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# Managing agricultural landscapes so that they maintain watershed functions as well as are productive

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## Abstract

Watershed functions that are based on the quantity, timing and quality of river flows are under the influence of land use by a combination of effects on the green and brown cover provided by plant canopies and surface litter layers, on the soil surface properties and soil structure, and on the landscape-level drainage network. Opportunities for 'eco-agriculture' to maintain and restore watershed functions can be understood on the basis of the relatively rapid options for restoring green and brown cover, the asymmetric (rapid degradation, slow recovery) dynamics of soil structure and the modification of landscape-level drainage that may have been a neglected topic in previous discussions of land use change. We focus here on the changes in soil structure as the 'slow variable' that tends to dominate the long-term opportunities for keeping watersheds productive as well as suppliers of quality water at the desired time.

## Introduction

***Watershed functions and the way they are affected by 'development' are much debated and are nearly everybody's concern…..***

When natural forests are logged or cleared by slash-and-burn methods for establishing tree crop plantations or upland food crops,
when roads are built on forested slopes and induce landslides and rapid pathways for mudstreams to reach the rivers,
when people start to live in upper watersheds and pollute streams by domestic use, livestock or use of agrochemicals,
when the demand for water increases because of greater use for lowland irrigation, industry or cities,
when fast-growing trees are planted that use more water than other vegetation,
when government agencies claim control and impose their solutions on the local community,
when the floodplains and wetlands that used to provide storage and buffer capacity are drained for 'development' or
when villages are built in places that are prone to flooding and mudslides, ….
the end result is '***problems with watershed functions***' that affect all of us one way or another.

***but there are many ways in which specific problems can be solved through combinations of forests, agroforestry and upland cropping…***

The standard solution to 'rehabilitation of watersheds' is to plant trees, usually under the control of 'foresters' in the hope of re-creating the benign conditions of a natural forest. Natural forests, however, provide livelihood options only at low population densities, so it cannot really solve current pressures on the land. Tree planting as such may actually increase the problem. Fast-growing trees with high water use will reduce dry-season flows of streams and rivers, while mixed and half-open systems that protect the soil can maintain water quantity and quality.

***once we have a common perception (criteria and indicators) of what exactly is the problem to be addressed.***

Because there are many potential 'solutions' we need to be clear and specific about what the problem is. A list of three criteria for ***water quantity*** (Transmit water, Buffer peak flows, Release water gradually), ***water quality*** (Reduce sediment loads and other pollutants, Maintain aquatic biodiversity) and integrity of the land surface (Control landslides, Reduce loss of fertile topsoil through erosion), needs to be combined with criteria that relate to biodiversity conservation and to the social and economic welfare of the people living in watershed areas.

***Once seen against these criteria, many 'solutions' are in fact causing new problems, the different stakeholder may in fact have opposite interests, and a broad process of negotiation may be needed to establish integrated natural resource management.***

Ecoagriculture can make solid contributions to resolving the apparent trade-off between maintenance of watershed functions and productive agriculture, if it addresses the issues in a way that links the patch, field, farm and landscape scales.

## Relating watershed functions to the agroforestry landscape mosaic

The basics of 'watershed functions' are well understood in most local ecological knowledge systems that have so far been explored (Joshi et al., 2004), as well as in formal eco-hydrological science. Their representation in general public debate and policy circles, however, leaves much scope for improvement.

Indonesia is rich in examples of landscapes where farmers have combined the use of trees for productive purposes with elements of the natural forest that provide environmental services and areas that are used for intensive food crop production. These 'agroforestry mosaic' landscapes can be seen as '*Kebun Lindung*' ('protective gardens') that offer great opportunity for combining development and environment targets (Pasya et al., 2004; Van Noordwijk et al. 2004a). Yet, there are obstacles in the recognition of these systems, as they may not meet the legal definitions of 'forest' or be in conflict with the existing land use regulation system and policies – even though it could pass the test when *functional* criteria and indicators would be used.

Essentially, watershed functions **that relate to the quantity, timing and quality of water flows** can be understood by considering steps in the pathway of water through the landscape (Ranieri et al., 2004). The main controls are:

1. ***green cover*** – intercepting raindrops and modifying the drip size (and therefore 'splash' power they have when reaching the ground), keeping a relatively small amount of water as water film on wet surfaces for rapid evaporation,
2. ***brown cover*** – the litter layer on the soil surface protects the soil from splash erosion, feeds soil biota that enhance soil structure, and acts as a filter for overland flow, reducing the sediment load
3. ***soil structure*** - at the surface and in the soil determines the speed at which water can infiltrate and hence the amount of 'excess' rainfall that travels over the soil surface as overland flow; depending on slope and connectivity of the

horizontal flow pathways ('pipes') a substantial amount of water can be passed on to streams as 'interflow' in a matter of hours after a rain storm event

4. ***soil water deficit* –** water uptake by vegetation between rain events creates space in the soil pores to absorb water; if the soil structure allows this water to infiltrate fast enough, water use can thus reduce overland flow
5. ***the drainage network*** -- the network of furrows, gullies, drains, roads, soil profile intersections along roads, temporary storage sites in ponds and wetlands, streamlets and streams determines how rapid overland flows and subsurface (inter)flows can reach rivers. Where land use change affects the timing of flow at a minutes-to-hours scale, the significance of changes in pathways looses importance with increased spatial scale (say for distances more than 10 km), as the travel time in the river itself (and its influence by the degree of channelling, propensity for use of flood plains and riparian wetlands) starts to dominate.
6. ***properties of the river bed*** – if the riverbed consists of stones, it can transport clean water at high velocity; where the river flows though (or meanders in) a landscape with alluvial material, the river can pick up sediment along its way during peakflows and carry high sediment loads regardless of the degree of soil protection in the uplands. Landslides (linked e.g. to earthquakes, road construction or decrease in soil anchoring by decay of deep tree roots) and volcanic ash deposits can provide soil material for transport, over and beyond what comes from the hillsides.
7. ***point sources of organic and chemical pollutants*** -- direct use of surface water for drinking and other domestic use is generally not safe downstream of human habitation. Water quality for other purposes, as well as for maintenance or restoration of the aquatic ecosystem, its biodiversity and use values, can be negatively affected by point sources of organic and chemical pollutants. Use of pesticides, imbalances between fertilizer inputs, uptake by plants (Cadisch et al., 2004) and off-take in harvested products and manure deposition into streams by domestic livestock (or domesticated elephants in ecotourism areas in northern Thailand…) can all make other efforts to maintain watershed functions useless from a user perspective.

A range of tools and models (Mathews et al., 2004; Ranieri et al., 2004) exist to relate the overall performance of a landscape to (subsets) of this list of influences, as well as to the 'natural capital' (including rainfall regime, slope, intrinsic soil conditions, nature of the vegetation replaced by human land use). For the specific analysis of agroforestry mosaics in Southeast Asia we use the WaNuLCAS model at plot level (Khasanah et al., 2004; Van Noordwijk et al., 2004c), GenRiver and SpatRain for daily time steps at watershed scale (Farida and van Noordwijk, 2004) and FALLOW (Suyamto et al., 2004) to analyse longer term trends in land use change linked to internal 'drivers' of change. In the remaining part of this contribution we will focus on the changes in soil conditions – as this may be the easiest part to manage for practitioners of 'eco-agriculture'.

## Soil physical degradation indicators

Using the soils under old-growth forest as a reference or baseline, soil degradation involves the loss of organic matter, declines in soil nutrient reserves, changes in soil biota and belowground food-webs as well as soil compaction and changes in water retention. The latter includes the capacity of soil to absorb water during rainfall events,

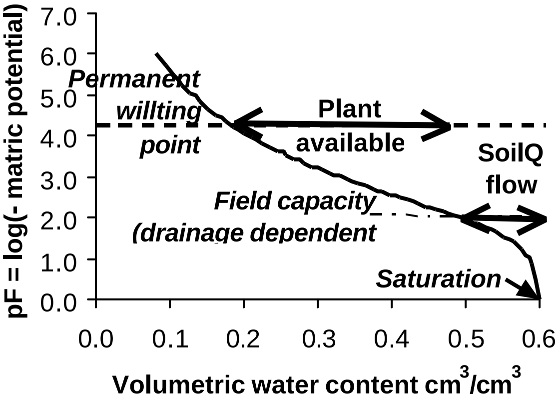

**Figure 1.** Key properties of the 'soil water retention curve' are the total water content at saturation, the amount retained 1 day after heavy rain ('field capacity') and the 'permanent wilting point; soil compaction primarily affects the soil close to saturation; the capacity for soil quick flow (SoilQflow) or 'interflow' depends on the difference between field capacity and saturated soil water content

release water during the first day(s) to groundwater and streams to reach 'field capacity' and retain water at tensions that are 'affordable' for plants to take up water (Fig.1).

The effects of compaction on these properties vary with soil type, but can be approximated by relating the actual bulk density (mass per unit volume) to a 'reference' value that can be estimated from the soil texture (sand, silt, clay and organic matter content) on the basis of large datasets for agricultural soils (Wösten et al., 1998). As a first estimate we may expect topsoils under natural forest to have a bulk density of about 70% of this reference value, while severely compacted soils may reach 1.3 times the reference value.

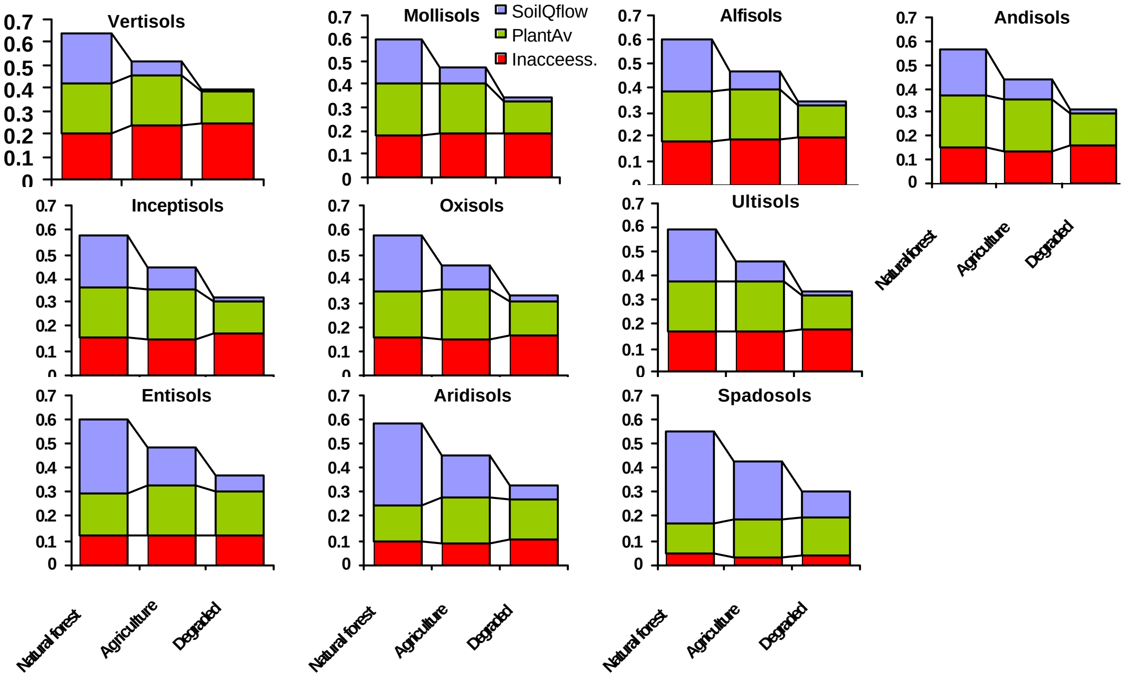

**Figure 2.** Upper-limit estimates of the effects of soil compaction on the key indicators of the water retention curve, based on the pedotransfer function of Wösten et al. (1998) and the tropical soil data base of Suprayogo et al. (2003), assuming that natural forests may have 0.7 times the bulk density of the agricultural soils used for the pedotransfer function, while degraded soils can increase bulk density up to a factor 1.3

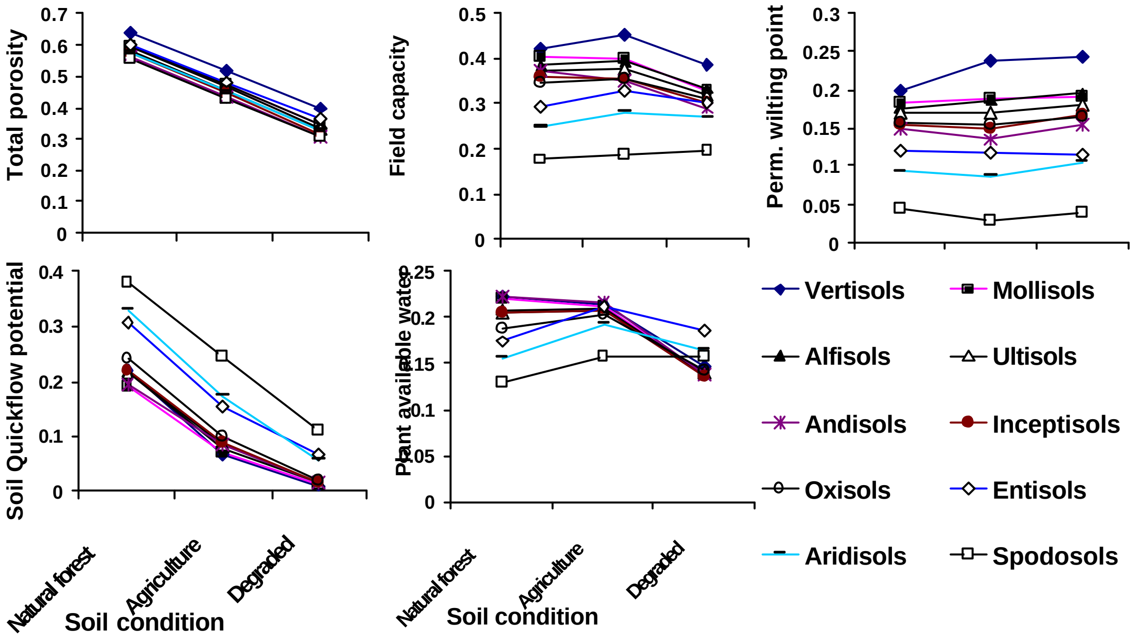

**Figure 3.** As figure 2, but allowing a direct comparison between the 10 soil groups

Averaged over the 10 main soil groups represented in the database of Suprayogo et al. (2003), the decrease in water-holding capacity from a 'natural forest' to a 'long-term agriculturally used' soil will be 0.136 $cm^3$ $cm^{-3}$, or the ability to temporarily store up to about 25 mm of rainfall if it applies to a topsoil of 20 cm. This storage capacity can be re-used in a rain event on the next day, as the water will by then have found its way to streams and rivers (or deep groundwater stores, if these are not yet saturated). Upon further degradation from agriculture to 'degraded lands' a further 0.081 $cm^3$ $cm^{-3}$ (or the ability to absorb 15 mm of rainfall) can be lost. This loss of storage capacity is likely to induce 'overland flow' conditions that can lead to flash floods and erosion.

The loss of 'plant available water' is small relative to the loss of temporary storage capacity in the 'soil quick flow' range: from forest to agriculture there can even be a small gain of 0.01 $cm^3$ $cm^{-3}$, while further compaction will cause a loss of 0.055 $cm^3$ $cm^{-3}$. The consequences of soil compaction for the pathways of 'excess' water flows (overland, subsurface lateral flow or deep groundwater pathways) are thus likely to be more pronounced than those for plant water availability on-site.

Compaction can, however, negatively affect the aeration of plant root systems, and an air-filled porosity at field capacity (numerically equal to the soil quick flow capacity) of 0.1 is often interpreted as a threshold for sensitive crops.

Soil compaction can be ***rapid*** – bulldozers, cars, animal hoofs and people can all apply sufficient pressure to compact a soil, especially when the latter is wet; in the absence of soil cover, detachment of fine soil particles and a process called 'slumping' also has the effect. The reverse process, creation of macroporosity, is ***slow*** – it may primarily depend on activities of earthworms and similar 'engineers' and turnover of woody roots. Once a soil is severely compacted, the recovery process may take decades or a century. Soil tillage is a poor substitute for biological structure formation: its effects are short-lived and by destroying biological structures it in fact creates an addictive effect: once started it is difficult to stop… Strategic 'tillage' like interventions, such as planting holes or crust-breaking can, however, set a long term biological soil recovery process in motion.

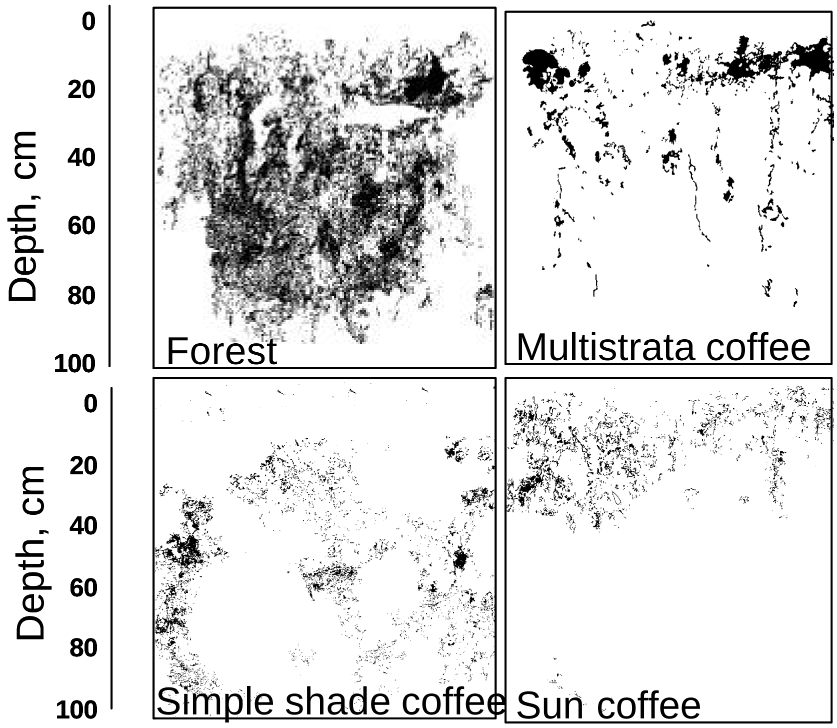

**Figure 4** Infiltration patterns for a blue dye that leaves a trace of colour in all macropores where it passes by, simulating what may happen during heavy rainfall, for four types of land use in the Sumberjaya ASB benchmark area in West Lampung (Indonesia); see Widianto et al. (2004) and Hairiah et al. (2004) for details on the methods and sites

Physical soil degradation can also have its primary effect via the reduction of the potential surface infiltration rate, through the formation of 'crusts' on the soil surface. In relatively dry climates this may even be the primary effect that leads to overland flow in conditions where the soil remains far from saturation.

> Where surface phenomena such as crusting rather than soil compaction dominate in the soil physical degradation process, recovery may be faster: any type of 'mulch' that protects the soil from the direct impact of rain and sunshine and stimulates soil biological activity may lead to recovery in a time frame of months.

It is thus important to correctly diagnose what type of degradation dominates in a given location, as it influences the time frames for potential recovery. Avoiding compaction on sites that are still in a 'natural forest' condition is probably more effective than 'rehabilitation' of degraded sites. Where surface processes dominate, however, rapid gains by mulch-based 'restoration' activities can be expected.

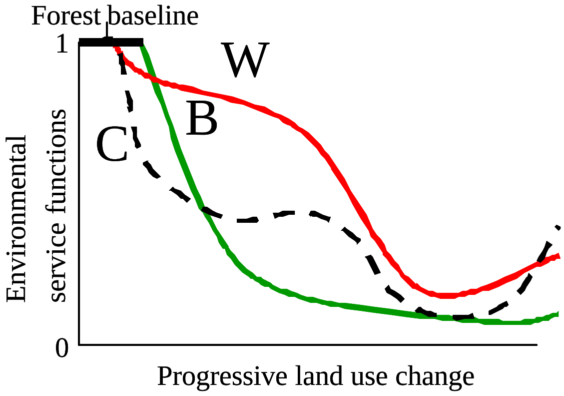

**Figure 5.** A semi-informed perception of the general trends in the three classes of environmental service functions B(iodiversity), C(arbon) and W(atershed functions) during progressive land use change, taken relative to a forest baseline

### *Measurement*

Standard soil physical textbooks and handbook of methods specify how 'bulk density' can be measured – but not how the data can be interpreted. Bulk density is strongly related to soil texture as well as soil organic matter content (which in itself depends on texture), so for a valid interpretation in the context of 'compaction' we need to derive a reference value for a soil with the same texture. A simple scheme is available in spreadsheet form on www.ICRAF.org/sea as part of the ecological models that can be freely downloaded.

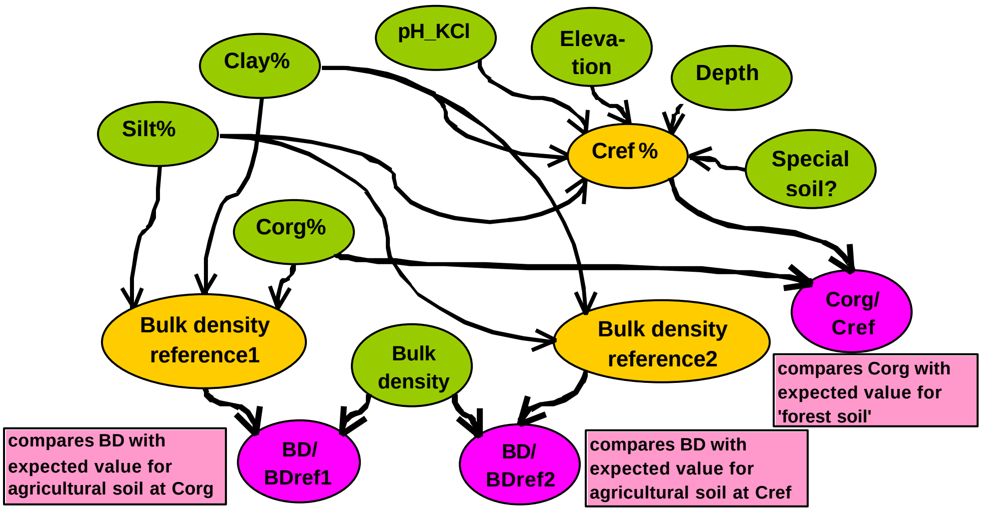

**Figure 6.** Schematic flow of the calculations that use various measured soil parameters to derive a 'reference' value for bulk density as well as soil organic matter content, and allow for interpretation of individual soil samples against a standardized baseline

### *Modelling physical degradation and rehabilitation processes*

While the water, nutrient and carbon balance of soils are well understood and the main processes are captured in simulation models that have reached considerable predictive ability, the dynamics of soil structure with decay and recovery of structure are still largely a black box, constraining further precision of e.g. water balance models. The WaNuLCAS (water, nutrient and light capture in agroforestry systems; van Noordwijk et al., 2004c) model uses the empirical BDref value as a 'fall-back' value to which soil structure decay reverts, in the absence of specific macropore creation activities of worms (and other soil engineers) that feed on surface mulch and fine root turnover, while woody root turnover creates macropores directly (Van Noordwijk et al., 2004d) Root turnover). This model description suggests that the most important parts of a tree for 'land rehabilitation' are the dead leaves that it sheds and the fine and coarse root turnover it induces.

A further complication arises when we realize that surface litter, depending on its size and weight, is prone to be carried away by wind or overland flow of water – leading to a differentiation into mutually enhancing zones of high infiltration and deposition of surface mulch, and zones of crusted soil with high runoff. Classification of litter sources by their propensity to transport is only just starting.

A macro version of the transport-deposition effect is known as the 'tiger bush' striped pattern in semi-arid lands – where the 'degraded' zones act as 'water harvesting' source areas for the vegetated parts. 'Land rehabilitation' can aim at strategically modifying the scale of this pattern, but not at a fully homogeneous state.

**Figure 7.** Differentiation into 'degrading' and 'rehabilitating' zones at different scales in the coffee landscape of Sumberjaya (Lampung, Indonesia): litter movement to deposition sites (above) and self-re-enforcing patterns of erosion and deposition at hill-slope scale; the rice-fields in the valley are an important 'filter' (right)

***Discussion: emerging principles***

1) Creation of local infiltration sites is often required as first step to break out from a soil degradation – surface runoff – erosion cycle; such sites will both reduce negative impacts on downhill neighbouring zones, as well as allow for a positive feedback loop of vegetation that enhances stimulates formation of soil structure, increasing infiltration and a further stimulus to plant growth. Triggers of such a positive feedback can be remarkably simple: stone lines (as used in the Sahel), planting holes made for trees (which may be the best part, initially, of 'reforestation' efforts and is often not considered as such) or small strips left to natural vegetation succession in between ploughed fields ('naturally vegetated strips') as used in the Philippines and Indonesia.
2) Taking a natural forest soil as baseline, soil compaction will initially have a stronger effect on the 'lateral flows' that affect 'watershed functions' than on the on-site productivity of the soil. Where protection of forest soils is feasible by reduction of the drivers of degradation, it is likely to be much more effective than efforts to rehabilitate degraded locations. Unfortunately, environmental governance and reward systems have difficulties in dealing with '***avoided degradation***', while '***rehabilitation***' is considered worthy of public investment.
3) Enhancing soil organic matter levels has little direct influence on 'plant available water', but a strong indirect effect via soil structure, depending on the texture of the soil and the rainfall regime; Susilo et al. (2004) discuss the relationship between total organic input in the agroecosystem and the various levels of the belowground food web
4) The most important part of a '***forest***' from a perspective of soil and water flows is likely to be in the litter and root turnover it produces and that, in turn, supports soil biota to maintain soil structure. Half-open ('agroforestry') land use systems with trees can approach the same functionality while providing better livelihood opportunities and income (see Van Noordwijk et al. (2004b) for discussion of

trade-off between relative ecological and relative agronomic functions, or REF and RAF).

5) For assessment and monitoring purposes new methods and models that provide 'internal controls' in the form of reference values for soil carbon and bulk density can be used to deal with the inherent variation in soil properties and the relationships between 'lateral flow' process across spatial scales.

The discussion so far has highlighted the ecological/technical side. If 'EcoAgriculture' is to achieve its aims, understanding of and actions targeting these technical aspects at farm management scale will have to be embedded in a structure of rules and incentives that relates downstream users of landscapes and stakeholders in maintenance of watershed functions to the decisions made on farm. The past focus of watershed managers on 'forest cover' per se may now give way to a more nuanced view in which land uses such as the 'kebun lindung' in Indonesia get the recognition that they are due (Pasya et al., 2004; van Noordwijk et al., 2004a).

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