by 50 % (Sengxua and Linquist, 2002). Returning rice straw also helps to maintain soil K supply because rice straw contains 4.8 kg of K /t. However, much of the rice straw is used either *in situ* or in feeding stalls for cattle on lowland rice farms. Some of the nutrient from straw is recycled in manure, but significant losses can occur, particularly of K. Retaining crop residues or using straw mulches also has potential to conserve water, particularly for dry season and upland cropping on sands. In northwest Cambodia, mulch at 2.5-5 t/ha greatly improved the yield of maize and to a lesser extent sunflower (Montgomery et al., 2016). While these studies were conducted on clay soils, mulch may have potential for increasing water saving and crop water use on deep sands also. Merkuria et al. (2016) reported increases in water productivity for crops on sands using biochar.

When incorporated into the soil, straw or crop residues may also be beneficial to crop production on sands. In paddy fields, straw mixed into the topsoil keeps the redox potential lower during the period of soil-water saturation loss, decreasing the extent of Fe^{2+} oxidation and minimizing losses in P availability due to reaction with Fe oxides (Seng et al., 2005). Other forms of organic matter added to the soil at planting, including cow manure, or residues from pre-rice pulse crops or green manures like *Sesbania*, can all help minimize losses of P during periods of soil-water saturation loss. Other options for minimizing the impact of periods of loss of soil-water saturation are the use of cultivars that are efficient in P uptake and use, and presumably would be able to cope with a temporary decline in P availability (Fukai et al., 1999); or to increases in soluble Al (Seng et al., 1999).

Some attempts have been made to grow green manure crops as an organic source of N in the wet-season lowland production system. *Sesbania rostrata* is the green manure crop with the most potential for this environment (Lathvilayvong et al., 1996). However, productivity of *S. rostrata* in much of the Mekong River valley is highly dependent on the soil P status. In Savannakhet and Champassak Provinces, the yield of *S. rostrata* increased 4- to 12-fold with the application 9 to 13 kg of P ha^{-1} (Schiller et al., 1998). Linquist et al. (1998) demonstrated that P levels required for optimizing potential *S. rostrata* biomass production and N fixation were substantially higher than those required for rice alone on the coarse-textured soils in lowland areas of much of central and southern Laos. While farmers previously failed to adopt *S. rostrata* or other green manure crops as a source of organic N in the wet-season lowland production systems due to low soil P levels, there may be an opportunity to re-introduce the practice given the increase in soil P status in the last two decades. On upland soils, alternatives to *S. rostrata* and stylo (*Stylosanthes* spp.) are needed as green manures for soil improvement, or to provide fodder (Lesturgez et al., 2004). Alternatively, mixed cropping systems of maize and legumes have been successful in northern Laos (Lienhard et al., 2020).

Conservation agriculture cropping involving minimum soil disturbance and crop residue retention is not commonly practiced but has a potential role in maintaining soil cover and soil organic matter levels and also has a role in erosion control on sloping land (Kassam et al. 2012). No-till and cover crops improve soil physicochemical characteristics (aggregate stability, organic carbon, and cation exchange capacity) as well as microbial abundance (total biomass, bacterial and fungal densities) in tropical grasslands of northeast Laos but similar studies with CA have not been reported on the sandy soils of the LMB (Lienhard et al., 2013).

6.3 Clay amelioration

Initial research on the sands (3-7 % clay) of NET (Noble and Suzuki, 2005) suggests very strong responses in growth can be achieved through clay amelioration. Application of clay to sandy soils has been suggested as a semi-permanent treatment to enhance water and nutrient retention (Noble et al., 2004). The use of claying presumes a readily-available local supply of clay. In NET, numerous deposits of high activity clay occur as lacustrine sediments (Sawaeng Ruaysoongnern, personal communication). Alternatively, where clay-rich subsoils occur, excavation and spreading of this clay may improve the properties of the sands and increase crop productivity (Hall et al., 2010). On deep sands in southwest Australia, clay-rich subsoils containing 30-50 % clay, added to increase soil clay content from 1 to 7 %, have boosted crop yields over a 15-year period by 30-50 % (Hall et al., 2015). The relevance of this technology for ameliorating the Prey Khmer (Arenosols) and the deeper phases of Prateah Lang Soil Groups of Cambodia, warrants further research. In northern Laos, Mekuria et al. (2014) found that bentonite clay addition to loam soils at 10 t/ha improved maize growth. Sengxua et al.

(2014) reported benefits for crop yield at one sandy soil site in Thasano district in Savannakhet province with addition of only 1 t of bentonite/ha. However, there were no further details reported on the longevity of responses.

6.4 Land use change

The subsistence production of rice in the lowlands has been the dominant land use in the LMB. However, social and economic changes occurring in the region are leading to land use changes. From 2006 to 2014, the forest cover of Cambodia declined from 59.6 to 46.9 % (LGN-TSP, 2018). Lowland rice farmers are leaving subsistence agriculture in favor of farming for cash income and to take advantage of off-farm employment (UNESCO, 2016). The decline in farm labor is leading to changes, for example, from transplanting of rice to direct seeding, as mentioned above. In addition, across Asia, rice consumption appears to have peaked. The demand is likely to decline over time, accelerating change in some areas to alternative crops and livestock production to supply the market demand for beef. Hence, expansion, diversification and intensification of production on the sandy terrain of the LMB is likely in the future. Many of the sands that currently grow lowland rainfed rice have low suitability for a wetland crop on account of poor water storage (Inthavong et al., 2012). Replacement of wetland rice is most likely on the marginal higher fields and those with sand profiles, by dryland crops and forages (Philp et al. 2019, Vial et al., 2019). These fields currently have a short period of water saturation and are most prone to crop drought. Instead of the cropping season being dictated by the time taken for soil water saturation to occur (Inthavong et al., 2012), early wet season cropping and forage production could take advantage of the 2-3 months of early wet season rainfall (see Fig. 2, 3). Deep rooted crops could also exploit more of the stored profile water than shallow-rooted rice crops. However, a more detailed water balance knowledge is required to underpin the development of these alternative cropping systems. In northwest Cambodia, Montgomery et al. (2016) showed that by shifting the sowing dates by 2 months to avoid the period of greatest drought risk and make better use of stored soil water in the clay soil profiles, it was profitable to double crop with maize and sunflower each year. With a more detailed understanding of the water balance on deep sands and sand on clay profiles, it should be possible to design cropping patterns with higher yield potential and water use efficiency than a single paddy rice crop, especially on the marginal, drought-prone rice fields with sandy soils.

7. Concluding remarks

Agricultural systems in the LMB region are undergoing rapid changes, with significant demands placed on the soil resources of this region to enable effective land use change and diversification of enterprises. Eswaran et al. (2001) estimated that Cambodia had 11.8 million ha characterised as moderately vulnerable to desertification whilst Laos had 3.5 million ha . In addition, 4.5 million ha of land is highly vulnerable to soil erosion in Cambodia in the southwest while 7 .6 million ha of land in the uplands of the northeast and southeast were moderately vulnerable.

A major barrier to the development of productive and sustainable management practices for sands in the LMB is the dearth of knowledge about the distribution and properties of such soils in the uplands. Land resource assessment of uplands in this region is an urgent priority to underpin agricultural development of these landscapes. The geographical proximity of Cambodia, southern Laos and NET, the similarities in geology and climate, and the prevalence of rainfed lowland rice as the major crop in lowland agro-ecosystems suggest that the cross-flow of research information about sandy soils amongst these regions should be helpful. Coordination and collaboration amongst these countries could minimize duplication of research, and maximize synergies in their collective research, given the multiple constraints affecting sands across these regions. However, exchange needs to be based on a critical examination of the similarities and differences amongst them in geology, agro-ecological conditions, in the prevalence of rainfed rice ecosystems, and in the soils used for rice and field crop production (Bell and Seng, 2004).

Land resource assessment is a relatively costly investment, but a range of new sensing technologies for mapping can reduce the cost of gathering the data and the preparation of maps. Moreover, the new digital soil mapping (DSM) technologies can be used to present soil attribute maps. As demonstrated by Field and Odgers (2016) and Chaplot (2010), DSMs to create soil attribute and land suitability maps is possible with current soil profile datasets in Laos (SSLCC, 1996). Within Cambodia, there are many regions where more extensive soil profile datasets are required before DSM can be completed. Land resource assessment needs to be underpinned by accessible soil-landscape databases so that point source, detailed chemical and physical profile data are also available.

There will also need to be parallel development of sustainable farming systems for the sandy uplands in the LMB. Given the multiple limitations on sands for crop production, farming systems research needs to access cost effective technologies for alleviation of acidity, for erosion control, the supply of balanced and complete nutrient supply and the utilization of organic amendments. In addition, practices that optimize water use efficiency and maintain water balance are critical not only for profitability but for sustainable land management, including in areas prone to salinity. Based on the drivers for land development in the LMB, there is a need for effective management of the sandy soil resources to ensure food security in the region without land degradation.

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Table 1. Chemical properties of surface layers (0-20 cm) of Prey Khmer Soil Group (deep sand) and Prateah Lang Soil Group (sand over clay) (White et al., 1997) of rice soils in Cambodia. For southern Laos the values are means from SLCC (1996): sands at < 500 mm elevation cover 0.09 million hectares while loamy sands cover 1.17 million hectares. (Data source: Oberthur et al., 2000a; White et al., 2000 and Seng et al., 2001b).

Property	Prey Khmer	Prateah Lang	Sands S. Laos	Loamy sands S. Laos
Sand (g /kg)	730	500	890	820
Silt (g /kg)	220	370	66	122
Clay (g /kg)	50	130	44	58
pH (1:1 H_2O)	5.6	4.0	5.5	5.4
Organic C (g /kg)	4.7	2.9	6.0	7.3
Total N (g /kg)	0.5	0.3	0.5	0.6
Exchangeable K (cmol /kg)	0.04	0.08	0.10	0.10
Exchangeable Na (cmol /kg)	0.05	0.55	0.12	0.17
Exchangeable Ca (cmol /kg)	0.61	1.2	0.79	1.13
Cation exchange capacity (cmol /kg)	1.45	3.71	1.61	2.25
Olsen extractable P (mg/kg)	1.3	0.4	6.5	8.3

Table 2. Soil profile description for a deep sand profile from Boeng Tuk commune, Kampot Province, Cambodia. Classified as similar to Prey Khmer Soil Group (White et al., 1997) and Plinthic Alisol (World Reference Base 1998). Described by: Sarith Hin, 16/12/2008 Location: Datum: IND60 Zone: 48 404320 mE 1167649. Elevation: 15 m asl on a low-gradient footslope.

Depth (cm)	Description
0-20	pinkish grey (7.5YR 6/2 moist), dark reddish grey (5YR 4/2 dry) fine sand; no mottles; very friable dry consistence, non sticky, non plastic; weak, fine, granular structure; common roots, fine; no coarse fragments; few, fine, low porosity, vughs void; clear, smooth boundary.
20-45	light reddish brown (5YR 6/3 moist) fine sand; no mottles; very friable moderately moist consistence, non sticky, non plastic; weak, fine, granular structure; few roots, fine; no coarse fragments; very few, fine, very low porosity, vughs void; clear, wavy boundary.
45-65	strong brown (7.5YR 5/6 moist) loamy sand; very few very fine reddish brown (2.5YR 5/4 moist) redox mottles; firm moderately moist consistence, non sticky, non plastic; moderate, medium, subangular blocky structure; no roots; very few, fine, very low porosity, vughs void; gradual, wavy boundary.
65-95	yellowish red (5YR 5/8 moist) sandy clay loam; red (2.5YR 5/6 moist) redox mottles; friable moist consistence, slightly sticky, slightly plastic; massive structure; no roots; very few, fine, very low porosity, vughs void; gradual, smooth boundary
95-160	light reddish brown (2.5YR 7/4 moist) sandy clay loam; many coarse red (2.5YR 5/6 moist) redox mottles; friable moist consistence, slightly sticky, slightly plastic; massive structure; no roots; very few, fine and very fine, very low porosity, vughs void.

Table 3. Relationship of rice dry matter and yield at sites along a toposequence in a sandy terrain of northeast Thailand to flooding regime, soil organic matter and clay. Source: Homma (2002).

	Lower	Middle	Upper
Total dry matter (t/ha)	8.4 ± 2.4	7.2 ± 2.3	4.1 ± 2.4
Yield (t/ha)	2.6 ± 0.6	2.5 ± 0.9	1.1 ± 1.0
Flooded days	88 ±3 3	66 ± 29	7 ± 15
Organic C (g/kg)	13.1 ± 4.9	6.7 ± 2.4	3.9 ± 2.2
Clay (g/kg)	26 ± 13.3	10 ± 12.0	3 ± 0.9

Table 4. Rice soils of Cambodia- constraints and opportunities for the growth of rice (after Seng et al., 2009).

Soil Group	Parent material	Profile	Main constraints	Opportunities
Prey Khmer	Old alluvial/ colluvial from sandstone, granitic detritus	Sandy to 40-100 cm	NPKS deficiency, S, Fe toxicity, Low water holding capacity, leaching, transplanting difficulties as sand settles, coarse sandy phase	Compaction at depth, fertiliser in small doses, deep rooted cultivars, direct seeding, clay layer at depth, use high tannin green manures that break down slowly, N placement, timing and depth
Prateah Lang	Old alluvial/ colluvial from sandstone and other mixed detritus	Sandy to 10-25 cm on clay sub-soil	NPKS (Mg, B) deficiency, S and Fe toxicity, Low water holding capacity, leaching, hard setting, shallow phase, ironstone, transplanting difficulties as sand settles	Upland crops on loamy phase, drainage, direct seeding, post-rice crops, supplementary irrigation, split fertiliser, deeper cultivation Use high tannin green manures that break down slowly, N placement at depth

Table 5. Soil chemical properties of two profiles from the District of Tramkak, Takeo Province classified as sandy soils. Profiles were classified as Site 6, Prey Khmer Soil Group, fine sandy phase and Site 4 Prateah Lang Soil, loamy subsoil phase (White et al., 1997).

Site	Depth (cm)	Total N $g\ kg^{-1}$	Olsen P $mg\ kg^{-1}$	KCl_{40} S $mg\ kg^{-1}$	DTPA Cu $mg\ kg^{-1}$	DTPA Zn $mg\ kg^{-1}$	DTPA Mn $mg\ kg^{-1}$	Hot $CaCl_2$ B $mg\ kg^{-1}$
6	0-12	0.05	7	1.5	0.24	0.38	30.7	0.3
	12-60	<0.2	4	<1	0.27	0.18	5.46	0.3
	60-100	<0.2	<1	<1	0.32	0.15	1.81	0.3
	100-120	<0.2	<1	<1	0.27	0.17	1.55	0.3
4	0-12	<0.2	14	3.3	0.51	0.42	27.9	0.2
	12-30	<0.2	4	8.9	0.6	0.51	24.1	0.3
	30-70	<0.2	4	3.0	0.5	0.12	7.49	0.2
	70-110	<0.2	1	4.3	0.64	0.19	2.32	0.4

Table 6. Soil pH and exchangeable Al in soils of Tramkak District, Takeo.

Soil Type	Depth (cm)	Phase	pH $CaCl_2$	Al (cmol kg^{-1})	ECEC (cmol kg^{-1})	Al saturation (%)
Prey Khmer						31
(Site 5)	0-6		4.3	0.14	0.45	
	6-20		4.3	0.29	0.56	52
	20-60		4.5	0.32	0.65	49
	60-85		4.1	3.24	5.6	58
	85-100		6.4	0	10.7	0
Prey Khmer (Site 6)	0-12	fine sandy	4.5	0.28	1.83	15
	12-60		4.2	1.57	1.81	87
	60-100		4.1	1.4	1.6	88
	100-120		4.2	1.32	1.48	89
Prateah Lang (Site 4)	0-12	loamy subsoil	4.2	0.4	1.6	26
	12-30		4.2	0.48	1.7	29
	30-70		5.7	0	2.8	0
	70-110		8.2	0	5.6	0

ECEC: effective cation exchange capacity

Table 7. Plant available water content (PAWC) of topsoil (0-20 cm) and subsoil (20-100 mm depth), grouped by soil texture class for profile data from Savannahket, Laos (Inthavong et al., 2011).

Texture	Topsoil (20 cm)		Subsoil (20-100 cm)	
	Clay%	PAWC (mm in 20 cm)	Clay%	PAWC (mm in 80cm)
Clay	44	-		104
Clay loam	25-33	35		82
Loam	16-18	26		97
Sandy loam	9-12	17		63
Loamy sand	6-7	11		45
Sand	4	9		37

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Table 8. Land capability ratings for upland cropping based on typical land quality values for the sandy soils of the Tramkak District in Takeo Province. The overall land capability rating is based on the rating of the most limiting land quality. Source: Bell et al. (2007). *Note*: The land capability ratings for specific crops will vary depending on individual crop requirements. The land quality values are averages for soil groups, and actual values may vary considerably at a given site.

Land qualities	**Prey Khmer soil (fine sand phase)**		**Prey Khmer Soil group (medium sand phase)**		**Prateah Lang (clay sub-soil phase)**	
	Values	**Capability**	**Values**	**Capability**	**Values**	**Capabilit**
Soil workability	Good, fair	Very high	Good, fair	Very high	Good-poor	Fair
Surface condition	Soft, firm	Very high	Soft, firm	Very high	Hardsetting	Low
Surface soil structure decline susceptibility	Moderate	High	Moderate	High	High	Fair
pH($CaCl_2$) (0-20 cm)	4.3-4.5	Fair	4.6-5 or 4.3-4.5	High-fair	4.6-5	High
pH ($CaCl_2$) (20-50 cm)	<4.3	Low	4.6-5 or 4.3-4.5	High-fair	4.3-4.5	Fair
Nutrient availability	High leaching, low PRI	Fair	High leaching, low P retention	Fair	Moderate leaching	High
Waterlogging	Very low	Very high	Nil, very low	Very high	Moderate	Fair
Inundation	Low	Very high	Nil, low	Very high	>50 cm	Very hig
Soil water storage (SWS) (mm/m)	35-50	High	35-50	Fair	High	Low
Rooting depth	>50 cm	Very high	>50 cm	Very high	Moderate-High	Fair-Lov
Water erosion risk	Moderate to high	High-fair	Moderate	High	Very low	Very hig
P export	High	Fair	High	Fair	Low - Moderate	High
Overall land capability	**Sub-soil acidity**	**Low**	**High leaching, low SWS, acidity**	**Fair**	**Hardsetting, waterlogging, inundation**	**Low**

Table 9 Yields of crop species (t/ha) from on-farm trials on Prey Khmer and Prateah Lang Soil groups in 2004 and 2005 in early wet season (EWS- May) and main wet season (MWS- mid-July to mid-August) planting. From Seng et al. (2009).

Soil group	**EWS 2004**	**EWS 2005**	**MWS 2004**	**MWS 2005**	**Mean**
Peanut					
Prey Khmer	2.50	0.28	1.59	2.04	1.67
Prateah Lang	0	1.13	1.28	1.72	1.03
Mean of all soils	1.44	1.85	1.84	2.25	1.85
Mung bean					
Prey Khmer	1.76	0.65	0.3	1.03	0.93
Prateah Lang	0	0	0	0	0
Mean of all soils	0.6	0.22	0.56	0.71	0.52
Maize					
Prey Khmer	1.5	1.13	1.14	1.40	1.29
Prateah Lang	0	0	0.78	0	0.2
Mean of all soils	1.88	0.86	2.13	1.31	1.55
Soybean					
Prey Khmer	1.03	0.26	0.35	1.23	0.78
Prateah Lang	0	0	0.90	0.53	0.72
Mean of all soils	0.35	0.2	1.43	1.20	1.31

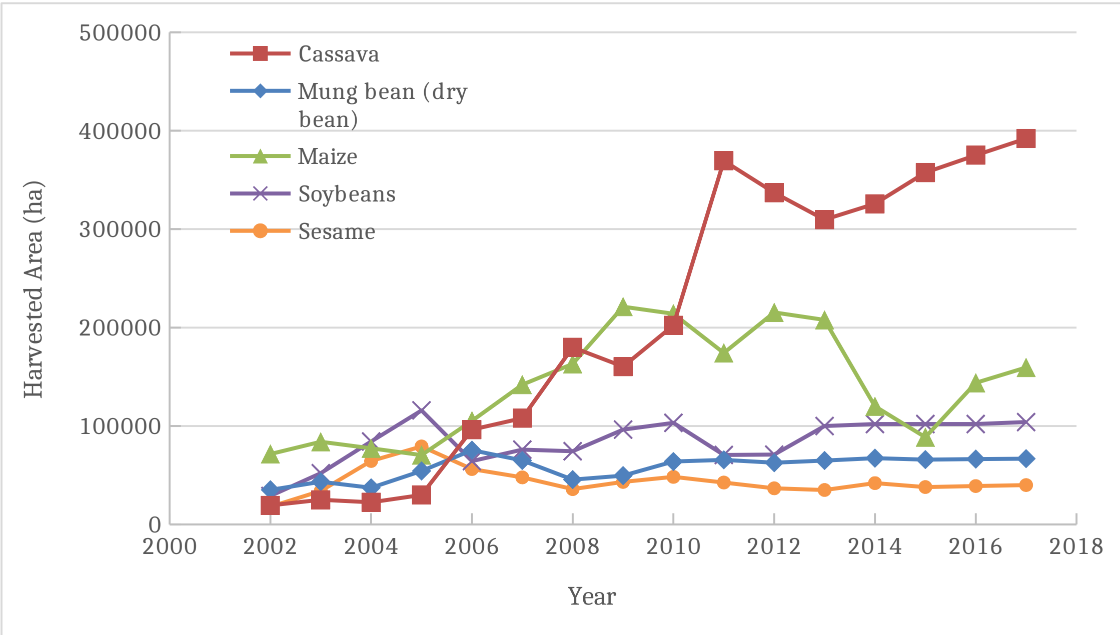

Figure 1. Harvested areas of non-rice crops in Cambodia from 2002 to 2017 (FAOSTAT, 2018).

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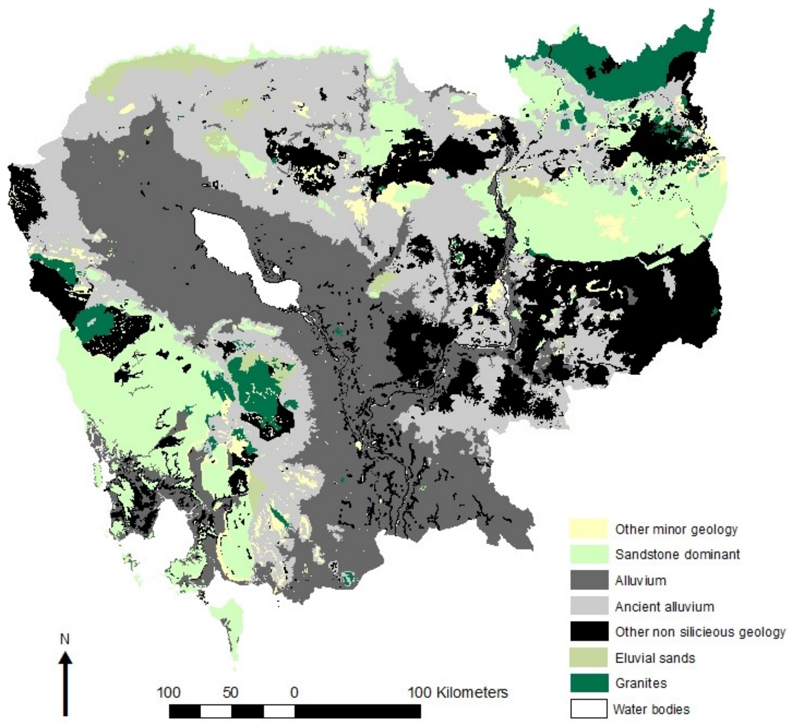

Fig.2. Generalised geology of Cambodia. Source: Mekong River Commission.

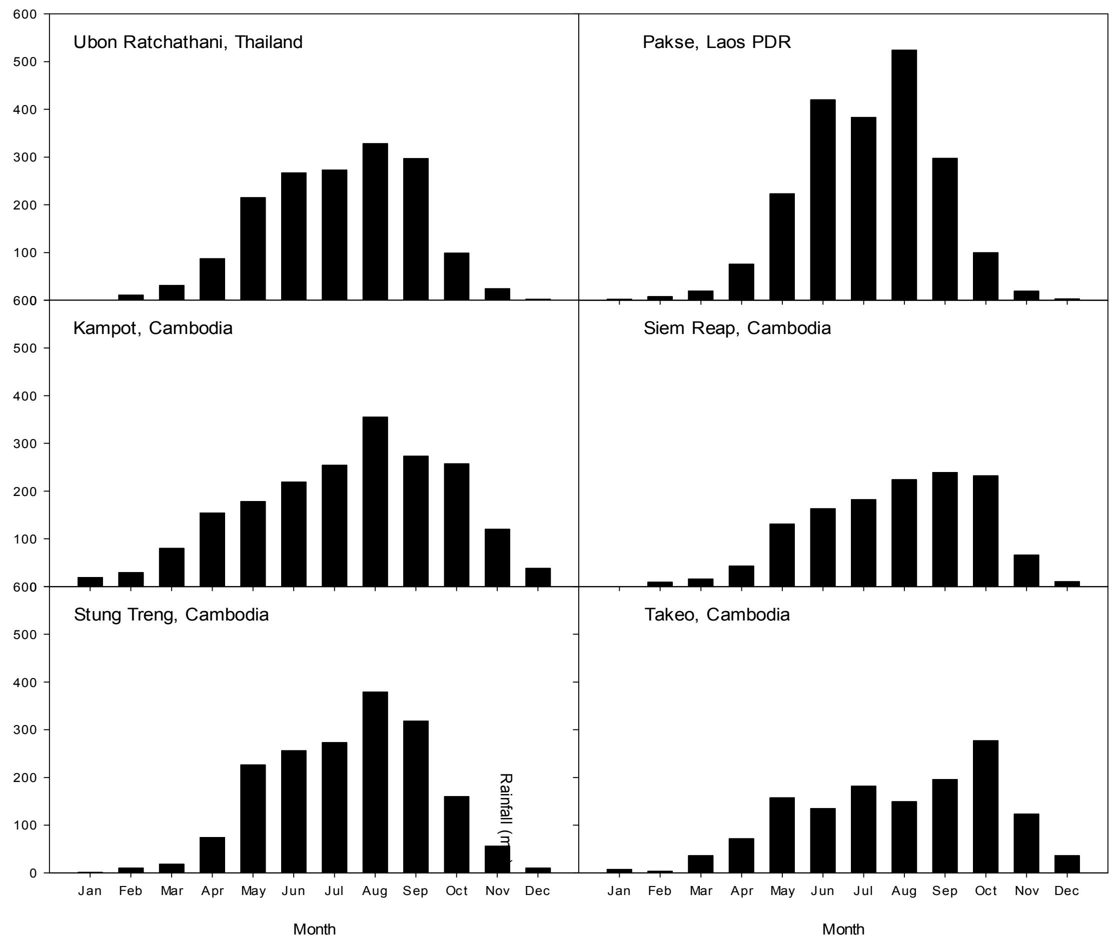

Fig. 3. Average monthly rainfall for Takeo, Siem Reap, Stung Treng and Kampot in Cambodia Pakse in Laos PDR, and Ubon Ratchathani in Thailand. Data for Thailand, Lao PDR, and Siem Reap, Kampot and Stung Treng sourced from CLIMWAT data (FAO, 2016); Takeo, Cambodia – data sourced from Bureau of Meteorology (40 years).

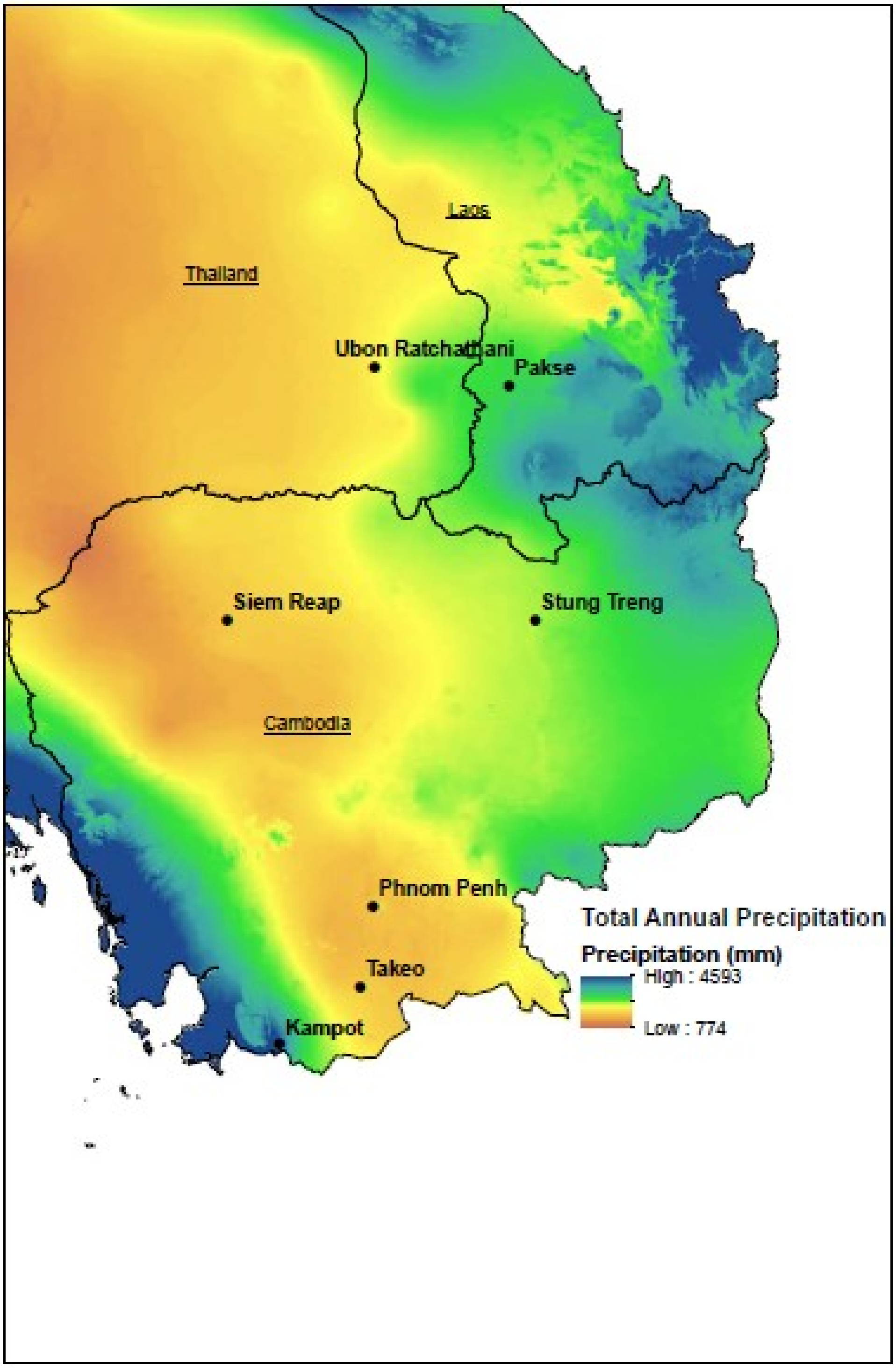

Fig. 4. Location map for rainfall stations (see Fig. 2). Total annual precipitation derived from the WorldClim bioclimatic variable: BIO12 (WorldClim, 2016). 1 km^2 spatial resolution with the temporal range of approximately 1970-2000 (Fick and Hijmans, 2017).

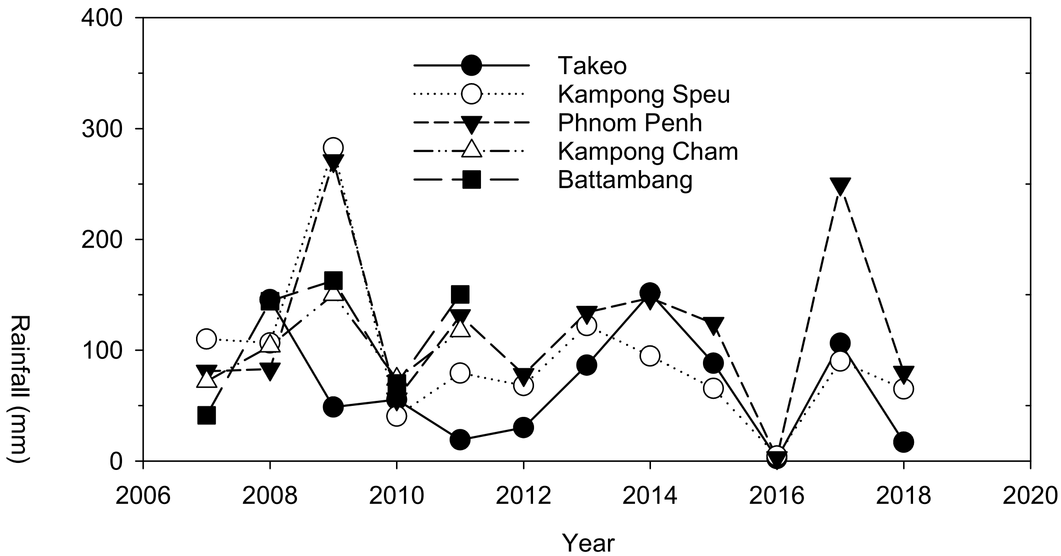

Fig. 5. Total rainfall (mm) in April (early wet season) at Takeo, Kampong Speu, Phnom Penh Kampong Cham and Battambang over the period 2007-2018. Source: Department of Meteorology, Cambodia. Note: rainfall records are incomplete which accounts for missing entries.

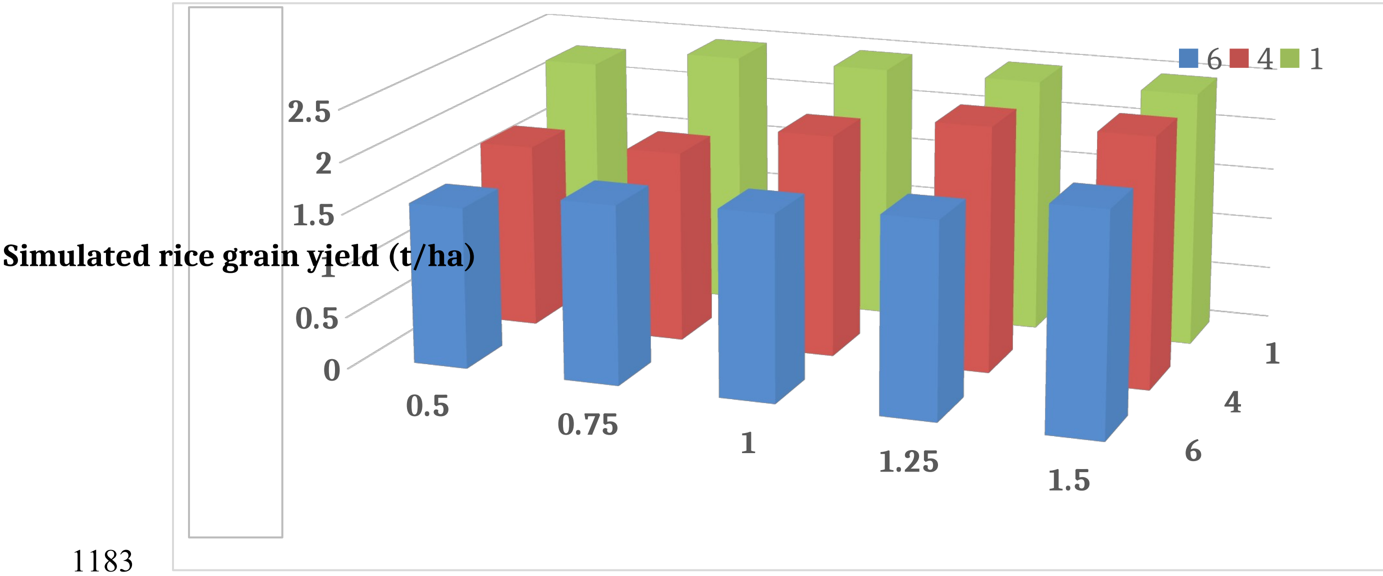

Fig. 6. Simulated grain yield (t ha^{-1}) for rice cv. KDML105 under different degrees of lateral movement of water (C_L) and deep percolation rates (mm/day) at Ubon Ratchatani, NE Thailand. (Fukai et al., 2000). $C_L < 1$ indicates net run-off, $C_L = 0$ indicates no lateral water flows and $C_L > 1$ indicates net run-on of water.