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Remote sensing and transect-based retrieval of spatial soil and terrain (SOTER) information in semi-arid Niger

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A methodology for retrieval and mapping of spatial soil and terrain data based on the SOTER approach has been developed for semi-arid Niger. Remote sensing technics and detailed ground transect investigations are used, and the collected data are integrated into a SOTER database and a Geographic Information System. Transect selection, their realization and the related problems with transect-based calculations are discussed. The method permits estimations of soil type coverages, present land use and soil degradation at different scale levels. The significant dynamics of soil redistribution are pointed out and attributed to present and past erosion events.

Keywords: SOTER; soil transects; remote sensing; Niger; GIS; degradation; multiple scales

Introduction

Decreasing yields and landscape desertification in semi-arid Niger are mainly caused by unsustainable land use systems (e.g. Ouattara, 1990). The application of appropriate agricultural management strategies by farmers however, needs to be adapted to the environmental setting (van Duivenbooden, 1995). Therefore a detailed knowledge of the biophysical environment and dynamics in the target area is crucial.

In order to include the significant spatial variability of agro-ecological conditions, a multi-scale approach has been advocated (Andriesse *et al*., 1994), but for biophysical characterization this method leaves possibilities for improvement. Therefore a transect method combined with remote sensing for extensive soil and terrain inventorying at multiple scales has been developed. The method is also an approach to overcome the inaccuracy of spatial soil extrapolations and presents a spatialization tool for SOTER (Soil and Terrain Digital Databases; ISRIC, 1993). Soil-geomorphic transects have been investigated from 1994 to 1996 throughout the study area in SW Niger (Fig. 1).

The principle of this method is to investigate the land and soils across transects at semi-detailed level for subsequent mapping at regional level. Through combination of remote sensing with transect, ground-truthing and secondary data the stepwise up- and

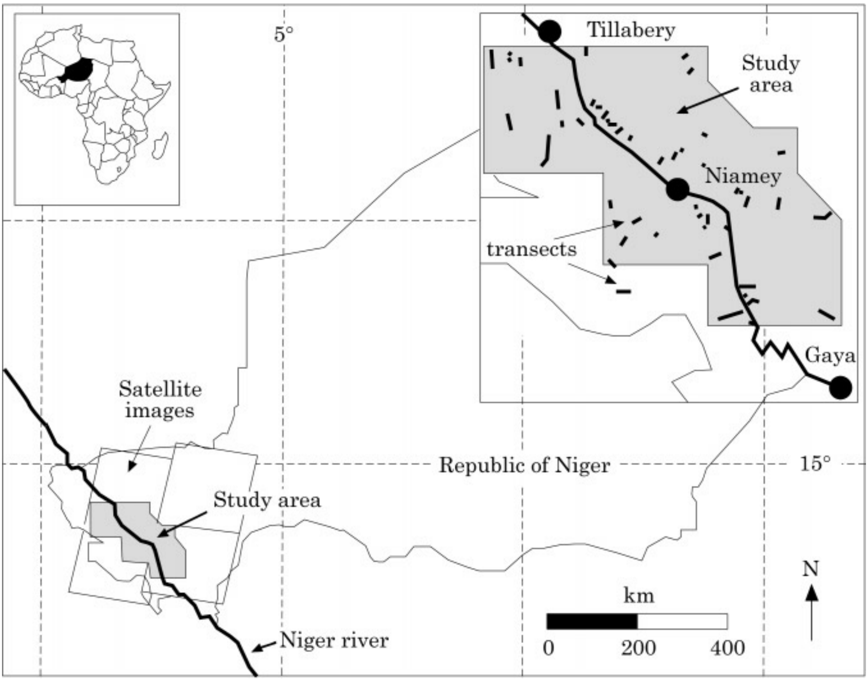

Figure 1. Study area and location of Landsat TM scenes.

downscaling between three database levels and scales is possible.

The aim of this work is to give an insight to the applied transect method and to show the utility of the developed database for multiple purposes (e.g. monitoring and extrapolation of soil degradation, targeting of land susceptible to erosion, need for anti-erosion measures, etc.).

Study area

The climate of the study area is semi-arid with annual precipitation ranging from 350 to 600 mm and with average monthly minimum and maximum temperatures between 16 and 42°C (Sivakumar *et al*., 1993). The precipitation is characterized by high variability in time, space, amount and intensity (Casenave & Valentin, 1989). Combined with crusted soil surfaces, this often leads to high surface runoff. The vegetation changes from grass savannah in the north, over bush savannah to tree savannah in the south. In geological terms the study area is situated on the transition of the Precambrian West African Craton or 'Liptako' region (basement complex) to the 'Continental terminal' (Ct) deposits of the 'Bassin des Iullemeden' dated from Eocene to Pliocene age (Greigert, 1966). The basement complex outcrops largely in the west of the area, whereas in the east the Ct deposits occur.

Methodology

Data structure

For data storage and management the method and data structure of SOTER is applied. The information is managed in (a) a Geographic Information System (GIS), which

Table 1. *Selected SOTER features from transect studies*

Terrain data	Soil data
Landform	Position in terrain component
Dissection	Degree of erosion or deposition
Lithology, texture group	Crusting
Depth to bedrock	Surface colour
Slope gradient and length	Surface stoniness
Surface lithology	Diagnostic horizons and properties
Surface drainage	Soil structure
Mesorelief	Soil consistency
Flooding	Soil texture
Type of vegetation and coverage	Soil colour
Land use and land use intensity	Soil depth
Type and degree of erosion or deposition	FAO classification

stores geometrical (map) information, and (b) a relational attribute database, which stores attributes and climate data. Queries are used for retrieval and classification of specific data from the database. The information of the attribute database is organized at three different levels (Table 1). (1) Terrain units: general terrain description such as major landform, general lithology. A terrain unit comprises one or more terrain components. (2) Terrain components: detailed terrain description with parameters such as surface form, surface drainage, slope form and length. A terrain component comprises one or more soil components. (3) Soil components: detailed description of soils with parameters such as erosion degree and rootable depth. For evaluation of soil variability, the original SOTER structure, allowing only one reference profile per soil component, was modified by Weller & Stahr (1995) by introducing the term ‘profile set’. A profile set contains a free number of soil profile (point data) descriptions. A soil profile is made up of a number of horizons which are described and analysed for chemical and physical properties.

Data collection

Figure 2 presents a scheme of activities, tools and their interactions in the frame of this approach. Remote sensing will be discussed separately below.

Collection of secondary data

Documents and maps containing SOTER-relevant data were collected in order to (a) get information of the biophysical setting in the study area; (b) collect existing data to feed the SOTER database from two types of documents: maps with accompanying explanations (area data) and documents with soil profile descriptions and analysis (point data with attributes); (c) locate areas with missing data; and (d) determine transect sites.

Area data

The types of existing maps are (a) topographic maps (IGN, 1966) at different scales

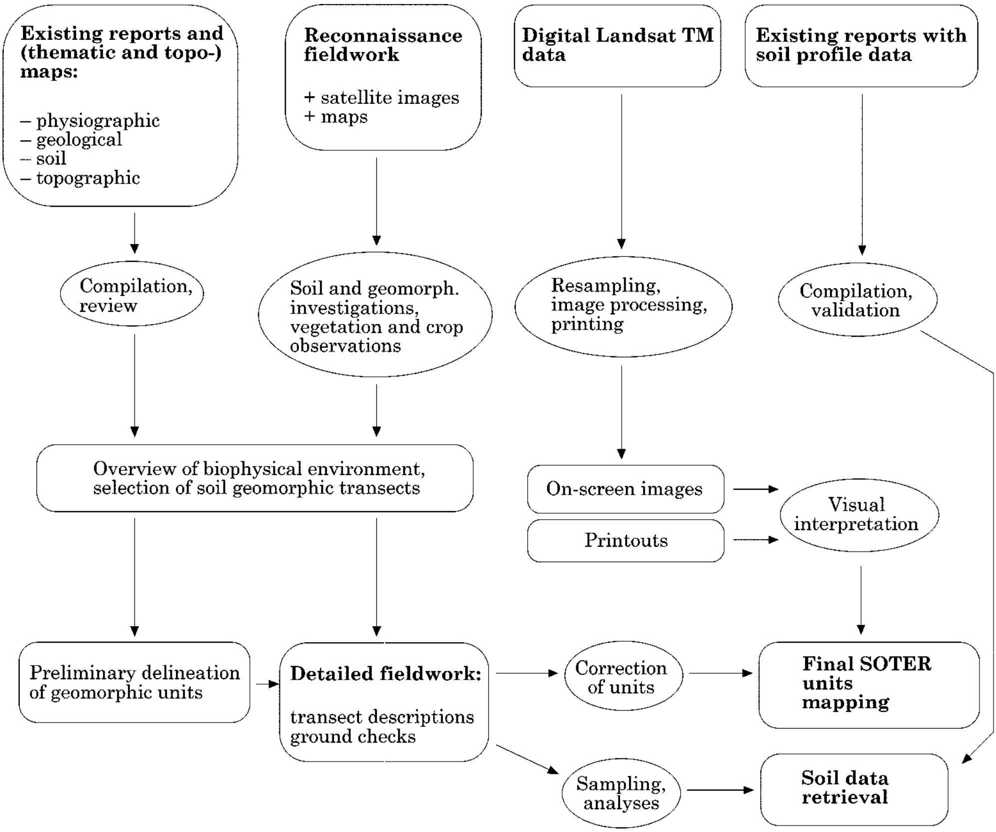

Figure 2. Flow chart with methods and interactions between activities.

(1:200,000−1:50,000); (b) soil maps (Gavaud & Boulet, 1967) at 1:500,000; (c) geological maps from Greigert (1961) at 1:1,000,000 and from Machens (1966) at 1:200,000; and (d) a physiographic map at 1:100,000 (INRAN, 1977).

Point data

Only soil profiles with precise geographical positioning or accompanying maps and a mandatory set of profile descriptions and analyses (ISRIC, 1993) are integrated. For the database 250 profiles from 22 documents were considered suitable. The soils were classified according to FAO (1990) and attributed to their respective profile set. Our own soil analyses complement the secondary data so that the soil inventory comprises over 400 profile data sets.

Remote sensing

Satellite images

The use of satellite images for land and soil investigations has been shown in studies by Courault *et al*. (1990) and Matheson & Ringrose (1994). Since in arid and semi-arid regions the relation between vegetation, soil and geomorphologic characteristics is very distinct (Löffler, 1994), satellite images are well suited for SOTER mapping in Niger. Digital Landsat TM5 scenes were chosen because of their wide band spectrum (three bands in the visible light and three bands in the near infrared), high resolution (30 m) and large ground coverage of 170 × 185 km. The following digital Landsat TM data were processed (positions in Fig. 1): TM 193/50 full scene, (07-04-85); TM 193/51 full scene, (03-02-88); TM 192/51 full scene, (31-12-86); TM 192/51 standard quarter scene (SW), (25-4-94); and TM 192/50 full scene, band 1-4, (18-09-92).

Scenes from dry seasons were chosen to reduce interference of vegetation cover. For data processing the raster-based geographic analysis system IDRISI (Eastman, 1996) was used. Further image treatment (e.g. equalization, filtering, overlay etc.) was carried out with Adobe Photoshop.

The satellite data were geometrically corrected with IDRISI both from ground control points taken with a Global Positioning System (GPS) and from distinct features (e.g. plateau edges) on topographic maps. Image processing included linear stretching, median filtering and hue saturation. From the channel combinations 7−4−3, 7−4−1 and 3−2−1 (all red−green−blue) tested for false colour composites, the combination 7−4−3 was considered most suitable for recognizing geomorphologic features (Löffler, 1994). Subsequently, the false colour images were interpreted visually on-screen and on printouts (1:50,000) by comparison with the above-mentioned thematic maps and ground-truth data (Table 1).

Aerial photographs

Aerial photos of four villages and their surrounding terrain allowed differentiation of fields, tracks and vegetation. Several overflights with a microlight plane were useful to better understand the relationships between landscape morphology, soil surface characteristics and corresponding satellite image features. On this occasion some transects already investigated in the field could be checked again from the air.

Soil geomorphic transect surveys

Transect investigations for characterization of areas can act simultaneously as interface between reconnaissance level (1:200,000−1:50,000) and detailed level (1:10,000−1:5000) (van Duivenbooden *et al*., 1996). For this study transects of several kilometres length have been chosen to obtain (a) an extensive inventory of the soils and their distribution in terrain units and components; (b) semi-quantitative information about soil type occurrence; and (c) spatial information about present land use and degradation features.

Transect selection, positioning and realization

The transects were selected and placed with the aid of satellite images and the above-mentioned maps using the following criteria: (a) locations, where differentiation between geomorphologic features in the satellite images is feasible; (b) minimum size (> 500 m) of geomorphologic features (van Duivenbooden *et al*., 1996); (c) minimum number of at least three to four transects per terrain component, to cover the spatial variability; (d) sufficient accessibility; (e) wide distribution across the study area in order to cover potential climatic effects and achieve representative terrain information in the study area (Fig. 1); and (f) location both near and far from main roads and villages in order to recognize former mapping errors, reduce own potential mapping

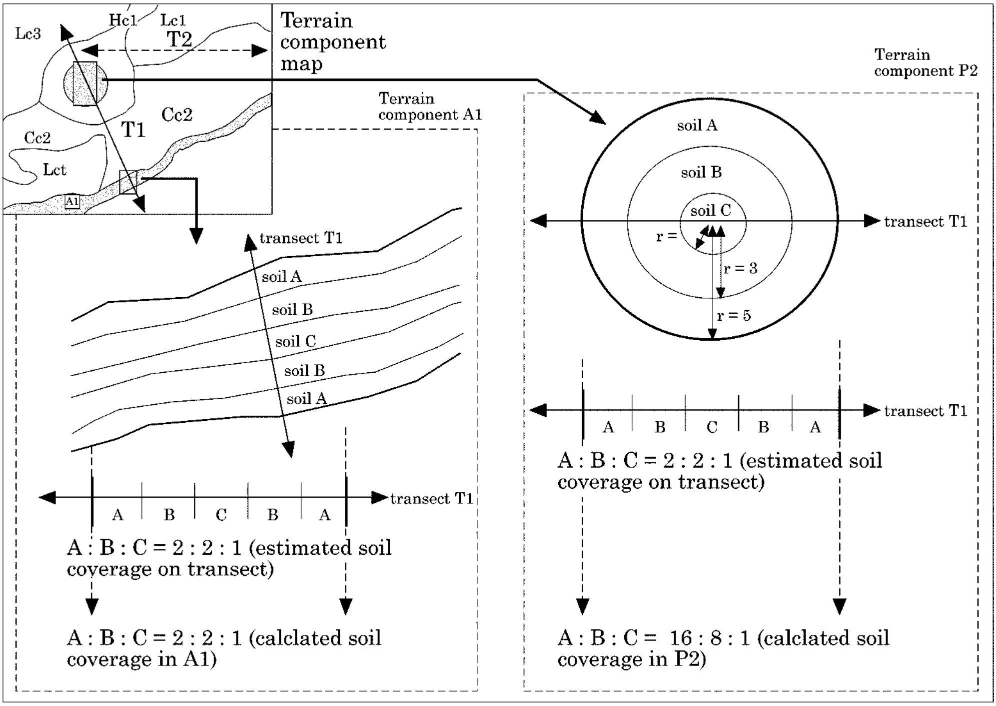

Figure 3. Effect of transect positionings on the estimation of the areal extent of soil components (r = radius).

errors due to poor terrain accessibility and include at the same time the range of land use types and intensities.

The geographic co-ordinates of transect starting and terminal points were defined in the terrain and determined with a GPS. The transect were positioned perpendicular to geomorphic unit boundaries (Fig. 3), crossing at least two different terrain components. Augerings, soil and terrain descriptions were carried out, depending on the homogeneity of the terrain, at every 50, 100 or 200 m intervals.

The rainy season was considered the best period for realization of the soil geomorphic transects because soils were sufficiently wet for augering or digging, and crop and vegetation characteristics were better visible.

Characterization of terrain, soil and surface features

During transect investigations the SOTER descriptions (Table 1) were used for terrain and land use characterization. Terrain features, crops and vegetation were described within a 25 m distance from the auger point, whereas soil surface parameters, more closely related to their respective soil type, were restricted to a 5 m distance.

In addition to the augerings, pits 30–100 cm deep were opened as a profile face for adequate horizon descriptions and sampling. Soil descriptions and classification were made according to the '*Guidelines for Soil Profile Descriptions*' (FAO, 1990) and the FAO classification (ISRIC, 1994). A special focus was placed on soil crusting that was determined according to Casenave & Valentin (1989) and on other soil degradation features. Soil surface colours were determined with the Munsell colour charts for later matching with satellite data (Pouget *et al.*, 1990).

Analyses of sampled profiles included: texture, pH (H_2O), electrical conductivity, exchangeable cations (Na, K, Ca and Mg), cation exchange capacity (CEC), carbonate content, total carbon, total nitrogen and total phosphorus.

Mapping

Areas with specific terrain and soil characteristics were identified and delineated on the basis of the above-mentioned criteria. The observed close relationships between soil, soil surface and geological substrate (Graef & Stahr, 1997) supported the mapping by visual interpretation of satellite images, but also extensive ground-truth data (Table 1) from reconnaissance tours and field transects were consulted.

Mapping units in the physiographic map (INRAN, 1977) were regrouped, new units were inserted and unit boundaries adjusted. In areas not covered by that map the delineation is based on satellite images, topographic maps (1:50,000) and more extensive ground checks and transect studies (Fig. 2). The maps are digitized at 1:50,000–1:100,000 with the GIS.

Results and discussion

Terrain units

Following the methodology described above, 17 terrain units with 53 terrain components were delineated and described (Stahr *et al*., 1996). An extract of the SOTER map is given in Fig. 4. It shows that the landscape of the region is essentially marked by plateaux or hills and by large pediment areas. The pediments, typical landforms of arid and semi-arid climates, are usually plain to softly undulating and weakly dissected. Their slopes do normally not exceed 1–2%. In addition higher gradient slopes (3–8%) occur in the hilly Liptako regions and near the Ct plateaux. Fixed Quaternary dunes with relative altitudes of 25–45 m and widths of 1–4 km occur throughout the area. Almost all geomorphic units are superimposed by at least thin aeolian deposits. Along the Niger river valley with clayey-loamy deposits terraces of different composition and age were distinguished (Ousseini & Morel, 1989). Figure 5 gives a quantification of terrain units in the study area. Likewise the coverage of terrain components can be quantified (Table 2).

Overview of soils

The soils of the study area can be grouped in (a) soils formed on the Ct; (b) soils formed on the granite basement; (c) soils formed on the basement with sedimentary rocks; and (d) soils formed or influenced from more recent material (Stahr *et al*., 1996). An overview of soils in selected terrain components with intensive land use is shown in Table 2. Soil types vary considerably within the terrain components and even within few metres distances (Manu *et al*., 1996). The study area is covered with 50–60% sandy soils, 20–30% loamy-clayey soils and 15–25% gravely soils (Graef & Stahr, 1997). Loamy-clayey and gravely soils are often covered with 10–50 cm of sand deposits.

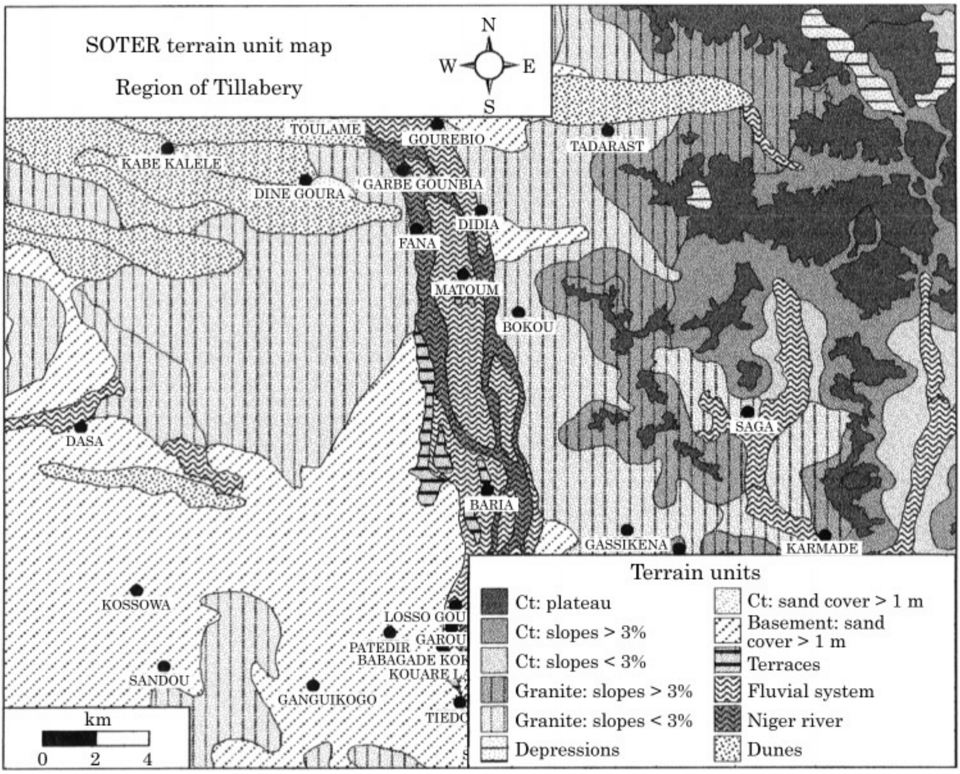

Figure 4. Examplary SOTER unit map of a selected area.

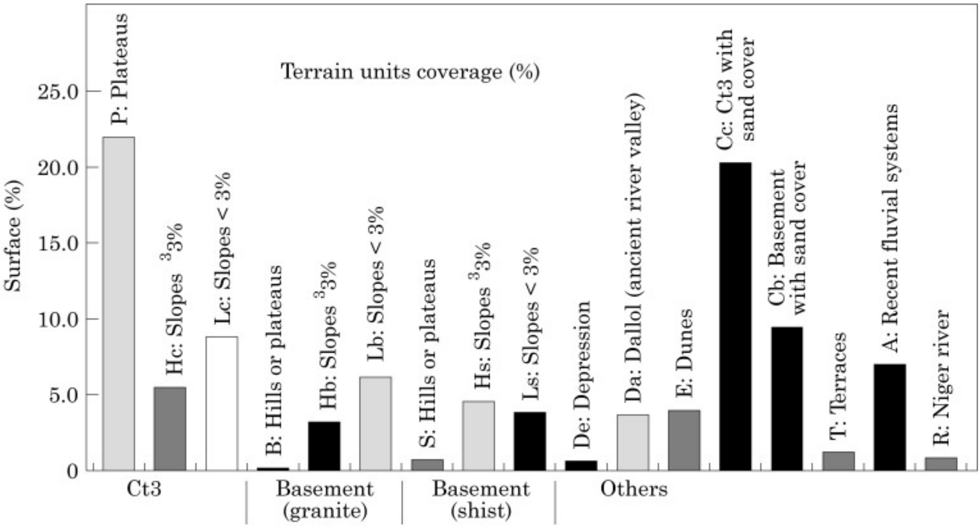

Figure 5. SOTER units coverage (km^2) in study areas.

Table 2. *Soil component coverage (%) of selected terrain components with intensive land use (N = 217)*

Terrain components (TC)	% of study area	Soil types in TC*				
		Arenosols*	'Arenic' soils	Acri-, Alisons	Cambisols	Leptosols
Lc1: Ct slopes < 3% formed through abrasion	1·2	13	20	40	27	< 1
Lc2: Ct slopes < 3% with residual hills and strong relief	2·6	9	65	< 1	< 1	26
Lc3: Ct slopes < 3% from colluvial deposits	5·0	9	52	18	9	12
E1: fixed dunes	1·5	100	0	0	0	0
E2: complex of dunes with depressions	2·3	86	14	0	0	0
Cc1: Ct plateaux with sand cover > 1 m	2·4	100	< 1	0	0	0
Cc2: Ct slopes < 3% with sand cover > 1 m	14·5	89	11	0	0	0
Cc3: Ct slopes ≥ 3% with sand cover > 1 m	3·1	79	21	0	0	0

* Arenosols: deep sandy soils; 'Arenic' soils: shallow stony or clayey soils with sand cover > 20 cm; Acri-, Alisols: clayey soils with clay translocation; Cambisols: clayey shallow soils; Leptosols: stony shallow soils (ISRIC, 1994).

Land use

Sandy soils have been traditionally of major interest for cropping to the smallholders in SW Niger. Presently, as a result of increasing population and decreasing yields, also marginal land is used for pasture or cropping (Graef & Stahr, 1997). These areas are predominantly covered with thin sandy or loamy-clayey soils (e.g. Lc1-3 in Table 2). Most of the land is used for millet or millet-based mixed cropping with cowpea, groundnut, sorghum or okra. (Table 3). Groundnut as a single crop is grown on thin sandy or loamy-clayey soils. Fallow land (weighted average of 35% for the selected terrain components) that is used at the same time for pasture has become extremely small and the fallow period has been reduced from 10–20 years to under 5 years (Wezel, 1998). Crop or fallow residues are traditionally burnt or left on the fields.

Land degradation

Land degradation is more often assessed qualitatively either from vegetation thinning or from soil erosion features (Matheson & Ringrose, 1994). Quantitative approaches, e.g. by Sterk *et al*. (1996), have shown soil changes due to wind erosion at field scale. Timing and quantity of soil flux has been determined by Chappell *et al*. (1998) *in situ* with ^{137}CS used as a radioactive tracer on a toposequence in SW Niger. The net soil flux was found to be 16 $\pm$ 2 t ha^{-1} year^{-1}.

The soil and terrain investigations described above enable a regional quantification of soil redistribution that can be attributed to (a) gradual deposition during past climates of the Holocene; (b) recent-subrecent (1–> 200 years) gradual deposition caused by cultivation, pastoralism and rain or sand storms; (c) very recent (1–25 years) sudden depositions caused by cultivation, pastoralism and rain or sand storms; and (d) wind and water erosion induced by farmers and pastoralist activities. This information is derived from determination of stratification bounderies and soil colour distribution in soil profiles (Graef & Stahr, 1998).

Table 3 and 4 show that the soil degradation differs between terrain components and among different agricultural use. A statistical correlation between the parameters was not proved. Deposition was only recorded to a depth of <1 m and if horizon stratification was clearly visible, so that the given figures are rather underestimated. Sand-dominated and therefore traditionally cultivated areas (e.g. E2, Cc2) have deeper sand depositions than areas with naturally thin sand cover (e.g. Lc1-3). The total rate of, for example, recent deposits <25 cm depth can be estimated as 2000 t ha^{-1} for 7·4% (weighted mean coverage) of the selected terrain components {1·25 dm (medium depth) $\times$ 1·6 kg dm^{-3} (medium bulk density) $\times$ 1,000,000 (dm^2 to ha conversion)}.

The observed gradual erosion process as a whole has caused deeper and higher soil deposits than sudden erosion events. But considering the short period of the observed shallow depositions <25 cm it is clear that recent soil degradation is taking place to a striking extent.

Transects

A total of 257 terrain components were investigated on 53 transects covering a total distance of 192 km (Fig. 1). The mean transect length was 3·6 km and it ranged from 0·5 to 12 km.

A second consideration is that even with transects cutting the terrain component boundaries at right angle the estimated cover percentage of soils is an approximation.

Table 3. *Landuse (%) of selected terrain components with intensive land use* (N = *217)*

Terrain component	% of study area	Millet	Fallow*	Millet/ pasture†	Millet/ cowpea‡	Millet/ groundnut‡	Millet/ sorghum‡	Millet/ ocra‡	Millet/ Groundnut	Bush
lc1	1·2	40	60	0	0	0	0	0	0	0
lc2	2·6	12	66	5	0	0	0	0	0	17
lc3	5·0	8	40	3	7	6	3	0	31	3
e1	1·5	42	26	19	0	13	0	0	0	0
e2	2·3	26	62	10	2	0	0	0	0	0
cc1	2·4	66	0	7	0	0	0	3	0	0
cc2	14·5	39	26	16	10	3	3	1	1	0
cc3	3·1	32	52	16	0	0	0	0	0	0

* Fallow fields are usually used for pasture; † crop and fallow alternating; ‡ inter (relay-) cropping.

Table 4. *Degradation features coverage (%) of selected terrain components with intensive land use* (N = *217)*

Terrain	% of	Average	Recent deposition (%)†				Gradual colluvial deposition (%)				Erosion (%)		No observed
component*	study area	slope (%)	0–25 cm	≥ 25–30 cm	≥ 50–75 cm	> 75 cm	0–25 cm	≥ 25–50 cm	≥ 50–75 cm	> 75 cm	moderate	severe	degradation (%)
lc1	1·2	1·3	67	0	0	0	0	0	0	13	0	20	
lc2	2·6	1·5	5	0	0	0	0	5	0	0	50	0	40
lc3	5·0	1·2	22	3	0	0	8	12	2	0	8	2	44
e1	1·5	3·0	3	0	0	0	0	19	13	0	13	26	26
e2	2·3	1·7	0	10	0	0	0	13	10	15	21	0	31
cc1	2·4	0·6	3	0	0	0	7	3	0	0	41	0	46
cc2	14·5	1·2	18	1	0	0	2	15	8	1	6	2	47
cc3	3·1	3·4	4	0	0	0	6	32	0	0	32	6	20

* Legend in Table 2.

† All values in % of terrain component area.

The geomorphic units shape can differ highly (Fig. 3) and the soil distribution in a geomorphic unit is not always predictable.

A transect crossing a longitudinal unit (transect T1 through A1) with the indicated soil distribution pattern will produce quite accurate results (estimated soil components ratios A:B:C of 2:2:1 *vs*. calculated soil component ratios of 2:2:1). In wide valleys characteristic soil distributions are found along toposequences. This has been demonstrated in Andriesse *et al*. (1994) with transects crossing inland valley agro-ecosystems. However, a transect crossing a circular unit (transect T1 through P2) with the indicated soil distribution pattern would lead to an overestimation of soil C (estimated soil components ratios A:B:C of 2:2:1 *vs*. calculated soil component ratios of 16:8:1).

Typical soil distribution patterns as indicated in Fig. 3, however, were hardly found along the transects. Consequently soil toposequential approaches can work only to a limited extent in this heterogeneous landscape (Hammer, 1994), so that the problems with estimations pointed out above exist no longer.

In spite of the limits realized, the transect method is highly practicable in terms of both fieldwork and manpower, and of its linkage to the database and the GIS. It takes an intermediating position between soil (point) data, terrain (area) data and satellite image data.

The transect data, retrieved on a semi-detailed level, together with the regional scale data, makes up- and downscaling of research questions and results between the three SOTER levels possible. This can be demonstrated with Fig. 5, in which three terrain units are selected and subdivided into eight terrain components (Table 2) of which the derived soil coverages are calculated.

Conclusion

The application of the presented methodology in SW Niger has proved that this is an effective approach for retrieval of spatial soil and terrain data and its integration into the SOTER database and a GIS. After SOTER mapping, it offers the possibility of precise spatial estimations of land use, degradation intensity and soil types within terrain components. It also allows extrapolation of research results to different scales. It is noted, however, that soil coverages are still estimations based on the transect results and that soil variability is often higher than can be registered on the transects. Remote sensing especially in this semi-arid region is an essential tool for surveying of the main features relevant for SOTER.

The methodology comprises mainly the characterization of biophysical parameters. For more extensive land use system characterizations, however, the socio-economic factors also need to be integrated. The SOTER database and map can be used for subsequent elaboration of sustainable land use scenarios.

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