Bell, R.W. and Seng, V. (2007) The management of agro-ecosystems associated with sandy soils. In: Management of Tropical Sandy Soils for Sustainable Agriculture: Symposium on the Management of Tropical Sandy Soils, 27th November – 2nd December 2005, Khon Kaen, Thailand, pp 298-304.

The management of the agro-ecosystems associated with sandy soils

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Keywords: agro-ecosystems; erosion, leaching, nutrient cycles, water balance, sandy texture

Abstract

Sandy soils are prevalent in tropical environments especially where felsic volcanic, or siliceous sedimentary rocks and their erosional products are found. Whereas some of these soils are only sandy in the surface layers, others are sandy throughout the root zone. In terms of the agro-ecosystems developed on sandy soils, the prime limiting factors and the main concerns for sustainability, vary according to their position in the landscape (steeplands, uplands and lowlands) and agro-ecological zoning. Sandy soils occur in arid, semi-arid and humid rainfall zones of the tropics and from coastal lowlands to high altitudes. Sloping sandy soils tend to be used for conservation reserves, forestry (including plantations) and for shifting cultivation, and may also serve as important water catchments. Sandy uplands and lowlands are used for a range of cropping systems including rice-based systems. Plantation crops and forestry are also prevalent. The continuously or seasonally waterlogged lowlands are largely developed for irrigated and rainfed rice cultivation. Tropical sandy soils have a wide range of limiting factors for agricultural use, these include nutrient deficiencies, acidity, water stress and poor physical attributes. The environments in which they occur are prone to degradation risks from nutrient decline, erosion, leaching, salinity, and acidification. Development of sustainable agro-ecosystems in these sandy terrains should be based on optimisation of key ecosystems processes: closing nutrient cycles, restoring hydrological balance; enhancing biodiversity and strengthening resilience of these processes to perturbations. A range of opportunities exist to achieve sustainability of sandy landscapes through plantation forestry, agroforestry, clay and other mineral soil amendments, maintenance of soil organic matter, balanced fertilisation, strategic irrigation, and breeding species for adaption to the constraints present. Management of agro-ecosystems associated with sandy soils will be explored with respect to agricultural productivity and sustainability, and the supply of ecosystem services.

Introduction

Sandy soils as defined in the World Reference Base (FAO-ISRAC-ISSS, 1998) contain <18% clay and >65% sand in the first metre of the solum. Generally, the main Reference Group for sandy soils is the Arenosol (FAO-ISRAC-ISSS, 1998). The nearest Soil Taxonomy equivalent is the Psamment sub-order (Van Wambeke, 1992). However, amongst tropical soils, sandy textures in the surface layers are more prevalent than sandy textures throughout the profile, and the shallow sandy soils may share similar attributes and constraints as deeper sandy soils for shallow rooted crops such as padi rice. Hence, in areas where lowland rice is prevalent it may be important to broaden the scope of sandy soils beyond the Arenosols to include those Reference Groups with members that are sandy in the surface layers: Regosols, Leptosols and Fluvisols.

Tropical sandy soils are prevalent in landscapes where felsic volcanic, or siliceous sedimentary rocks and their erosional products are found. They are also prevalent in desert regions, and as beach deposits and dunal features in coastal zones. The lower Mekong River Basin in Southeast Asia has an extensive area of sandy soils (Mekong River Commission, 2002). Other major provinces for sandy soils in tropical environments include: the Sahel zone of West Africa, the Kalahari basin (covering two-thirds of Botswana and Angola), and Northern Australia. However, smaller but still significant areas of sandy soils occur in most tropical regions including parts of central Vietnam, Pakistan, Saudi Arabia, Iran, and Brazil (FAO, 2005).

In terms of the agro-ecosystems developed on sandy soils, the prime limiting factors and the

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main concerns for sustainability, vary according to topography, *viz*, steepland (>12% slope), uplands and lowlands; sub-divided further by agro-ecological zoning. Sandy soils occur in arid, semi-arid and humid rainfall zones of the tropics and from coastal lowlands to high altitudes. For the purposes of this paper, we will exclude sandy soils in desert regions due to their low potential for land use except where irrigation water is available.

Sandy soils in steeplands tend to be used for conservation reserves, forestry (including plantations) and for shifting cultivation, and may also serve as important water catchments. Sandy uplands comprise all those soils that are neither seasonally waterlogged nor steep. They are used for a range of field cropping systems depending on the agro-ecological zoning and elevation. Plantation crops and forestry are also prevalent. Sandy soils in the continuously or seasonally waterlogged lowlands are largely developed for irrigated and rainfed rice cultivation especially in Asia. While sandy soils are not highly suitable for rice cultivation, because rice is the major subsistence crop in Southeast Asia, sandy soils commonly are used for this purpose. Rice is also common in West Africa. Because of the shallow rooting zone of padi rice which is restricted to 0-20 cm, the surface texture has a more dominating influence on lowland rice than in upland cropping. Hence it is common to refer to soils in lowlands as sandy if they have sandy surface textures regardless of the subsoil texture. Indeed, White *et al.* (1997) in their Cambodian Agronomic Soil Classification system (CASC), developed for rice soils, restricted their consideration of soil properties to the 0-50 cm depth. The continuously or seasonally waterlogged lowlands are also important fisheries habitats, for aquaculture and for flood control.

The environments in which tropical sandy soils occur are prone to degradation risks from nutrient decline, erosion, leaching, salinity, and acidification. Management of agro-ecosystems for sustainable production on these landscapes will need to find technologies to overcome these constraints for economic viability of the enterprises. Development of sustainable agro-ecosystems in these sandy terrains should be based on optimisation of key ecosystems processes: closing nutrient cycles, restoring hydrological balance; enhancing biodiversity and strengthening resilience of these processes to perturbations. A range of opportunities that exist to achieve sustainability of agro-ecosystems in sandy landscapes will be outlined.

Development of sustainable agro-ecosystems in sandy terrains

Sustainable agro-ecosystems need to simultaneously satisfy three sets of criteria: economic viability; ecological processes; and social acceptability (Lefroy et al., 1992). This represents an advance on earlier thinking that focussed on economic viability of agro-ecosystems. It also recognises that focussing only on ecological processes will not be sufficient for sustainable agro-ecosystems since economic viability continues to drive many key decisions by farmers, and society increasingly is expressing a voice about the practice of agriculture in terms of the quality of food it delivers to markets and the off-site impacts of agriculture.

Economic viability of agriculture

Tropical sandy soils have a wide range of limiting factors for agricultural use: these include nutrient deficiencies, acidity, low water storage and poor physical attributes. Limiting factors may have a major bearing on the economic viability of agriculture on sandy soils. For example, a large province of sandy soils in Western Australia was deficient in the micronutrients, Zn, Cu and Mo (Bell *et al*., 2004). Until the discovery of these deficiencies and practical means of correcting them, it was not economically viable to use these sandy soils for agriculture.

Low nutrient levels are common on sandy soils, and crops grown on these soils commonly express multiple nutrient disorders which limit productivity of crops (e.g. Northeast Thailand, Bell *et al*., 1990). While fertiliser can correct these disorders, it is often difficult to achieve the optimal mix of nutrients and other soil amendments to make it economic (e.g. Ragland and Boonpukdee, 1987). Failure to diagnose all the limiting nutrients in a soil will lead to ineffective use of fertilizer and poor responses to those fertilizers that were applied. The widespread use of N alone often provides poor returns from fertilizer investment since on sandy soils deficiencies of P, S, K and/or micronutrients also commonly limit crop production.

In part the difficulty of fertilizing crops when there are multiple deficiencies is lack of availability of appropriate fertilizer products. In Thailand, for example, there are a large range of fertilizer products available, but limited understanding by farmers of the types most suited for particular soils and crops (Bell *et al*., 1990). A range of NPK formulations are commonly available in the Thai market but they vary in S content (Chunyanuwat *et al*., 1993). Since S deficiency is quite common in Northeast Thailand, NPK formulations with different S content may give quite different responses in crops (Bell *et al*., 1990). Similarly, NPK formulations in Thailand vary in B content which would affect responses since large areas of sandy soils in Northeast Thailand are low in B (Bell *et al*., 1990). Market supply of micronutrient fertilizers varies nationally and locally and in many places such fertilizers are not readily available, e.g. Bangladesh (C. Johansen, pers. comm.). Finally, according to Ragland and Boonpukdee (1987) responses to fertilizers alone on sandy soils in Northeast Thailand are poor without addition of organic matter.

The high percolation rates of the deep sands are a major limiting factor for rainfed agriculture. Drought is the most important consequence for crops. However, leaching of N and other nutrients may also limit productivity of these soils even when water is not limiting. For example, the deep sandy Prey Khmer soil in Cambodia has lower potential productivity for rice even with fertilizer application than the other major sandy lowland soil (Prateah Lang), which has a higher clay content in the subsoil (White *et al*., 1997).

Acidity is common on sandy soils. Where lowland rice is the main crop, flooding alleviates acidity (Kirk, 2004). However, for rainfed crops, acidity may give rise to a range of fertility constraints including Al and Mn toxicities and deficiencies of nutrients (Dierolf *et al*., 2001). Poor N fixation in legumes is often a consequence of soil acidity due to the low tolerance of Rhizobia to acidity, and to low levels of plant available Mo.

Salinity is a common constraint on sandy soils wherever irrigation is used in semi-arid environments. In sandy coastal zones, salinity is associated with seawater intrusion (White *et al*., 1997). Less well recognised is dryland salinity, which arises from perturbation of the hydrological balance in rainfed environments. It is a major problem in Northeast Thailand where a large percent of soils are sandy: currently dryland salinity affects about 12% of the lowland soils but is predicted to spread to cover up to 30% (Yuvaniyama, 2001).

Optimisation of key ecosystems processes

In undisturbed ecosystems, key processes such as the cycling of nutrients, hydrological balance, energy capture and flow, biodiversity, and resilience maintain ecosystem function. Disturbance of ecosystems for agriculture alters each of these processes. It has been argued that sustainable agro-ecosystems could be developed by mimicking the operation of the key ecosystem processes (Lefroy and Stirzaker, 1999). Hence a way forward for sustainable agriculture in sandy terrains is to understand key ecosystem processes that operated in pre-existing ecosystems and to model agriculture on those processes. However, there are practical limits to the application of this approach. Firstly, there are as yet inadequate studies of ecosystem function in tropical sandy terrains. Secondly, where harvested products are exported from the location from which they were produced, the nutrient cycle is interrupted and nutrient supply needs to be maintained through inorganic and/or organic inputs.

Closing nutrient cycles

In undisturbed ecosystems, the cycling of nutrients through the biomass and soil compartments ensures that leakage of the store of nutrients is negligible (Grierson and Adams, 1999). Small amounts leave the ecosystem but may be offset by accretion in rainfall, by nitrogen fixation etc. However, most agricultural systems allow significant nutrient losses through harvested product removal, leaching, gaseous losses, and erosion. While these losses may be offset by fertilizer use or the return of crop residues to the field, the losses of nutrients still represent inefficiency in nutrient use and may have off-site consequences. Sandy soils in Northeast Thailand, for example, have lost considerable nutrient capital since the clearing of dipterocarp forests (Noble et al., 2000) and changed nutrient cycles and hydrology have made these soils prone to acidification. Nutrient budgets calculated for farm land in Northeast Thailand show large net losses at the field scale and at regional scale (Lefroy and Konboon, 1998).

Restoring hydrological balance

Water balance considers the partitioning of rainfall to evaporation, transpiration, runoff, deep drainage and to the change in soil water storage. In sandy terrain, the runoff component may be low especially in the pre-existing ecosystems. Change of land use to agriculture would normally alter hydrological balance by changing runoff, transpiration and deep drainage components (Lefroy and Stirzaker, 1999). Northeast Thailand is a relevant case study demonstrating the consequences of hydrological change in a sandy terrain. The development of dryland salinity appears to be related to a change in the landscape water balance following clearing of the forest for agriculture (Williamson *et al*., 1989). Rapid clearing in Northeast Thailand occurred in the 1960’s (Ruaysoongnern and Suphanchaimart, 2001). Prior to that, the salt stored in the halite strata of the near-surface sedimentary formation was not mobilised because the vegetation used most of the rainfall allowing little deep drainage to groundwater. However, under rice-based and upland cropping, significant deep drainage to the groundwater occurs annually and this has caused watertables to rise regionally over time. When groundwater reaches the soil surface or within 2 m of the surface, discharge of salt occurs annually at the soil surface. The gentle relief of the Northeast Thailand and the widespread shallow halite-bearing sediments place large areas of Northeast Thailand at risk of dryland salinity.

As the development of salinity in sandy soils of Northeast Thailand is essentially a water balance problem (Williamson *et al*., 1989), its long term solution will come from changes in land use that decrease deep drainage to regional groundwater. Given the current prevalence of lowland rice cultivation, this will prove a challenge in the short term. Tree planting or revegetation with perennial vegetation across a significant portion of the landscape may be needed to restore water balance, but the minimum amount needed to be effective is not known. Currently upland areas are mostly targeted for tree planting. More extensive agroforestry planting in lowlands may also be needed to help restore the water balance.

However, wherever large areas are seasonally flooded, deep drainage will continue. Lowland rice is uniquely dependent on surface hydrology and the duration of standing water in relation to crop growth stages (Fukai *et al*., 2000). Marked alteration of the hydrology of sandy terrain inevitably occurs with its cultivation. High deep drainage rates are a common problem in the sandy lowland rice soils of Cambodia (White *et al*., 1997), Laos and Northeast Thailand (Fukai *et al*., 1995). Deep drainage rates varied from 1 to 6 mm d^{-1} on sandy soils (Fukai *et al*., 1995). Model simulations for Ubon in Northeast Thailand show about a 50% increase in rice yield if the deep drainage rate of a sandy soil (6.3 mm d^{-1}) under puddled conditions could be reduced to 1.4-1.8 mm d^{-1} (Fukai *et al*., 2000).

Fields in the high or upper terraces of the sandy lowlands lose large amounts of water, particularly after heavy rainfall, through surface runoff and subsurface lateral water movement, while those in the lower terraces may intercept the flows from the upper paddies (Fukai *et al*., 2000). Moreover, location of on-farm drains, and road embankments and drains under roads can markedly affect where the runoff is directed. Lateral redistribution of water results in water availability and rice growth duration varying by 30 days or more, within quite small areas. Fukai and colleagues have used simulation models to estimate the sensitivity of rice yield to the effect of variation in one parameter while all others are held constant. In sandy terrain at Ubon in Northeast Thailand, the influence of run-on to the lower terrace diminished as the deep percolation rate was reduced from 6 to 1 mm d^{-1}. With 1 mm d^{-1}, there was almost no water stress throughout the growth period and hence the effect of water movement was small, whereas, with 4-6 mm d^{-1}, rice experienced periods with standing water interspersed with periods of water stress. In this case, simulated grain yield was strongly influenced by variation in lateral water movement.

Enhancing biodiversity

Agricultural ecosystems generally involve a decrease in biodiversity relative to the prior native ecosystems that existed. This is particularly the case where monocultures of cereals or plantation crops dominate the landscape. Biodiversity in these monoculture-dominated agro-ecosystems is usually greatest around villages and home gardens, and in the remnants of the prior ecosystems especially in less favoured agricultural environments such as riparian zones along rivers, streams and wetlands. Enhancing biodiversity within the agricultural system can be achieved through agroforestry, intercropping and crop diversification. *In situ* conservation of wild relatives of crop species has an important role in conserving genes that may be useful in future breeding programmes (Rerkasem, 2004). Flora in greatest need of conservation is in the sandy uplands due to their widespread use for agriculture. Conservation in the steeplands is often compromised by short rotation shifting cultivation, but there are cases in Southeast Asia of the compatible use of steeplands for agriculture and the conservation of biodiversity (Rerkasem, 2004).

Opportunities to improve sustainability of sandy landscapes

Sandy soils represent an ongoing challenge for water and nutrient management at landscape and field scales. Productivity on these soils tends to be low, even when recommended agronomic practices are followed. However, there are a number of promising avenues for sustainable development of agro-ecosystems dominated by sandy soils.

Maintenance of soil organic matter

Sandy soils generally have lower organic matter levels than heavier textured soils given similar rainfall, temperature, land use and tillage. Clay levels on deep sandy soils may be too low to protect organic matter from oxidation (Baldock and Nelson, 2000). Reducing tillage may help maintain organic matter levels. Perennial crops will also tend to maintain higher organic matter levels. However, there are practical limits to the levels of organic matter that are achievable on sandy soils (Shirato *et al*., 2005). Research with the aim of boosting organic matter levels in sandy soils often fails to recognise this limit and as a result there has been much wasted investment on organic matter management. Organic matter levels can be enhanced in sandy soils through minimum tillage, zero burning and retaining crop residues. Slowly decomposing litter appears to build organic matter levels over a period of several years on sandy soil in Ubon, Northeast Thailand (Naklang *et al*., 1999).

Clay and other mineral soil amendments

Possibly the most effective long term investment in improving productivity and sustainable use of sandy soils would be to increase their clay content. Application of clay to sandy soils has been suggested as a semi-permanent treatment to enhance water and nutrient retention in Northeast Thailand (Noble *et al*., 2004). Enhanced clay content would allow soils to accumulate increased organic matter levels, and hence retain more water and nutrients and buffer soils against significant change in chemical properties. However, this strategy is limited by the availability of clays, the cost of transporting the required amounts of clay and by a still rudimentary knowledge about potential benefits. Initial research on the sandy soils of Northeast Thailand suggests very strong responses in growth can be achieved by clay amelioration. Further work is ongoing to demonstrate the benefits of this technology. Northeast Thailand has numerous deposits of high activity clay in lacustrine sediments, S. Ruaysoongnern (pers. Comm.). The relevance of this technology for other parts of the region, particularly for the Prey Khmer (Arenosols) and Prateah Lang (Acrisols) soils of Cambodia (White et al., 1997; Bell and Seng, 2004) warrants further investigation.

Balanced fertilization

Sandy soils commonly suffer from multiple nutrient deficiencies. These problems can be compounded by Al toxicity. For this reason, the concentration of research on N or NP fertilizer use that has yielded significant benefits for farmers on loam and clay soils often gives disappointing results on sandy soils. Our research on farmers’ fertilizer use on sandy soils in Southern Cambodia suggest that they over-used N and under-used P, K and hardly used S (Ieng *et al*., 2002). Even a focus on NPK fertilizer use may lead to ineffective fertilizer programmes since S and micronutrient deficiencies such as B, Zn, Cu and Mo are common. Bell *et al*. (1990) reported extensive areas of multiple deficiencies on sandy soils of Northeast Thailand yet as discussed above S contents of fertilizers vary and relatively little use of B fertilizer has occurred despite there being solid evidence of crop yield responses to this element. The challenge for achieving balanced crop nutrition in sandy terrain is to provide simple advice and tailored fertiliser advice and products so that it can be efficiently delivered to large numbers of small farmers. Nutrient budgets may be a useful strategy for guiding farmers to consider the important issues for balanced nutrition and sustainable crop production. However, it needs to be supported by a parallel business development approach that seeks to supply fertilizers of the right type in the markets where they are needed, at an affordable price.

Plantation crops, forestry and agroforestry

Where the pre-existing ecosystems were forests or woodlands, a sustainable agro-ecosystem probably needs to incorporate a similar vegetation structure, as plantation crops, plantation forestry, or agroforestry. The soil cover provided by perennial vegetation minimises erosion and nutrient leaching, while the decrease in cultivation intensity and frequency helps maintain soil organic matter levels and soil structure. Ecosystems benefit from restoration of water balance, closed nutrient cycling, and enhanced biodiversity. Agroforestry may provide similar benefits to plantations (Young, 1997).

Breeding species for adaption to the constraints

Where a soil constraint is widespread and difficult to overcome by conventional agronomy, there is a strong case for breeding for tolerance to the stress. In sandy soils, this would commonly mean breeding for drought tolerance first, followed by tolerance of mineral disorders, including soil acidity.

Management of agro-ecosystems associated with sandy soils

Ecosystems provide a range of services that tend to be undervalued, and those existing on sandy terrains are no exception. Changed water balance which is the consequence of land use for agriculture in most cases, gives rise to land degradation that has on-site and off-site effects. Sandy soils in river basins deliver water that is used for a variety of purposes downstream. Changed water flow patterns and changed water quality may harm downstream wetlands and riparian zones on which the livelihoods of communities depend. Changed water flow patterns may give rise to downstream flooding events that impact on major settlements and cities. Excess nutrients or sediment from sandy terrains may cause harm to fisheries and fisheries breeding places. Hence there is a need to develop institutional arrangements that pursue integrated river basin management outcomes that recognise the connection between upstream and downstream users and achieve equity between their respective costs and benefits (Kam *et al.*, 2001). Such institutional arrangements need to incorporate the range of stakeholders that have an interest in the structure and function of river basin management, including government natural resources management agencies representing both production and conservation, private sector business, educational institutions and civil society groups.

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