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Implications of soil complexity for environmental monitoring

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International proposals for national soil and environmental monitoring lack adequate awareness of the diversity and complexity of soils. These need to be considered in sampling and reporting. This paper provides examples of the diversity and complexity of soil and environmental conditions in Bangladesh and Ghana, including differences between physiographic regions, within soil toposequences, between and within neighbouring fields, and in areas of shifting cultivation. These examples show that large numbers of sites would need to be sampled and monitored to provide the information required for the national environmental accounting envisaged. Detailed studies are needed in countries with relevant soil monitoring capacities to determine the scale of sampling required and the feasibility of conducting national monitoring. Where the latter is considered infeasible, the contribution that more limited measures could make to environmental monitoring needs to be examined. There is scope for useful academic studies to be made of environmental variability and practical monitoring techniques.

Keywords: Monitoring; Shifting cultivation; Soil complexity; Toposequence

1. Introduction

The United Nations Statistical Commission recently adopted the System of Environmental-Economic Accounting, Central Framework, as an international standard [1]. Following this up, the FAO Statistics Division, in its annual country data questionnaires on land use, added items considered necessary for calculating greenhouse gas (GHG) emissions. The objective is to provide countries with information brought up to date regularly to help them identify, assess and report GHG emissions from their agriculture, forestry and other land use sectors as part of the data they regularly report to FAO [2]. *Inter alia*, the list of items to be reported includes soil erosion, land degradation and topsoil carbon content as indicators of environmental health status and change within undefined ‘soil types’ (apparently the units shown on global-scale soil maps). This undertaking follows a number of other international initiatives that aim at monitoring soil properties, in particular soil organic carbon, soil erosion and land degradation: for example, the Global Terrestrial Observation System through its Carbon programme [3], the EU forest soil monitoring programme [4], the Globalsoilmap.net project [5] and the UN-CCD desertification monitoring activities [6].

Almost all reports on this subject indicate a lack of awareness of the very wide range of soils and soil properties that can occur within countries and within the broad ‘soil types’ referred to, and of the impracticability of making significant averages of soil properties

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(such as kg of soil carbon per hectare) within such units. Consequently, there is a risk that mere numbers will be collected and will find their way into national and international assessments of soil quality and environmental change which would not merely be harmful in itself, but it would also waste public funds and human resources on the collection and processing. This paper seeks to review the practical problems inherent in soil monitoring and possible solutions based on the authors' long experience of mapping, classifying and evaluating tropical soils.

2. Problems in soil monitoring

Monitoring soil properties implies making regular observations that can be extrapolated with a good level of confidence over a larger area with assumed similar properties. Measurements can be either direct (by soil sampling) or indirect (by use of proxies). Both methods pose a number of problems.

Areas with similar soil properties were traditionally determined by soil surveys and were represented on soil maps by soil mapping units (SMU). Yet, at all but the largest scale of mapping, SMUs are rarely homogeneous: they generally represent one or more extensive soils (usually soil series) associated in various proportions with other soils. To obtain significant average values of soil properties in an SMU, one would need to take into account the properties of every included soil and the proportion that each occupies in the SMU, and then repeat this for every SMU in a mapped area. Additionally, the properties of individual soils themselves vary in homogeneity, as will be described later; and the recognition of such variability may depend on the level of soil classification and the scale of soil mapping. Highly detailed soil maps would be required to make useful extrapolations of results, but such large-scale soil maps are rare, particularly in developing countries [7].

Old (so-called legacy) soil maps and SMUs also pose a temporal problem for monitoring. National, regional and global soil maps and the information they contain were often based on information gathered over a period of time. This implies that the recorded values of soil properties cannot be used as baseline values linked to a specific year (or sometimes even to a decade). This limitation is aggravated by differences and changes in survey techniques and soil classification that occurred over time, both within countries and between different countries.

The description, sampling and analysis of soil profiles is an expensive undertaking that, at each stage, is confronted with the spatial and temporal variability of soil properties over short distances and within a short time period (as is described later in this paper), and in the accuracy and reproducibility of laboratory analytical methods. Using more detailed soil information − such as spot or soil profile information at field level, and extrapolation and interpolation of the soil property values between observations using kriging, advanced analytical methods [8,9], spline functions and other pedometric techniques and methods based on Remote Sensing [10,11] − cannot easily deal with soil diversity, unless very large numbers of sites or soil profiles are sampled. Soil depth and bulk density are essential parameters in determining soil carbon stocks [12] that are often overlooked in monitoring.

Remote sensing has great advantages for monitoring, but its use needs to be backed up by adequate ground truthing, which has not always been practised. In the past, the use of proxies in satellite image analysis − such as decrease in the greenness of vegetation as an indicator for soil degradation − did not take into account soil properties and soil diversity, which consequently led to unsatisfactory results. For instance, three different studies that all used the same GIMMS image-based NDVI trends for monitoring soil degradation came to startlingly different conclusions on the extent and intensity of soil degradation in sub Saharan Africa, despite using the same base material.[1] Estimates of the total degrading area in the region varied from 10% [13] to 37% [14]; and significant differences were noted in the zone north of the Sahel and in tropical humid areas, generally interpreted as improving [13], degraded [14] or not possible to interpret because of cloudiness [15]. Subsequent follow up studies [16] and [17] established that results obtained under (14) were the most reliable.

Other errors are linked to different ways of processing the raw satellite data to compute NDVI time series. For instance reprocessing of the GIMMS data-set to produce the latest version up to 2012 (GIMMS data-set 3g) yields significantly different results from the earlier 2003 (1g) and 2006 (2g) versions although the patterns are related. Using GIMMS1g, Bai and Dent [18] reported that, for the period 1981–2003, 23% of China was degrading. Using the extended, reprocessed 3g data-set, they calculated that for the period 1981–1996 only 1.8% was degrading and that for the period 1996–2012 12.6% was degrading [19]. Only the most recent analysis for China explicitly accounts for soil variability (by calculation of residual trends within individual soil and terrain mapping units).

The importance of recognising soil diversity and complexity for designing realistic soil monitoring programmes is illustrated below using information from Bangladesh and Ghana as examples. Successive sections describe environmental diversity in physiographic regions within countries; soil and environmental diversity in soil toposequences within such regions; soil fertility differences between and within fields; and temporal and spatial complexity in areas under shifting cultivation (slash and burn agriculture).

3. Recognising soil diversity and complexity

3.1. Diversity within countries

National environmental monitoring requires, as a first step, the recognition of the macro-environmental units that exist in the country. In Bangladesh, 18 physiographic regions have been recognised within the country's land area of 135,193 km^2 (figure 1). These units are based on differences in geology and geomorphology that determine soil and hydrological conditions which, in turn, influence natural vegetation and land use [20]. Thirteen floodplain regions occupy 79% of the country; four regions on uplifted Pleistocene blocks occupy 9%; and one hill region over Tertiary sedimentary rocks occupies 12%. The regions range in size from 8 km^2 in Region M (St Martin's Island) in the south-east to 23,069 km^2 in Region D (Ganges River Floodplain) in the west which occupies 17.7% of the country.

Most of Bangladesh is intensively cropped by small farmers (average holding size <0.6 ha) in one, two or three growing seasons in a year with rice the dominant crop, but forest (degraded to various extents) remains in the Sunderbans (mangrove) in the south-west of the Ganges Tidal Floodplain (Region E), in small remnant patches on the Madhupur Tract (N) and in substantial parts of the hill region (R). In the latter region, forested areas are interspersed with large areas under shifting cultivation, with tall grasses or bamboo on fallow land (some of it seasonally burned) and small areas under plantation tree crops (including tea).

The physiographic regions are not homogenous units. Each region comprises a wide range of environmental conditions that differ in kind from other regions or in the proportions in which particular conditions occur. For instance, the old and young Tista

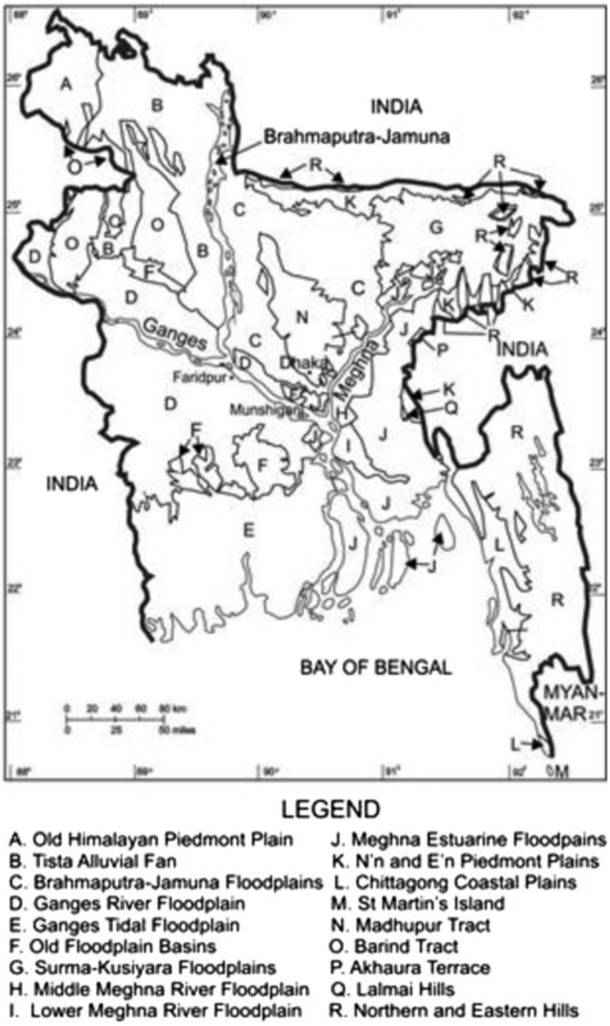


Figure 1. Bangladesh: physiographic regions.

alluvial fans in Regions A and B include significantly different proportions of General Soil Types, soil textures and seasonal depth-of-flooding 'land types' (table 1).[2] Such differences influence the kinds of crops that farmers grow on different land and soil types and the cultivation methods that they use. Table 2 illustrates the different proportions in which three major dry-season cereal crops are grown in Dinajpur District (mainly in Region A) and in the adjoining Rangpur District (mainly in Region B).

Several regions have been divided into subregions with different proportions of the component soils and land types. For example, the Ganges River Floodplain (D) has been divided into four major subregions separating the active river floodplain within and adjoining the Ganges river from three meander floodplain areas, respectively, south-west, north and east of the river channel; and three of these major subregions have been divided into

Table 1. Differences in soils and land types between Regions A and B.

General soil type			Subsoil texture class			Land type		
	Region A (%)	Region B (%)		Region A (%)	Region B (%)		Region A (%)	Region B (%)
Noncalcareous Alluvium	1	11	Organic	m	0	Highland (0)	58	29
Noncalc. Grey F'plain Soil	15	54	Sand	m	5	Medium Highland (<90)	35	50
Noncalc. Dark Grey F. S.	19	12	Loam	41	55	Medium Lowland (90−180)	1	8
Noncalc. Brown F. S.	35	11	Clay loam	44	21	Lowland (>180)	0	4
Black Terai Soil	24	0	Clay	9	10	Settlement and water	6	9
Others	m	3	Settlements, water	6	9	Land area (km^2)	3931	12,963
Settlements, water	6	9				River area (km^2)	0	245

Notes: The IUSS-ISRIC-FAO [17] classification of the included soils is: noncalcareous alluvium = Eutric Fluvisol; noncalcareous grey and dark grey floodplain soils = Eutric Gleysols; noncalcareous brown floodplain soil = Dystric Cambisol; black Terai soil = Umbric Cambisol.
Source: [16]. m = minor. The land type figures in brackets = normal depth of seasonal flooding (cm).

further subregions reflecting differences in landform age and/or sediment composition (figure 2 and table 3). In total, Bangladesh's 18 regions were divided into 66 subregions.

In addition, climatic conditions vary widely between different parts of Bangladesh, providing differences in the length of growing seasons and in exposure to such environmental hazards as drought and floods. Mean annual rainfall ranges between <1250 mm in the centre-west and >5000 mm in the north-east, and the length of the rainfed *kharif* growing season ranges from <170 days in the centre-west to 290 days in the north-east [23,24]. Mean annual rainfall and the begin- and end-dates of the *kharif* growing season also vary within the larger regions and subregions. For example, mean annual rainfall in Region D ranges between <1250 mm in the extreme west and >2000 mm in the east; and the mean length of the *kharif* growing season ranges between 27 May−18 November in the west and 3 May−14 December in the east of the region, a difference in length of almost two months. These differences are sufficient to influence the number and kinds of crops per year that farmers can grow in different parts of the region and the relative risks of drought and flood damage involved.

3.2. Complexity within toposequences

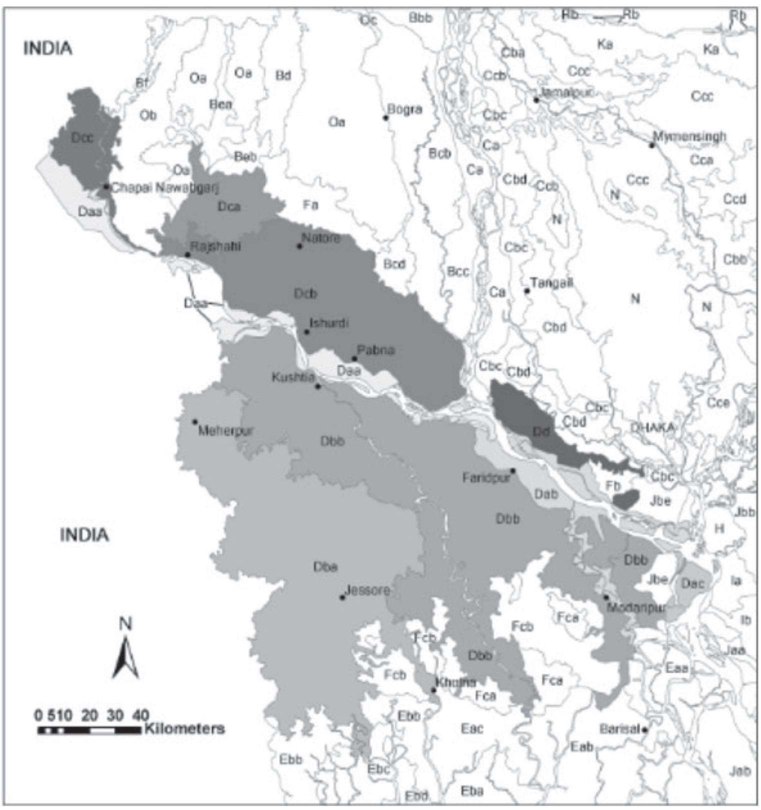
Individual soils rarely occupy the whole of the landscape in a particular area. There, generally, are several different soils between the highest and the lowest parts of the local relief, reflecting differences in drainage between higher and lower sites, and sometimes differences in the composition or age of the soil parent materials.

Table 2. Proportions of cultivated area occupied by three major dry-season cereal crops in Dinajpur and Rangpur districts in 2010–2011.

District	Total area (km^2)	Cultivated area (km^2)	Boro rice (%)	Wheat (%)	Maize (%)
Dinajpur	6652	4939	58	18	8
Rangpur	9666	6393	73	3	4

Source: [22]. Crop proportions rounded to nearest whole number.

Figure 3 illustrates the differences in hydrological and soil properties that commonly occur within lateral distances of a few hundred metres in Bangladesh's floodplain regions: i.e. within the land area of individual villages. Note the differences in soil texture, soil reaction (pH) and seasonal depth of flooding between the highest and the lowest parts of



Subregions in Region D

Da Active Ganges Floodplain
- Daa Ganges
- Dab Ganges-Jamuna
- Dac Ganges-Meghna

Db South-western
- Dba Old
- Dbb Younger

Dc Northern
- Dca Old with calcrete
- Dcb Younger
- Dcc Mixed Ganges-Mahananda

Dd Eastern

Figure 2. Ganges river floodplain (Region D).

Table 3. Proportions of major general soil types in Region D subregions.

Subregion	Area (km^2)	CA (%)	NCDG (%)	CDG (%)	CB (%)	ML (%)	Other (%)	S + W (%)
Daa	1496	77	0	4	13	0	0	6
Dab	1486	39	0	23	30	0	0	8
Dac	276	67	0	5	20	0	3	5
Da	3225	60	0	12	21	0	m	7
Dba	6367	m	7	58	20	1	3	11
Dbb	8229	3	5	61	19	m	2	10
Db	14,596	2	6	60	19	m	2	10
Dca	988	0	7	64	1	7	13	8
Dcb	3752	2	6	52	23	4	1	12
Dcc	741	m	11	50	25	1	5	8
Dc	5481	1	7	54	19	4	4	11
Dd	627	m	2	80	6	0	0	12
D (land)	23,069	8	6	54	19	2	1	10
River	627							
Total D	23,696							

Notes: Percentages refer to the land area.
Abbreviations and classification of the soils in the IUSS-ISRIC-FAO [17] system: CA = Calcareous Alluvium (Calcaric Fluvisol). NCDG = Noncalcareous Dark Grey Floodplain Soil (Eutric Gleysol). CDG = Calcareous Dark Grey Floodplain Soil (Calcaric Gleysol: mainly Chromic, but Ghior series is Vertic). CB = Calcareous Brown Floodplain Soil (Calcaric Cambisol). ML = Made Land (Calcari-Fimic Anthrosol). S + W = Settlement + water. m = minor (<0.5%).
Source: [16].

the relief (2–3 m in this example); also the relationship of crops grown to depth-of-flooding land types. The six soil series named in this toposequence include some of the major soils in Region D. Table 4 indicates the range in important properties of these six soil series for which laboratory data were given in the reports on the reconnaissance soil surveys of the Districts occupied in whole or in part by the Ganges River Floodplain. Similar differences for a wider range of soil properties were found between fields within toposequences in detailed studies in rice-growing areas in Indonesia and Thailand [25].

Figure 4 is a detailed soil map of 880 × 220 yards (approx. 800 × 200 m) sample strip in Ghana's forest zone with an elevation difference of ca 30 m between the highest and the lowest points. It illustrates a common kind of soil toposequence in tropical Africa where remnants of an ancient landscape (peneplain) occupy the highest parts, soils on the slopes are formed in material from the underlying, deeply-weathered rock and the valleys have alluvium washed down from the adjoining slopes and brought in from areas upstream. In fact, the soils on level summits are commonly formed in fine material brought to the surface from subsurface layers by termites and ants over many thousands of years (as in Akumadan series in figure 4); and similar material on slopes commonly overlies a residual layer of quartz gravel and ironstone concretions of variable thickness (the 'stone-line') which overlies the weathered rock (as in soils 4−7 in figure 4).

Such soil patterns within physiographic regions can be mapped as soil associations (SMU's, or *catenas*, meaning linked as in a chain). But, individual soils (soil series) are rarely homogeneous throughout their extent. On detailed surveys, soil subseries and phases can be recognised within soil series to map local differences in properties such as slope, depth, content of gravel, degree of erosion, etc. which may influence soil fertility, use or management; in Bangladesh, there can also be environmental and land use differences between soils inside and outside flood-protected and irrigated areas. Additionally,

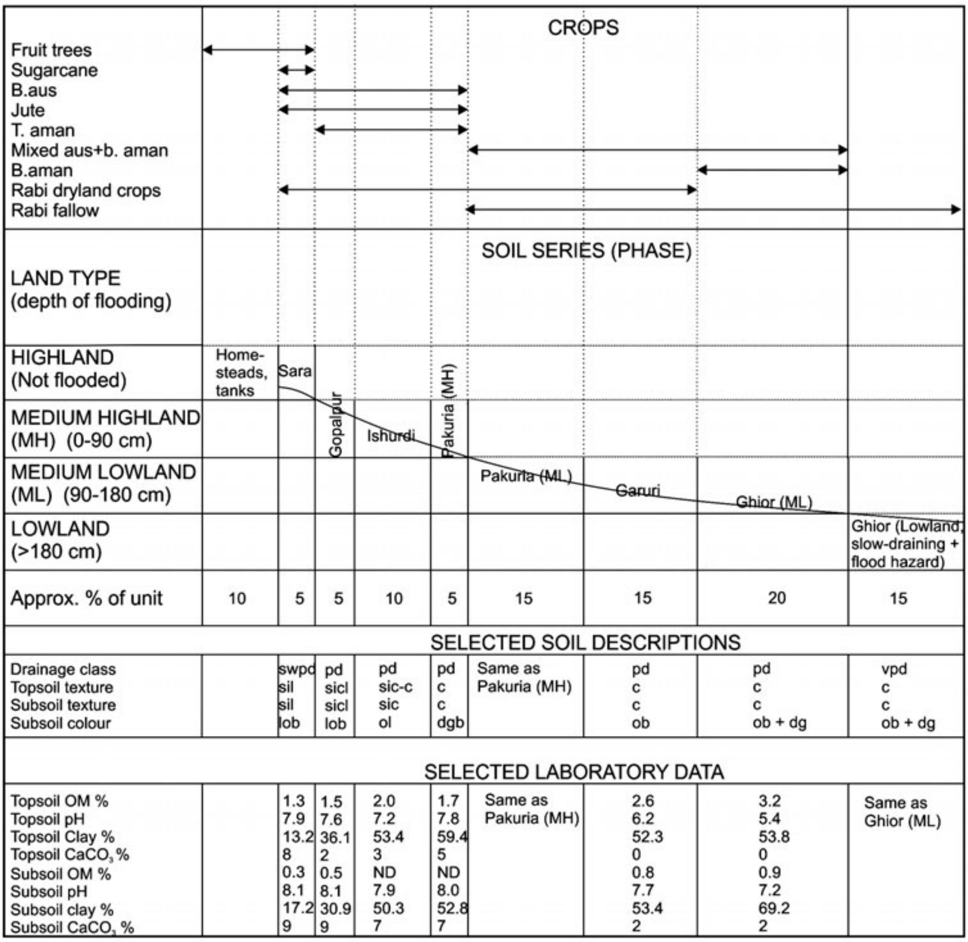


Figure 3. Traditional cropping patterns, land types and soils on the Ganges river floodplain.
Notes: The profiles were not taken from a single toposequence. The laboratory data are for single profiles. They do not indicate ranges in contents within soil series. Most of the soils are mottled yellow-brown in the subsoil: faintly in ridge soils; more strongly in lower slope and basin soils. All except Sara soils have prominent dark grey coatings on the surfaces of subsoil cracks and pores. Abbreviations: Drainage class: swpd = somewhat poorly drained; p = poorly drained; vp = poorly drained. Texture: sil = silt loam; sicl = silty clay loam; sic = silty clay; c = clay. Colour: lob = light olive-brown; ol = olive; ob = olive brown; dg = dark grey; dgb = dark greyish brown. Laboratory data: OM = organic matter (=organic carbon X 1.5).

boundaries between soils are usually not sharp, but one soil merges into another as properties gradually change downslope; and the proportions of the different soil series in a toposequence vary from place to place within regions and subregions because of variations in the relief and sometimes in sediment or rock properties.

In Bangladesh, as in many other tropical countries, farmers may have fields on more than one kind of soil in such toposequences, which enables them to grow different crops or crop varieties on different sites and to spread the risk of crops being damaged or destroyed by natural disasters such as drought or floods. One farmer studied in Bangladesh had 17 separate fields in his 1-ha holding dispersed over three depth-of-flooding land types and – in an area with three growing seasons in a year, and adapting to differences in

Table 4. Mean and range values of selected topsoil and subsoil properties in six major soil series on the Ganges river floodplain.

Property	Soil series					
	Sara	Gopalpur	Ishurdi	Pakuria	Garuri	Ghior
Topsoil clay						
Mean %	20.5 (13)	32.8 (8)	47.4 (9)	58.0 (5)	59.6 (7)	69.9 (9)
Range %	9−38	20−46	30−56	42−65	50−71	64−76
Topsoil pH						
Mean	7.8 (13)	7.7 (8)	7.3 (9)	7.4 (4)	6.2 (7)	6.0 (9)
Range	7.4−8.9	7.1−7.9	5.9−8.1	6.6−7.8	5.4−7.0	5.4−6.8
Topsoil carbon						
Mean %	0.79 (12)	0.96 (8)	1.24 (9)	1.41 (5)	1.55 (7)	2.61 (9)
Range %	0.37−0.93	0.73−1.24	0.68−2.08	0.99−2.04	0.91−2.0	1.57−4.56
Subsoil carbon						
Mean %	0.24 (12)	0.37 (8)	0.41 (9)	0.55 (5)	0.50 (7)	0.63 (9)
Range %	0.08−0.38	0.21−0.66	0.13−0.68	0.35−0.87	0.23−0.70	0.41−1.17
Topsoil nitrogen						
Mean %	0.08 (12)	0.09 (8)	0.11 (9)	0.10 (5)	0.13 (7)	0.22 (9)
Range %	0.03−0.09	0.06−0.12	0.05−0.20	0.06−0.14	0.07−0.19	0.10−0.35
Topsoil $CaCO_3$						
Mean %	5.38 (13)	4.2 (8)	3.9 (9)	2.3 (5)		
Range %	2.5−10.9	2.0−10.5	0–9.6	0–5.0		
Depth to $CaCO_3$						
Mean cm	−	−	16.5 (2)	17.8 (2)	32.3 (7)	34.3 (8)
Range cm	−	−	3−10	17.8=	15.4−45.7	15.2−53.3

Note: The mean figures in brackets are the number of samples averaged.

weather and market prices between years − practised 61 different annual rotations with different crops and varieties on his farm over a seven-year period [24].

3.3. Field-level complexity

A detailed soil sampling study in Bangladesh showed great variability between and within fields in two areas that had probably been continuously cultivated for several decades or longer [24]. Topsoil samples were taken at intervals of 5 yards (4.58 m) along two transects: one of 250 yards (229 m) on a seasonally-flooded Grey Floodplain Soil (Dhamrai series) on the Jamuna Floodplain (in Region C); the other of 500 yards (458 m) on an upland Deep Red-Brown Terrace Soil (Tejgaon series) on the Madhupur Tract (Region N). Three randomly-selected 10 × 10-yard squares were also sampled at 1-yard intervals along each transect, and three further 1 × 1-yard squares within each of those squares were sampled at 1-foot (30 cm) intervals. Reaction (pH), organic carbon, nitrogen and available phosphorus (Bray) were determined on all the samples; particle size and cation exchange capacity were also determined on all the line-transect samples.

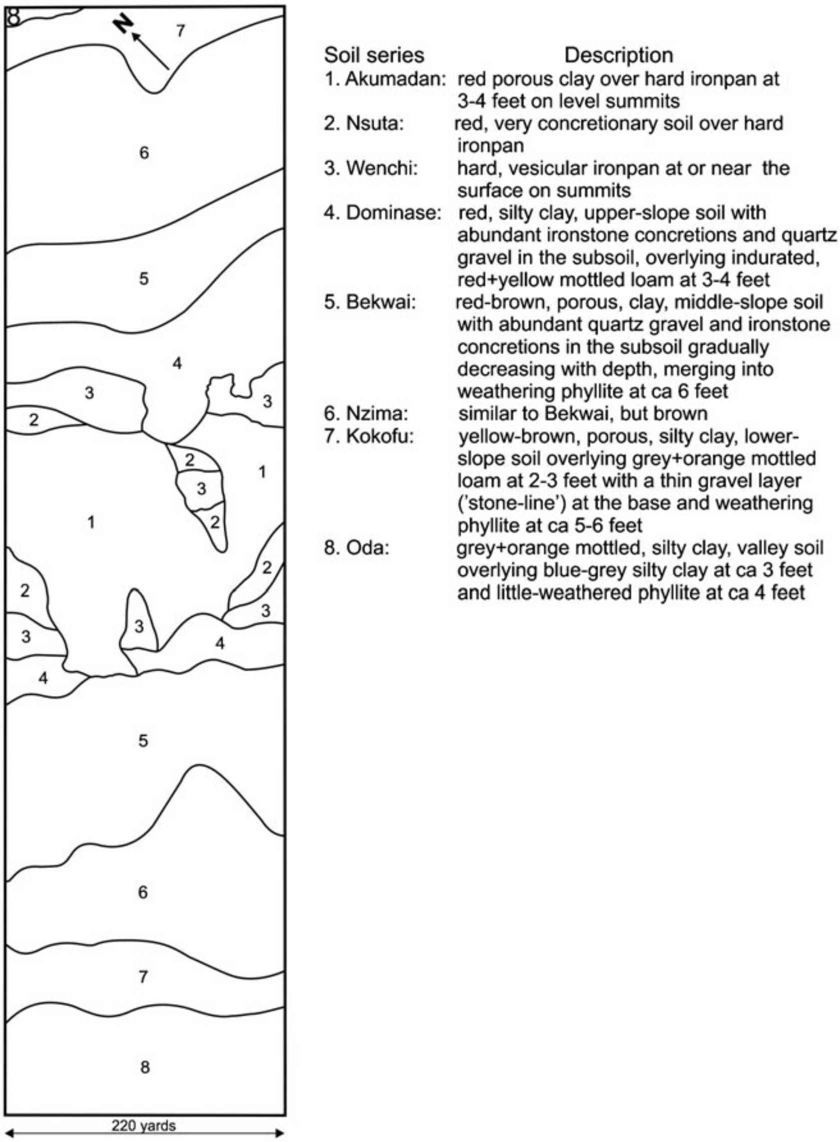


Figure 4. Soil topsequence over peneplain remnants and lower birimian phyllites in the Ghana forest zone.

Figures 5 and 6 illustrate the variability in four of the fertility properties along the two line transects. Table 5 shows the range and variability of the fertility data for the two soils. Note, in particular the great variations in available phosphorus contents, including within fields; also the great differences between the lowest and the highest organic carbon contents in the two soil series sampled.

Use of groundwater for irrigation in Bangladesh in the past 30 years has introduced a further level of soil complexity. Groundwater within the upper 120 m of Holocene sediments is contaminated with arsenic in parts of Regions C, D, G and J; (groundwater in

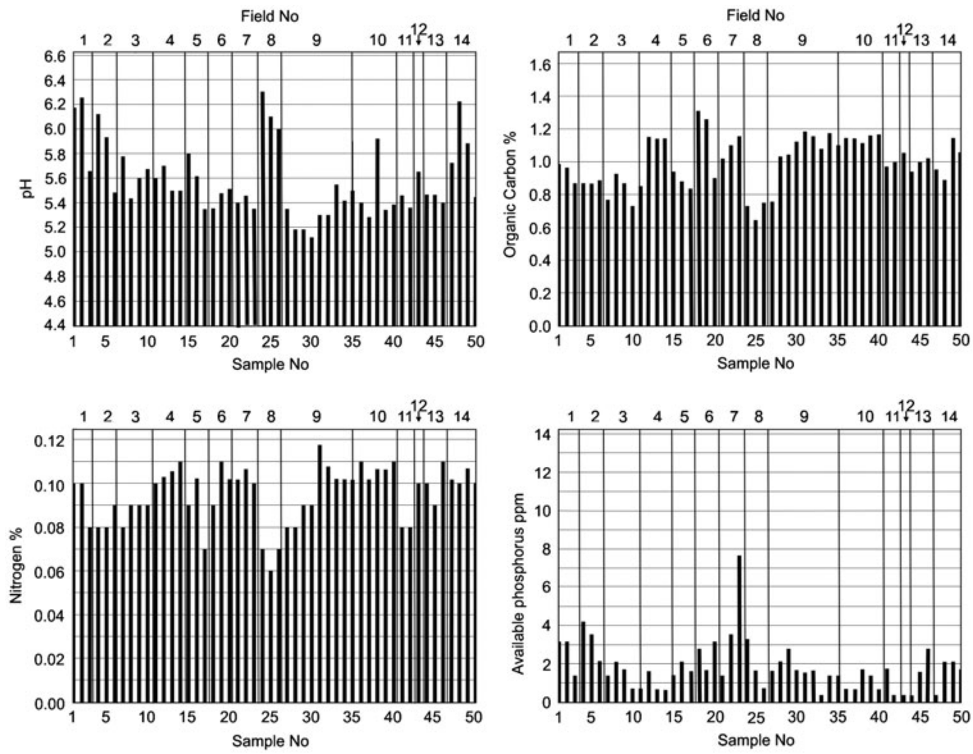


Figure 5. Variations in topsoil fertility properties on 250-yard transect on Dhamrai series.

deeper Pleistocene and Tertiary sediments is not contaminated) [26]. So-called shallow tube-wells (STW) capable of irrigating ca 4 ha of wetland rice can add arsenic (As) to topsoils on a variable scale due to differences between STW sites in the As content of groundwater, in the amounts of water added to soils with different permeability and under different crops (e.g. rice vs. wheat), in the number of years for which the soils have been irrigated, in amounts of As immobilised by iron oxidised by aeration as water flows along field channels and across fields, and amounts leached by floodwater on sites seasonally flooded for different durations. Data have been reported for some of these variations at a few individual study sites [27], but comprehensive studies remain to be carried out to determine variations in topsoil As contents between and within sites on different soils in different physiographic regions and over time. Similar detailed spatial and temporal studies are needed in other countries where irrigation water is contaminated with As or other harmful elements, and with salt in some countries.

3.4. Soils under shifting cultivation

Soils under natural vegetation are variable on a local scale. Leaf-fall from different plant species, uprooting and rotting of trees, and disturbance by soil animals over many thousands of years can create local variations in organic matter contents and other properties. This local variability can be increased in areas under shifting cultivation, and the variations will change over time during the cultivation and fallow cycle, as described below. In some African savannah areas, further spatial variability is provided by termite mounds which

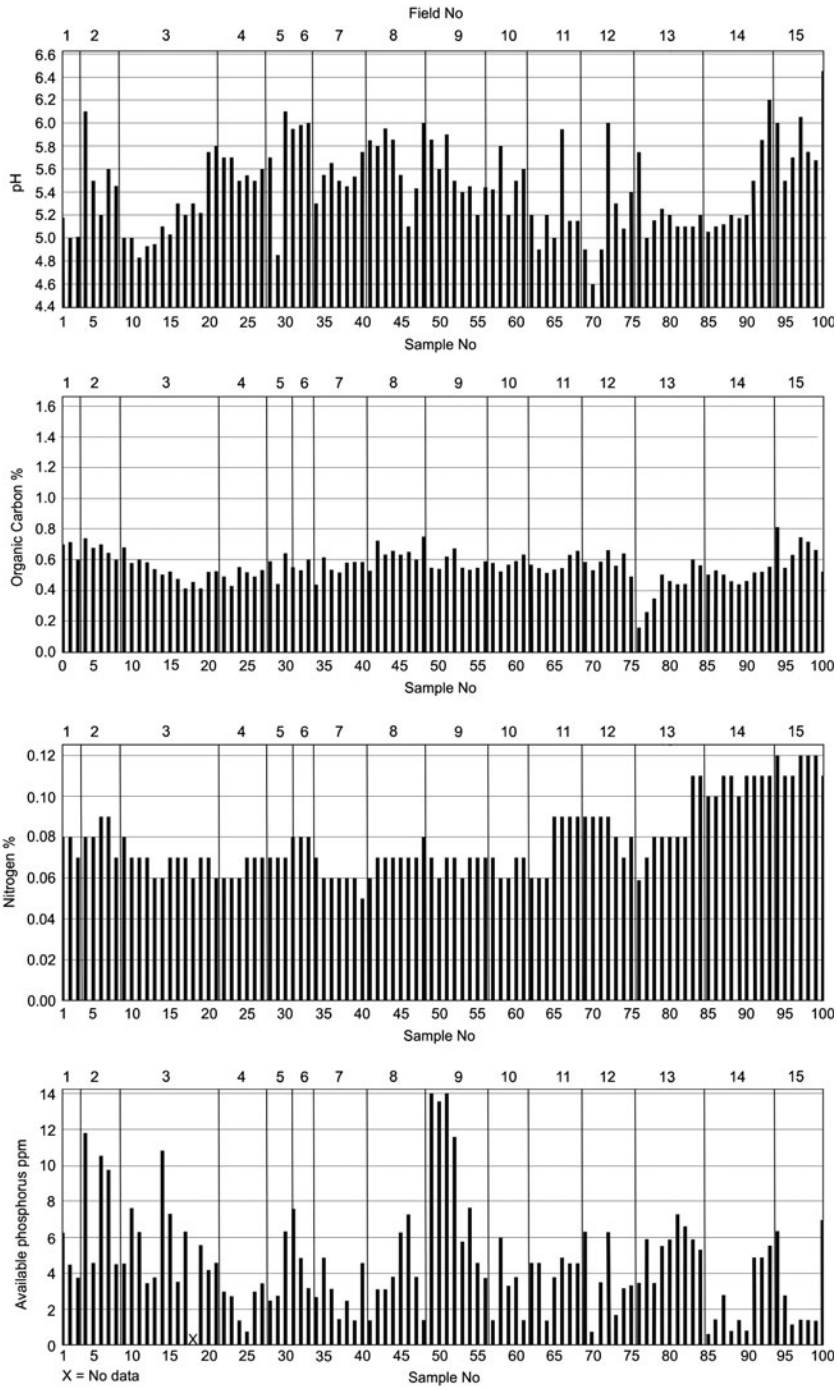


Figure 6. Variations in topsoil fertility properties on 500-yard transect on Tejgaon series.

Table 5. Variation of soil fertility properties in Dhamrai and Tejgaon topsoil samples.

	pH		Organic carbon (%)		Nitrogen (%)		Available phosphorus (%)	
Measure	Dhamrai	Tejgaon	Dhamrai	Tejgaon	Dhamrai	Tejgaon	Dhamrai	Tejgaon
Mean	5.46	5.09	1.01	0.53	0.097	0.074	2.44	6.50
Range	4.97–6.64	4.47–6.45	0.65–1.38	0.17–0.81	0.05–0.12	0.04–0.12	0.00–16.45	0.70–32.90
SD	0.31	0.36	0.13	0.07	0.01	0.011	1.66	4.38
CV (%)	5.7	7.1	12.5	12.4	10.3	14.9	68.0	66.8

Source: [20]. SD = Standard Deviation; CV = Coefficient of Variation.

can occupy up to 30% of the land area [28]. There will be similar small-scale, spatial and temporal variability in permanently cultivated areas because of inherited 'natural' fertility properties supplemented by variability introduced by practices such as cultivation on ridges/mounds or in furrows/holes, terracing, the irregular distribution of manures and fertilisers within fields over time, and differences in practices between fields cultivated by different farmers.

Figure 4 illustrates the range of different soils and soil properties that can occur in a soil toposequence in the Ghana forest zone. Typically, the physical and chemical properties of individual soil series identified in such toposequences are reported on soil samples taken from single profile pits dug in each soil unit. These samples indicate properties only at the point of sampling; they do not take into account the range of soil conditions that may occur within each soil unit caused by, for example, the gradual lateral transition in soil drainage properties between upper and lower sites within a toposequence and differences due to local differences in leaf-fall and accumulation from different vegetation species. In the Ghana forest zone, for instance, two trees (*Afzelia africana* and *Chlorodendron excelsa*) sometimes exude large amounts of calcium carbonate in radial cracks and between growth rings [29] such that, after the trees fall and decay, the hard lime masses or concretions persist in the soil, possibly for many centuries, creating considerable local variations in soil pH and calcium contents within soils that are generally strongly acid.

In their classical study of soils under shifting cultivation, Nye and Greenland [30] recognised local soil complexity both on sites under natural vegetation and in those cleared for cultivation. They, therefore, took composite samples from 50 soil cores from each of the 0.25 acres (0.1 ha) plots in sites they sampled in Ghana. Table 6 shows the differences between composite topsoil samples taken from a site under 40-year-old secondary forest and immediately after the vegetation on that site had been cleared and burned. Note in particular the big differences in pH, available phosphorus and exchangeable cations. Field observations in cleared sites indicate great point to point variation in the amounts of ash left by different trees and shrubs (figure 7), suggesting related local differences in soil fertility properties; and further changes would be expected to occur in the following months during the cultivation period and in the subsequent years of fallow vegetation regrowth. Soil fertility in areas under shifting cultivation is complex temporally, therefore, as well as spatially.

Table 6. Comparison of topsoil chemical properties before and after forest clearance in Ghana.

Site	Depth (cm)	pH	C (%)	N (%)	Av. P (ppm)	K (meq)	Ca (meq)	Mg (meq)
Forest	5	5.21	2.22	0.210	9.8	0.41	5.7	1.21
Cleared site	5	7.90	2.26	0.198	30.0	2.01	19.9	2.70

Source: [26].

Figure 7. Irregular distribution of ash and burnt vegetation on a newly cleared site under shifting cultivation. Source: http://blog.bloomtrigger.com/why-deforestation/.

4. Conclusions and recommendations

4.1. Monitoring

It is not clear from the literature how the kinds of data envisaged for national-scale environmental monitoring described above in Section 1 will be collected and analysed. Few developing countries now have soils organisations with the capacity to carry out the scale of fieldwork and laboratory analyses needed [31]. Soil maps in ex-colonial countries were mainly made on reconnaissance survey scales and they are now 40−60 years old. Since those surveys were carried out, there are likely to have been great changes in soil properties because of the introduction of more intensive agriculture, including irrigation and heavy use of fertilisers in some areas, and reduced bush-fallow periods and soil erosion in other places. Analysis of old aerial photos and more recent satellite images may enable changes in vegetation and some kinds of land use to be measured since the original soil and land use surveys were made, together with areas changed by some kinds of soil erosion; but it is unrealistic to expect analysis of satellite images to measure changes there may have been in soil fertility between fields and within fields in areas of small-holder farming or in areas under shifting cultivation: soil properties in such areas are variable on a micro-scale, and they are dynamic, not static.

In soil fertility sampling in areas with small fields, it is usual to take samples from several points in a field to make a bulk sample from which average fertility levels can be estimated. In the detailed soil variability study in Bangladesh described in Section 3.3 above, calculations were made of the number of samples that would need to be taken in order to make a composite sample that would 'represent' an area at different confidence levels for each fertility component [24]. Table 7 shows the number of samples required to predict the overall mean of selected properties at 95% and 99% confidence levels in one of the 10-yard square sampled areas of Dhamrai series referred to above. More such studies are needed in order to design relevant sampling intensity in different environments.

Given the soil variability described above and the dearth of information on such variability, it would be unpractical at present to make reliable or useful estimates for the range in properties (such as in kg of organic carbon per hectare) on a national or 'soil type' scale. Besides, given the likely range in soil properties within toposequences in different parts of physiographic regions and between different regions, it seems unlikely that a sufficient number of samples could be taken on a regular basis for monitoring change on a national scale, even in a small country like Bangladesh.

Further problems for sampling arise from the fact that soil fertility and such properties as salinity vary through the year during seasonal, cropping and irrigation cycles. Changes caused by differences in weather between years – e.g. in soil salinity levels – also complicate interpretation of data for monitoring. Differences between years in flood extent and duration in countries such as Bangladesh may similarly create interannual differences in soil fertility properties and remain to be studied. In rice-growing countries, measurement and monitoring of methane gas emissions in small fields managed by different farmers within toposequences in different regions provide a challenging problem for national reporting.

International initiatives in environmental monitoring have often focused on soil organic carbon alone because of the climate change implications, but other soil constituents may deserve more urgent attention in particular countries (e.g. arsenic in Bangladesh and salinity in Pakistan) for human health and food security implications.

4.2. New measures required

For financial reasons, soil monitoring has become an exercise almost exclusively undertaken on international initiatives or by industrial countries. Global and regional initiatives

Table 7. Number of samples required to obtain desired mean values of selected topsoil properties at two confidence levels based on samples from a 10 × 10-yard square in Dhamrai series.

Property	95%					99%				
pH – range desired	0.1	0.2	0.5	1.0	2.0	0.1	0.2	0.5	1.0	2.0
No required	168	42	7	2	1	290	73	12	3	1
C (%) – range desired	0.01	0.02	0.05	0.1	0.5	0.01	0.02	0.05	0.1	0.2
No required	984	246	44	10	1	1705	427	69	18	1
N (%) – range desired	0.005	0.01	0.02	0.05	0.1	0.005	0.01	0.02	0.05	0.1
No required	62	16	4	1	1	107	27	7	2	1
P (ppm) – range desired	0.5	1	2	5	10	0.5	1	2	5	10
No required	961	42	11	2	1	287	72	18	3	1

Note: Samples were taken on a 1 yard (0.9144 m) grid within three randomly selected 10 × 10-yard squares on the 250-yard (228.6 m) linear traverse.

Source: Adapted from Table 14.8 in Brammer [20]. 10 yards = 9.144 m.

have often ignored local soil expertise and soil institutions in developing countries, and it is desirable to include these resources to a greater extent, for instance through the Global Soil Partnership [32].

To reduce or avoid the cost of expensive ground-based monitoring, international initiatives have tended to focus on remote sensing and satellite image analysis. This proxy approach depends heavily on ground truthing and on statistical methods for accurate and reproducible results to be obtained. Pedometrics or the use of mathematical, statistical and numerical methods to predict the distribution of soil properties and the associated uncertainties in space and time should be further promoted.

New techniques in soil analysis − in particular the use of visible and near infrared (vis-NIR) spectroscopy that allows quick, accurate estimation of soil attributes such as soil organic matter, nutrients, water, pH and heavy metals − should be further explored and a global soil spectral library established [33]. Satellite-based soil observations can quantify variations in NDVI/net primary productivity *within* the mapping units of at least small-scale soil maps [19] and offer promising avenues to enhance future soil monitoring, but they must be backed up by adequate numbers of ground observations and activity by the relevant national institutions.

The Land Degradation Assessment in Drylands project (LADA) developed approaches for the participatory mapping of land degradation at different scales [34,35]. At global level a two-pronged approach was applied using, on the one hand, a systematic study of corrected trends of NDVI to capture net primary production changes over a 23-year time period [36] and, on the other hand, the development of a global land degradation information system combining a wide range of global databases to reflect the status and trends of ecosystem services [37]. At national level, this methodology used hard data on soils, vegetation, water resources and land use, and it included groups of stakeholders and local experts to assess land degradation at subnational level in Argentina, China, Cuba, Senegal, South Africa and Tunisia. The national methodology was backed up by selected detailed and fast sampling exercises in the main land use systems of the country [38]. The method deserves to be tested for application in more countries and for a wider range of factors required for national-scale environmental monitoring.

4.3. Further steps

From a practical point of view, the first need in national environmental monitoring is to obtain detailed information on relevant environmental properties and their variability. Countries where active soil and agricultural research institutions exist could undertake relevant field studies, laboratory analyses and data assessment to determine the practicality and costs of conducting such monitoring on a regular basis. The extent to which satellite technology can contribute to monitoring deserves to be thoroughly tested by ground-truthing studies in a wide range of environments.

Nevertheless, for institutional as well as financial reasons, detailed national soil monitoring on the scale envisaged will be unpractical in many developing countries. Therefore, measures need to identified and examined that could at least provide indications of environmental health and change in such countries. It might be feasible, for instance, to collect soil samples regularly from some or all of the sites used for national crop sampling, or to set up a number of regularly monitored sites adjoining (not on!) agricultural/forestry/livestock research stations and relevant university campuses. Results from such sites, particularly if linked to a standardised land use classification [39], could provide useful indications of environmental health and change. Academic institutions could also make valuable contributions by undertaking studies in environmental variability and practical monitoring techniques.

Clearly, there is an urgent need for further research to be carried out by national and international agencies in order to identify practical means to establish reliable and manageable systems of national environmental monitoring and accounting related to individual countries' institutional and financial capacities, with international support where necessary. Many countries will require the resuscitation or strengthening of soil and agricultural research institutions with appropriate funding. That step is urgently required anyway in order to support the increased agricultural production, which is needed to meet rapidly growing population and market demands [31]. The needs of environmental monitoring provide an additional reason to revitalise such institutions.

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Notes

1. GIMMS = Global Inventory Modelling and Mapping Studies. NDVI = Normalised Difference Vegetation Index.
2. General Soil Types are groups of soils that formed in a similar way and that have broadly similar properties. This nontechnical system was designed to enable nonspecialists in Bangladesh to make use of the technical information provided in soil survey reports. Tables 1 and 3 give correlations with relevant units in the World Reference Base for Soil Resources [21].

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