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Agroforestry, buffering water flow, coffee, criteria and indicators, litter layer, macroporosity, protective garden, soil bulk density, soil structure, watershed functions

Chapter 12

Watershed functions in productive agricultural landscapes with trees

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Abstract

Watershed functions are often discussed in terms of deforestation and reforestation, but require a more careful diagnosis of problems and solutions. Criteria and indicators that are based on the quantity, timing and quality of river flows are influenced by a combination of effects, including the green and brown cover provided by plant canopies and surface litter layers, the soil surface properties and soil structure, and the landscape-level drainage network. Opportunities for agroforestry and other forms of conservation farming to maintain and restore watershed functions are dependent on the relatively rapid options for restoring green and brown cover, the asymmetric (rapid degradation, slow recovery) dynamics of soil structure and on modification of landscape-level drainage. Data for the watersheds of Mae Chaem in northern Thailand and Way Besai in Lampung, Indonesia, indicate that land-cover change has a relatively small effect on low river flow. 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 are nearly everybody's concern. Clearing natural forests to grow crops or build roads can reduce the amount of water that enters the soil and increase overland mudstream flows. Human habitation and industry can lead to streams becoming polluted while increasing the demand for clean water. Building on floodplains and wetlands can reduce water storage and buffer capacity and put the new developments at risk of flooding. New fast-growing crops and planted trees can use more water than existing vegetation. And governments can claim control of waterways and impose national solutions on them that do not take account of the local effects.

The end result of all these changes is that there are 'problems with watershed functions' that affect people one way or another. These problems will generally be attributed to deforestation, and reforestation is the default solution in public debate. The standard approach to 'rehabilitation of watersheds' is to plant trees, usually under the control of foresters, in the hope of recreating the benign conditions of a natural forest. Natural or planted forests, however, provide livelihood options only at low population densities, so reforestation cannot really solve current pressures on the land. Furthermore, tree planting in relatively dry areas may actually increase the problem: fast-growing trees with high water use will reduce dry-season flows of streams and rivers.

Agroforestry 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 patch, field, farm and landscape scales.

In this brief description of current approaches to agroforestry solutions to watershed problems, we will consider the following four basic steps, and discuss the concepts and tools required for each:

1. Diagnosis of problems at watershed scale.
2. Comparing land-use options on the basis of buffering functions.
3. Modelling physical degradation and rehabilitation processes in the analysis of trade-offs between profitability and watershed functions.
4. Negotiations between stakeholders of solutions on the basis of trade-offs.

Diagnosis of problems at watershed scale

Because there are many potential solutions to problems with watershed function, we need to be clear and specific about what the problem is, and this requires a common perception (criteria and indicators; Figure 1). A list of criteria for the contribution of watersheds to water quantity (the capacity to transmit water, buffer peak flows and release water gradually), water quality (reduce sediment loads and other pollutants and maintain aquatic biodiversity) and integrity of the land surface (control landslides and 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.

The relationship between full (as provided by a forest) and partial (agroforestry) tree cover and hydrological functions in terms of the five watershed functions listed in Figure 1 involves different time scales and trade-offs between total water yield and the degree of buffering of peak river flows relative to peak rainfall events. The role of land use can be analysed in terms of changes in evapotranspiration, linked to the presence of trees; infiltration, linked to conditions of the soil; and the rate of drainage linked to the drain network in the landscape.

van Noordwijk et al. (2003) completed a detailed analysis of both the 4000 km^2 Mae Chaem catchment in northern Thailand (mean annual rainfall 1500 mm, population density 20 km^{-2}; mean annual river flow 20–30 m^3 s^{-1}) and the 500 km^2 Way Besai catchment in Lampung, Indonesia (mean annual rainfall 2500 mm, population density 160 km^{-2}; mean annual river flow 15–20 m^3 s^{-1}). Daily rainfall and river flows for these two watersheds are shown in Figure 2.

The two rivers have very different patterns: the largely forested Mae Chaem shows a very strong seasonal pattern, falling nearly dry for a few months of the year; the Way Besai (only 15 percent forest) has approximately continual flow. These differences, of course, primarily relate to the rainfall pattern. They show, however, that commonly used indicators such as the ratio of maximum and minimum flow of the river, Q_{max}/Q_{min} cannot be used to analyse the condition of watersheds, without regards to rainfall.

The indicators of Figure 1 are all expressed in dimensionless form, relating river flow (discharge) to rainfall. For the analysis of the Mae Chaem and Way Besai situations, a new 'buffering indicator' was developed (van Noordwijk et al. 2003) that relates the frequency distribution of daily river flow to the frequency distribution of point-level rainfall. It can be used to test perceptions of increased flooding and peak flows. The Way Besai data relate to a 23-year period where forest cover was reduced from almost 30% to less than 10% in 2002. The main effect of this land-cover change was to increase the total water yield as a fraction of total rainfall. The total discharge in the month with the lowest flow, expressed as a fraction of annual rainfall, showed considerable variation between years but did not change along with total water yield. The buffering indicator was negatively correlated with the total water yield, but for

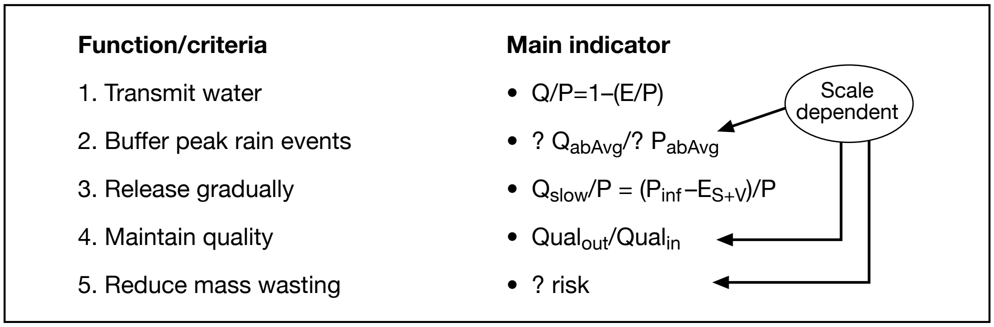

Figure 1. *Indicators for the five criteria. The quantitative properties of river discharge change along the river course, and lead to scale dependence of three out of the five criteria. Q = river flow; P = precipitation;* E_{S+V} *= total evapotranspiration minus evaporation of canopy intercepted water; abAvg = sum of all above average values; inf = infiltration.*

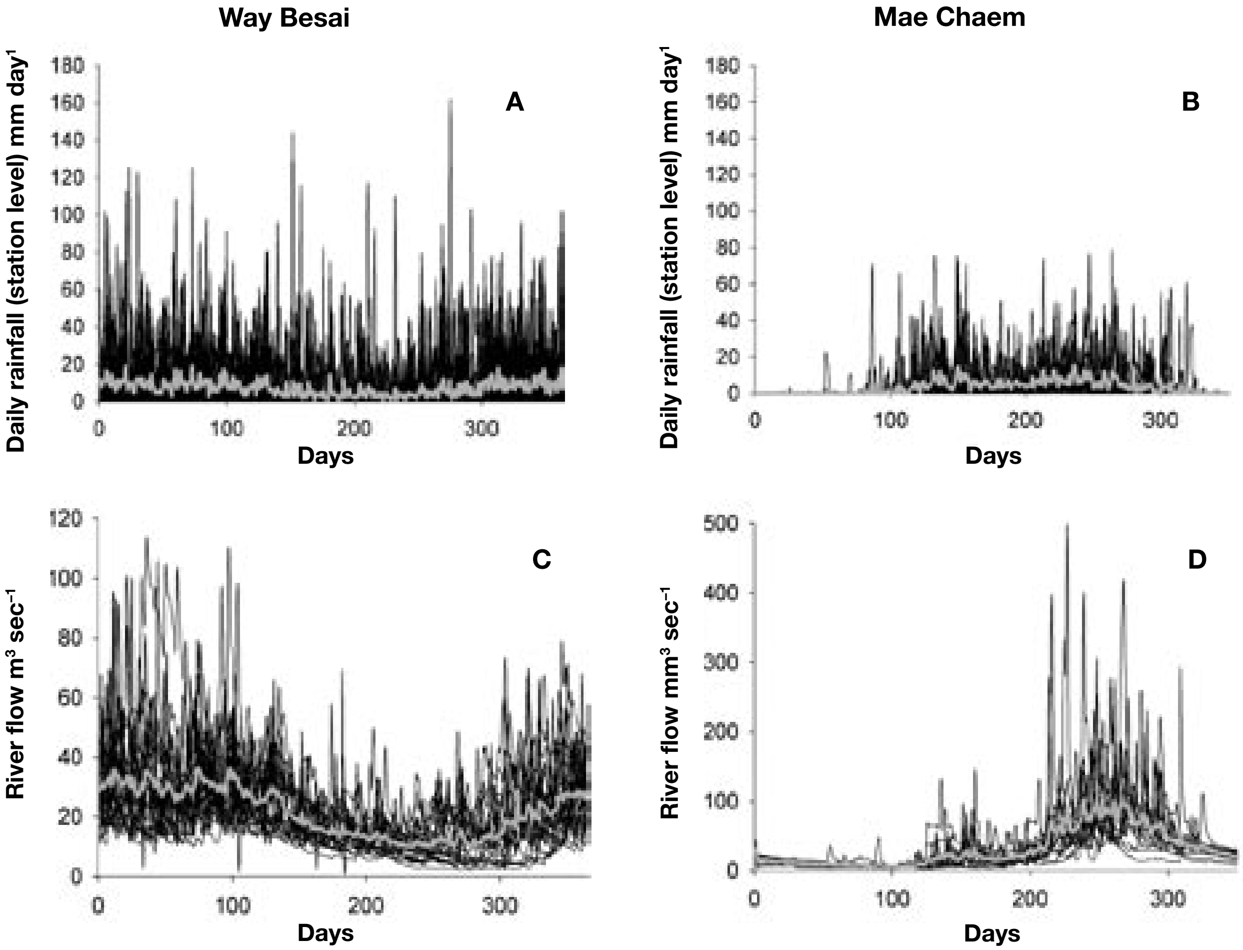

Figure 2. *The records of rainfall (A and B) and river discharge (C and D) of the Way Besai for the 1975–1998 period (A and C), and Mae Chaem for the 1988–2000 period (B and D). The thin dark lines trace the maxima and minima of daily values for the observation periods, the solid lighter line indicates the mean daily values (van Noordwijk et al. 2003).*

the other indicators the trade-off explained only a small part of the total variation. This suggests that in this catchment area the potential downstream benefits of more water are not associated with negative changes in river flow during the driest month or with less buffering of peak events.

A spatially distributed water balance model determined the current land cover situation as being between natural vegetation of forest on a porous soil, and degraded land with grassland on a compacted soil. Without fine-tuning of the model, an acceptable agreement between the model and actual measurements was obtained for the Way Besai (Table 1) and Mae Chaem (Table 2) catchment areas for each of the various indicators, within the range of forest to degraded lands.

This analysis, presented in very condensed form here, suggests that changes in forest cover can modify a number of quantitative characteristics of river flow, but that rainfall (and any change in rainfall characteristics between measurement periods) dominates the outflows. As rainfall tends to have complex patterns of variation over time, it is not easy to tease out a land-use change signal from the noisy background. Much of the attribution of change in river flow to land-cover change in public debate may not survive close scrutiny.

By comparing the results from the model with the measurements taken in the field we can conclude that models that link the space–time characteristics of rainfall via

Table 1. *Indicators of watershed functions for Way Besai, comparing actual data (averaged over 20 years) with simulations of different environments: the current LU (land use) mix; an 'all forest' approximation of natural vegetation; and a 'degraded lands' scenario with grass cover on a compacted soil. GenRiver simulations use rainfall data, soil information, land-cover type and sub-catchment structure of the watershed area (van Noordwijk et al. 2003).*

Indicators	Actual data	GenRiver		
	Current LU	Current LU	Natural vegetation	Degraded land
Total discharge fraction	0.61	0.53	0.44	0.62
Buffering indicator	0.79	0.82	0.80	0.68
Relative buffering indicator	0.66	0.66	0.55	0.49
Buffering peak events	0.86	0.81	0.76	0.78
Highest monthly discharge relative to mean rainfall	1.92	2.19	1.65	1.58
Lowest monthly discharge relative to mean rainfall	0.39	0.54	0.50	0.46
Overland flow fraction	*	0.11	0.00	0.36
Soil quick-flow fraction	*	0.10	0.02	0.00
Slow flow fraction	*	0.30	0.29	0.25

* indicates data not available.

Table 2. *Indicators of watershed functions for Mae Chaem, comparing actual data (averaged over 20 years) with simulations of different environments: the current LU (land use) mix; an 'all forest' approximation of natural vegetation; and a 'degraded lands' scenario with grass cover on a compacted soil. GenRiver simulations use rainfall data, soil information, land-cover type and sub-catchment structure of the watershed area (van Noordwijk et al. 2003).*

Indicators	Actual data	GenRiver		
	Current LU	Current LU	Natural vegetation	Degraded land
Total discharge fraction	0.21	0.19	0.13	0.32
Buffering indicator	0.89	0.90	0.93	0.81
Relative buffering indicator	0.49	0.45	0.54	0.40
Buffering peak events	0.91	0.88	0.91	0.79
Highest monthly discharge relative to mean rainfall	3.16	3.67	3.01	3.37
Lowest monthly discharge relative to mean rainfall	0.20	0.22	0.27	0.24
Overland flow fraction	*	0.00	0.00	0.00
Soil quick-flow fraction	*	0.08	0.03	0.17
Slow flow fraction	*	0.14	0.08	0.12

* indicates data not available.

the dynamics of macropores in the soil to the dynamics of river flow can fairly well reproduce the time series of data from intensively studied (sub)catchments.

Comparing land-use options on the basis of buffering functions

Long time-series with consistent data of land-cover change are scarce and much of the existing variation in land cover in agriculturally used landscape mosaics is not represented in empirical data. Further inference on land-use options has to rely on analysis of the various contributing factors and on synthetic models. 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 factors are:

- Green cover – leaves intercept raindrops and modify the drip size (and therefore the splash power they have when they reach the ground), keeping a relatively small amount of water as water film on wet surfaces for rapid evaporation.
- 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.
- 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 rainstorm.
- 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.
- 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.
- Properties of the riverbed – if the riverbed consists of stones and the river banks are stable, it can transport clean water at high velocity. Where the river flows through (or meanders in) a landscape with alluvial material, the river can pick up sediment along its way during peak flows and carry high sediment loads regardless of the degree of soil protection in the uplands. Landslides (linked, for example, 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.
- Point sources of organic and chemical pollutants – direct use of surface water for drinking and other domestic use is not generally 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 deposition of harvested products or manure 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.

Modelling physical degradation and rehabilitation processes in the analysis of trade-offs between profitability and watershed functions

A range of tools and models (e.g. Matthews 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 regimen, slope, intrinsic soil conditions and nature of the vegetation replaced by human land use).

For the specific analysis of agroforestry mosaics in Southeast Asia we use the WaNuLCAS (Water, Nutrient and Light Capture in Agroforestry Systems) 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 (Forest, Agriculture, Low-value Lands Or Waste; 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 chapter we will focus on the changes in soil conditions – as this may be the easiest part to manage for practitioners of agroforestry and other forms of eco-agriculture.

Using the soils under old-growth forest as a reference or baseline, soil degradation involves the loss of organic matter, a decline in soil nutrient reserves, a change in soil biota and below-ground food-webs, soil compaction and a change in water retention. The latter includes the capacity of soil to absorb water during rainfall events; release water during the first day(s) after a rainfall to groundwater and streams to reach field capacity; and retain water at tensions that are appropriate for plants to take up water (Figure 3).

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 (and which depends on 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 (BD) of about 70 percent of this reference value, while severely compacted soils may reach 1.3 times the reference value (BDref).

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}, equivalent to the ability to temporarily store up to about 25 mm of rainfall in 20 cm of topsoil. This is storage capacity that 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 agricultural 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 owing to soil compaction is small relative to the loss of temporary storage capacity. 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.

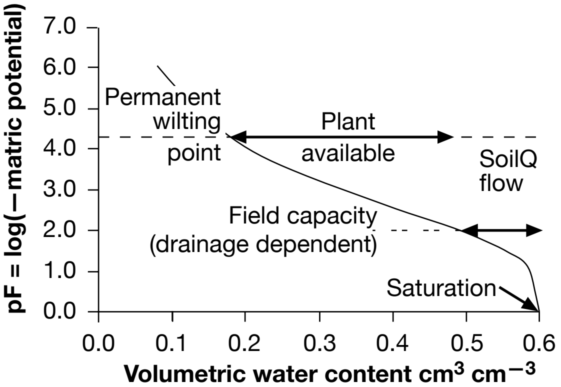

Figure 3. *The main properties of the soil–water retention curve are the total water content at saturation, the amount retained one day after heavy rain (field capacity), and the permanent wilting point. Soil compaction primarily affects the soil close to saturation; the capacity for soil quick-flow (SoilQflow) or interflow depends on the difference between field capacity and saturated soil water content.*

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

A relatively simple method to visualize and analyse changes in soil macroporosity linked to land cover makes use of the infiltration of a dye (Figure 4). The infiltration patterns can be interpreted on the basis of the general macroporosity of the soil and specific impacts of cracks, old root channels and activity of earthworms or other soil biota.

Soil compaction can be rapid; bulldozers, cars, animal hooves 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 same effect. The reverse process, creation of macroporosity, is slow; it primarily depends on the activities of earthworms and similar 'engineers' and the turnover of woody roots. Once a soil is severely compacted, the recovery process may take decades or up to 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 tillage stops, the soil structure generally degrades rapidly. Strategic tillage-like interventions, such as planting holes or crust breaking can, however, set a long-term biological soil recovery process in motion.

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

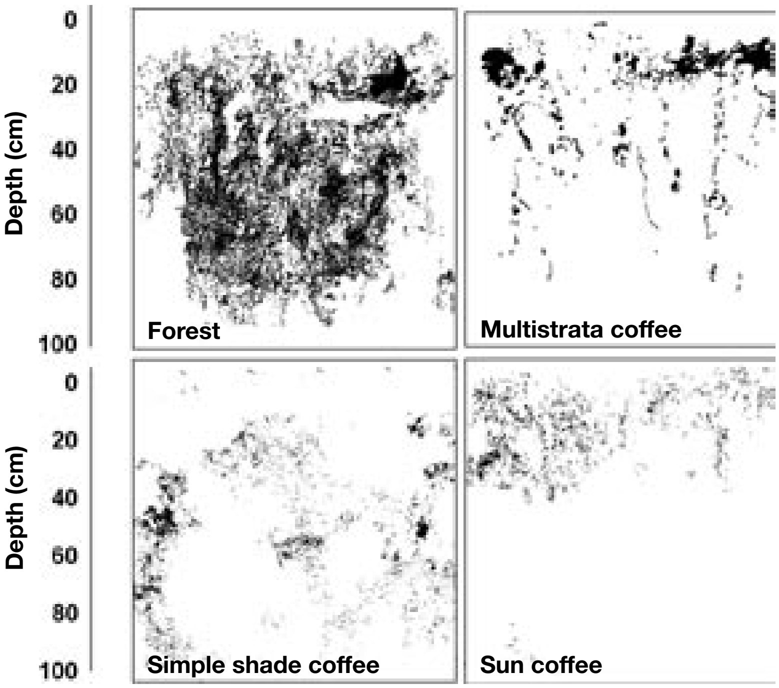

Figure 4. *Infiltration patterns for a dye that leaves a dark trace in all macropores it passes through. This simulates what may happen during heavy rainfall on four types of land use in the Sumberjaya benchmark area in West Lampung, Indonesia; see Hairiah et al. (2004) and Widianto et al. (2004) for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

in conditions where the soil remains far from saturated. 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 that stimulates soil biological activity may lead to recovery in a timeframe of months.

It is thus important to correctly diagnose what type of degradation dominates in a given location, as this will influence the timeframe for potential recovery. Avoiding compaction at sites that are still in a natural forest condition is probably more effective than trying to rehabilitate degraded sites. Where surface processes dominate, however, rapid gains by mulch-based restoration activities can be expected.

Standard soil physical textbooks and handbook of methods specify how BD can be measured – but not how the data can be interpreted. Bulk density is strongly related to soil texture and 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.

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 in terms of decay and recovery are still largely a black box, constraining further precision of models of water balance for example. The WaNuLCAS model (van Noordwijk et al. 2004c) uses the empirical reference value for bulk density, BDref , as a 'fall-back' value to which soil structure decay reverts in the absence of specific macropore creation activities, which create macropores directly (van Noordwijk et al. 2004d). 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 of the land into mutually enhancing zones of high infiltration with 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.

For a full understanding of the tradeoffs between productivity (or profitability) of land use and the implication for watershed functions we thus have a reasonably well-equipped tool kit. There are complications, however, such as the differences in time course of profitability and the substantial variation in soil properties, often at short spatial range, with substantial differences between soils in susceptibility to compaction.

Negotiations between stakeholders of solutions on the basis of trade-offs

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 ecohydrological 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 and other elements of the natural forest that provide environmental services with 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 to the recognition of these systems, as they may not meet the legal definitions of forest or be in harmony with existing land-use regulation systems and policies – even though they could pass the test when functional criteria and indicators would be used.

In negotiating solutions to local problems, the following aspects may require specific attention:

1. Creation of local infiltration sites is often the first step required to break out from a soil degradation–surface runoff erosion cycle. Such sites will both reduce negative impacts on downhill neighbouring zones and allow for a positive feedback loop of vegetation that stimulates formation of soil structure, increasing infiltration and acting as 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 (that 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 ('natural vegetative strips', see Chapter 7 this volume) as used in the Philippines and Indonesia.
2. Taking natural forest soil as a 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 tend to be reactive, and have difficulties in dealing with avoidance of 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 below-ground 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 effects, 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 BD 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 of soil structure and function. If agroforestry 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 relate both the downstream users of landscapes and the stakeholders in maintenance of watershed function to the decisions made on-farm. The past focus of watershed managers on forest cover per se may now give way to a more subtle 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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References

Cadisch, G., P. de Willigen, D. Suprayogo, D.C. Mobbs, M. van Noordwijk and E.C. Rowe 2004. Catching and competing for mobile nutrients in soils. Pp. 171–191, in: van Noordwijk, M., G. Cadisch and C.K. Ong (eds) Below-ground Interactions in Tropical Agroecosystems. CAB International, Wallingford, UK.

Joshi, L., W. Schalenbourg, L. Johansson, N. Khasanah, E. Stefanus, M.H. Fagerström and M. van Noordwijk 2004. Soil and water movement: combining local ecological knowledge with that of modellers when scaling up from plot to landscape level. Pp. 349–364, in: van Noordwijk, M., G. Cadisch and C.K. Ong (eds) Belowground Interactions in Tropical Agroecosystems. CAB International, Wallingford, UK.

Farida and M. van Noordwijk 2004. Analisis debit sungai akibat alih guna lahan dan aplikasi model GenRiver pada DAS Way Besai, Sumberjaya. [Analysis of changes in river flow in response to land use change, and application of the GenRiver model to the Way Besai watershed in Sumberjaya]. *Agrivita* 26: 39–47.

Hairiah, K., D. Suprayogo, Widianto, Berlian, E. Suhara, A. Mardiastuning, C. Prayogo and S. Rahayu 2004. Alih Guna Lahan Hutan Menjadi Lahan Agroforestri Berbasis Kopi: ketebalan seresah, populasi cacing tanah dan makroporositas tanah. [Thickness of the litter layer, earthworm populations and soil macroporosity as influenced by land use in coffee-based agroforestry]. *Agrivita* 26: 68–80.

Khasanah, N., B. Lusiana, Farida and M. van Noordwijk 2004. Simulasi Limpasan Permukaan dan Kehilangan Tanah pada Berbagai Umur Kebun Kopi: Studi Kasus di Sumberjaya, Lampung Barat. [Simulation of surface runoff and soil loss in relation to age of coffee gardens: case study in Sumberjaya, West Lampung]. *Agrivita* 26: 81–89.

Matthews, R., M. van Noordwijk, A.J. Gijsman and G. Cadisch 2004. Models of below-ground interactions: their validity, applicability and beneficiaries. Pp. 41–60, in: van Noordwijk, M., G. Cadisch and C.K. Ong (eds) Belowground Interactions in Tropical Agroecosystems, CAB International, Wallingford, UK.

Pasya, G., C. Fay and M. van Noordwijk 2004. Sistem pendukung negosiasi multi tataran dalam pengelolaan sumberdaya alam secara terpadu: dari konsep hingga praktek. [Negotiation support systems for sustainable natural resource management: from concept to application]. *Agrivita* 26: 8–19.

Ranieri, S.B.L., R. Stirzaker, D. Suprayogo, E. Purwanto, P. de Willigen and M. van Noordwijk 2004. Managing movements of water, solutes and soil: from plot to landscape scale. Pp. 329–347, in: van Noordwijk, M., G. Cadisch and C.K. Ong (eds) Belowground Interactions in Tropical Agroecosystems, CAB International, Wallingford, UK.

Suprayogo, D., Widianto, G. Cadish and M. van Noordwijk 2003. A Pedotransfer resource database (PTFRDB) for tropical soils: test with the water balance of WaNuLCAS. In: D. Post (ed) MODSIM proceedings, July 2003, Townsville, Australia.

Susilo, F.X., A.M. Neutel M. van Noordwijk, K. Hairiah, G. Brown and M.J. Swift 2004. Soil biodiversity and food webs. Pp. 285–307, in: van Noordwijk, M., G. Cadisch and C.K. Ong (eds) Belowground Interactions in Tropical Agroecosystems. CAB International, Wallingford, UK.

Suyamto, D.A., M. van Noordwijk and B. Lusiana 2004. Respon petani kopi terhadap gejolak pasar dan konsekuensinya terhadap fungsi tata air: suatu pendekatan pemodelan. [Coffee farmers' response to market shocks and consequences for watershed functions: a modelling approach]. *Agrivita* 26: 118–131.

van Noordwijk, M., J. Richey and D. Thomas 2003. Landscape and (sub)Catchment Scale Modeling of Effects of Forest Conversion on Watershed Functions and Biodiversity in Southeast Asia. Alternatives to Slash and Burn, BNPP Activity 2 Technical Report. [http://www.worldagroforestrycentre.org/sea/upload/meine/FVOBAct2_all_2.pdf]

van Noordwijk, M., F. Agus, D. Suprayogo, K. Hairiah, G. Pasya, B. Verbist and Farida 2004a. Peranan agroforestry dalam mempertahankan fungsi hidrologi daerah aliran sungai (DAS). [Role of agroforestry in maintenance of hydrological functions in water catchment areas]. *Agrivita* 26: 1–8.

van Noordwijk, M., G. Cadisch and C.K. Ong 2004b. Challenges for the next decade of research on below-ground interactions in tropical agroecosystems: client-driven solutions at landscape scale. Pp. 365–379, in: van Noordwijk, M., G. Cadisch and C.K. Ong (eds) Belowground Interactions in Tropical Agroecosystems. CAB International, Wallingford, UK.

van Noordwijk, M., B. Lusiana and N. Khasanah 2004c. WaNuLCAS 3.01, Background on a model of water nutrient and light capture in agroforestry systems. International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia.

van Noordwijk, M., S. Rahayu, S.E. Williams, K. Hairiah, N. Khasanah and G. Schroth 2004d. Crop and tree root-system dynamics. Pp. 83–107, in: van Noordwijk, M., G. Cadisch and C.K. Ong (eds) Belowground Interactions in Tropical Agroecosystems. CAB International, Wallingford, UK.

Widianto, D. Suprayogo, H. Noveras, R.H. Widodo, P. Purnomosidhi and M. van Noordwijk 2004. Alih guna lahan hutan menjadi lahan pertanian: apakah fungsi hidrologis hutan dapat digantikan sistem kopi monokultur? [Conversion from forest to agricultural land: is the hydrological function affected by conversion from forest to coffee monoculture?] *Agrivita* 26: 47–52.

Wösten, J.H.M., A. Lilly, A. Nemesand C. and Le Bas 1998. Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning. Report No. 156, Staring Centre (SC-DLO), Wageningen, the Netherlands.