Classification of soil magnetic susceptibility and prediction of metal detector performance – case study of Angola

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Abstract

Soil magnetic properties can seriously impede the performance of metal detectors used in landmine clearance operations. For a proper planning of clearance operations pre-existing information on soil magnetic susceptibility can be helpful. In this study we briefly introduce a classification system to assess soil magnetic susceptibilities from geoscientific maps. The classification system is based on susceptibility measurements conducted on archived lateritic soil samples from 15 tropical countries. The system is applied to a soil map of Angola, resulting in a map that depicts soil magnetic susceptibilities as a worst case scenario. An additional layer depicting the surveyed mine affected communities in Angola is added to the map, which demonstrates that a large number of those are located in areas where soil is expected to impede metal detector performance severely.

Keywords: Angola, soils, soil classification, magnetic susceptibility, metal detector, landmine detection

1. INTRODUCTION

Angola is one of more than 75 countries worldwide affected by landmines and/or unexploded ordnance (UXO). Many of these countries are located in the tropics and Angola belongs to the most contaminated places[1]. The country suffered from a long lasting civil war which began with its independence from Portugal in 1975 and ended in 2002. It is estimated that 500,000 to 1 million landmines remain as a legacy of the armed conflict and still represent a deadly hazard to large parts of the civil population. According to the Landmine Impact Survey 1,988 communities representing 8 % of all communities in Angola are affected by landmines[2]. Because of the widespread landmine problem and the currently ongoing clearance operations, Angola was chosen as an example for applying our classification system and producing worst case maps that support mine detection.

The electromagnetic induction based metal detector is the most widely used instrument for clearing mine fields and it will remain the most important technique in the future since it is inexpensive and easy to use. The response to the signal generated by the metal detector is influenced by various properties of the metal object, the detector technology and sometimes very considerably by the soil properties itself. This impeding effect on the detector can mainly appear on soils with strong magnetic properties. The main influencing parameter is soil magnetic susceptibility and to a much lesser degree electrical conductivity[3]. The problem is aggravated by the fact that modern anti-personnel mines have a plastic body and only a minimum metal content within the ignition device. This causes a low contrast between the mine signal and the background signal of the soil.

The negative effects of soil properties on the detection of low metal compounds are as follows: (i) The sensitivity of the detector can be reduced to such an extent that the object can no longer be detected at the required depth (ii) False alarms may be generated (iii) Some detectors can be made totally unusable in extreme cases[4].

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A series of ferrimagnetic and antiferromagnetic minerals induce magnetic properties of soils. These minerals include magnetite, titano-magnetite and maghemite which are the main contributors to magnetic susceptibility and to a lesser extent further iron oxides and iron hydroxides. Only the first three minerals will – if present in sufficient amounts – lead to magnetic susceptibilities that are high enough to have a negative effect on the performance of metal detectors. High initial contents of these minerals are often associated with ultrabasic and basic magmatic parent rocks. Basalts and andesites in particular can contain high proportions of magnetite and titano-magnetite. In addition, there is an unanimous contribution to soil magnetic susceptibility from the pedogenic neoformation of magnetite and maghemite which is reported in numerous publications[e.g.5,6,7,8].

The variable contributions of lithogenic or pedogenic magnetic minerals to bulk magnetic susceptibility of soils cannot be easily quantified. Despite the deficit in identifying the cause it is possible to classify soils with respect to the effect, namely bulk magnetic susceptibility. This classification may be useful for prediction purposes in aiding the planning of landmine clearance operations. It may also help to choose a proper detection technique. The approach to classify and map soils with respect to the detectability of landmines was pursued so far only by Hannam and Dearing[9]. They provide maps depicting soil magnetic properties of the severely land mine-affected Bosnia and Herzegovina. Their concept of mapping relies on data from mainly European sites and is based on a sophisticated approach of regionalisation. Thus it is applicable in temperate regions.

The mine clearing community has expressed considerable interest in site specific information on crucial soil properties. Conventional soil maps do not contain the information necessary for assessing metal detector performance. Therefore there is a need for a database as well as soil maps containing information on soil magnetic properties. Das et al. express this need and point out that the required information would have the following benefits[4]: (i) Demining organisations could select detectors according to the specific soil properties and predict their effectivity. (ii) Equipment developers and scientists could assess the application potential of their equipment in different soil regions around the world. (iii) Scientists would have the information required to set up more suitable test beds simulating the properties of different soils around the world.

With regard to these demands the aim of this investigation is to look whether the influence of pedogenesis and parent rock can be quantified and whether the corresponding results can be used to predict magnetic properties based on soil information. In a subsequent step the results were adapted and applied to soil maps based on the FAO soil classification scheme[10] which is the most common soil classification system on the global scale. An algorithm was created that extends the original classification system to allow its universal application to all tropical countries where a FAO soil map is available. The application of this algorithm is demonstrated for Angola which serves as a pilot area for this approach.

2. DATABASE

The database used for this study results from the measurement of magnetic susceptibility on 511 lateritic soil samples from 15 countries of the entire tropical belt[11]. The samples are part of the archive of the Federal Institute for Geosciences and Natural Resources in Hannover, Germany and were collected in the following countries (the number of samples is given in brackets): Australia (85), Brazil (85), El Salvador (10), Ghana (43), Guatemala (8), Hawaii (19), India (55), Madagascar (47), Mexico (4), New Caledonia (20), Phillipines (8), Puerto Rico (27), Sri Lanka (24), Uganda (48), Venezuela (28). Volume-related magnetic susceptibility (κ) was measured at the low frequency (465 Hz) with a Bartington MS2B instrument.

3. CLASSIFICATION SCHEME FOR SOIL MAGNETIC SUSCEPTIBILITIES

The classification of the results is based on the thresholds given in Table 1. These limits which were agreed upon in a European standards workshop can be used to assess magnetic soil effects on metal detectors that are used in landmine clearance operations[12].

Table 1. Classification of soil magnetic susceptibilities as to their impediment on the performance of metal detectors[12]. Colours are added to mark the individual classes.

Classification		Magnetic susceptibility κ [10^{-5} SI]
🟢	neutral	0 – 50
🟡	moderate	50 – 500
🟠	severe	500 – 2000
🔴	very severe	> 2000

The results of the susceptibility measurements of this study are depicted in Fig. 1 and in Table 2. In an initial step the magnetic susceptibilities are classified based on parent rock material. Subsequently both, the parent rock and the degree of weathering are used for classification. In both cases the classified data is then statistically evaluated.

Soil samples used in this study are grouped into 6 large groups of parent material. These are (i) ultrabasic, (ii) basic (+ intermediate) and (iii) acid magmatic rocks, (iv) clay and clay slates, (v) phyllites and (vi) sandstones. In Table 2 the results of the measurements are given for the separate groups of parent rocks. The classification was made according to Table 1 and the results are visualised in box plots in Fig. 1.

Table 2. 90% quantile and median of susceptibilities [10^{-5} SI] against parent rock, n represents the sample size on which the values are based. The classification is according to the limits given in Table 1.

Rock type	n	Median	Classification	90 % quantile	Classification
Ultrabasic	107	1496	🟠	8018	🔴
Basic/(-intermediate)	119	937	🟠	3187	🔴
Acid	171	44	🟢	733	🟠
Clay/clay slate	74	40	🟢	710	🟠
Phyllite	21	28	🟢	2059	🔴
Sandstone	19	32	🟢	572	🟠

The medians in table 2 and in the box plots in Fig. 1 reveal that tropical soils deriving from ultrabasic and basic igneous parent rocks are – on average - likely to cause severe problems when working with a metal detector. The medians of soils of other parent material indicate that they are most often not likely to deteriorate metal detector performance. However, in these groups highly susceptible soils may occur in rare cases. The high variability of magnetic susceptibilities within a rock group is due to mineralogical variations in the composition of the parent rock as well as due to possible neoformation of magnetic minerals as a part of pedogenesis.

The availability of geochemical data for the archived samples allows for the calculation of a weathering index for each sample. The degree of weathering is quantified by calculating an index based on the ratio of $SiO_2/(Al_2O_3+Fe_2O_3)$. This ratio indicates the desilification as well as the enrichment of iron and aluminium. Both processes are typical features of lateritic soils. A combined plot of susceptibility vs. weathering index is depicted in the right side of Fig. 1.

The influence of pedogenesis on susceptibility is evident in the right plot of Fig. 1. The graph shows that the highest susceptibility values coincide with high degrees of weathering (low index). This indicates an enrichment or neoformation of magnetic minerals.

The degree of weathering as shown on the x-axis of the scatter plot in Fig. 1 is divided into 3 classes. The classes are < 1, 1 – 3 and > 3. They are marked with lines in the scatter plot in Fig. 1. Within each class the median and 90 % quantile were calculated. In a subsequent step the classification scheme was adapted to different soil types of the Angolan soil map as illustrated in Table 3 and Fig. 2.

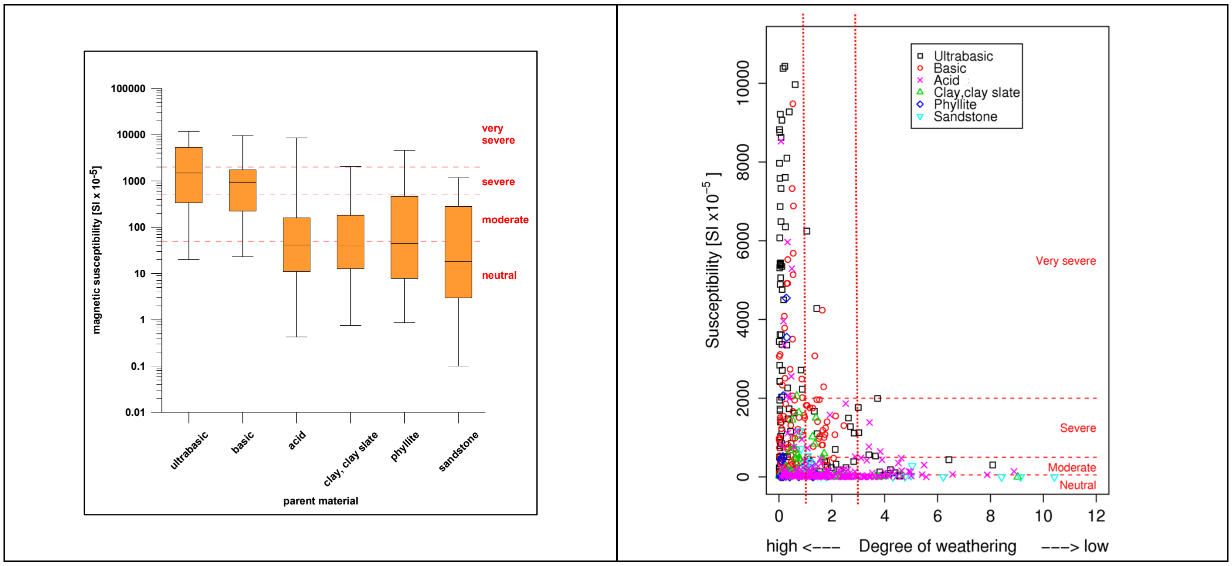

Fig. 1. Results of susceptibility measurements on 511 tropical soil samples. The box plot on the left hand side shows the results grouped by parent rock. The boxes show the upper and lower quartiles while the bars in the centre show the median. The scatter plot on the right hand side depicts the susceptibilities from all rock groups. Magnetic susceptibility is plotted against the degree of weathering calculated from $SiO_2/(Al_2O_3+Fe_2O_3)$. The classification in both plots is taken from Table 1.

4. CLASSIFICATION OF THE SOIL TYPES OF ANGOLA

The set of soil samples originally divided into 6 groups of parent rock and 3 degrees of weathering was adapted by aggregating rock types into more comprehensive groups. Aggregation is based on similar susceptibility ranges of different parent rocks as indicated by the medians in Table 2 and Fig. 1 (left). As a result two groups of parent rock types divided into three degrees of weathering formed. For these new groups the medians and 90 % quantiles of susceptibilities were calculated. These values are given in Table 3 including their classification according to Table 1. The classification scheme in Fig. 2 is based on Table 3.

Table 3. Medians and 90 % quantiles of magnetic susceptibilities of 511 tropical soil samples, calculated for 2 groups of parent rock and 3 associated degrees of weathering.

Rock type	**Degree of weathering***	**n**	**Median**	**Class.**	**90 % quantile**	**Class.**
ultrabasic, basic (intermediate) igneous rocks	0 - 1	158	1390	● (orange)	7327	● (red)
	1 - 3	46	990	● (orange)	2257	● (red)
	3 - 10	13	187	● (yellow)	1300	● (orange)
acid igneous rocks, claystones, phyllites, sandstones	0 - 1	114	72	● (yellow)	2001	● (red)
	1 - 3	125	33	● (green)	591	● (orange)
	3 - 10	55	27	● (green)	436	● (yellow)

*The degree of weathering is calculated from the ratio of $SiO_2/(Al_2O_3+Fe_2O_3)$ - a low number means that desilification is high and thus the degree of weathering is high.

4.1 Assignment of soil types to degrees of weathering

The classification scheme developed here predicts soil magnetic susceptibility as a function of parent material and degree of weathering. In older soil classification systems the extent of soil forming processes such as desilification and enrichment of Fe and Al was expressed by terms like *fersiallitic soils* and *ferralitic soils* (Table 4). In modern classification systems[10,13] soils of the tropics are characterized by other designations; in Table 4 soil types according to the FAO or WRB system are arranged by their degree of chemical weathering as well as their degree of pedogenetic development: *Nitisols* represent the least developed soils while *Ferralsols* and *Plinthosols* represent final stages of pedogenesis. Within the WRB system only two kinds of soil horizons fulfill the conditions set by Preetz et al.[11]: *Ferralic* and *plinthic* horizons are defined as subsurface horizons which result from long and intensive weathering and are dominated by highly resistant minerals such as (hydr)oxides of Fe, Al, Mn and Ti. As a consequence, *Ferralsols* and *Plinthosols* can be assigned to the highest possible level of weathering ("0-1" according to Table 4, cf. Fig. 2). The only remaining soil type that belongs to *ferralitic soils* represent *Acrisols*. Their level of weathering can be rated as "1-3" according to Table 4 (cf. Fig. 2). These preliminary considerations lead to a general, soil-based classification scheme as presented in Fig. 2.

Table.4. Assignment of soil types to degrees of weathering.

Soil types according to FAO[10], WRB[13]	**Soil map of Angola[17]**	**Degree of weathering according to Fig. 1 (r.)**
(all other soils)	....	3 – 10 (low)
Nitisols (NT)	slightly leached to leached soils (Lessivés)	3 – 10 (low)
Lixisols (LX)	fersiallitic soils	3 – 10 (low)
Acrisols (AC)	paraferralitic soils, slightly ferralitic soils	1 – 3 (moderate)
Ferralsols (FR)	slightly ferralitic soils, typical ferralitic soils	0 – 1 (high)
Plinthosols (PT)	soils with lateritic materials near the surface	0 – 1 (high)

The assignment of deeply weathered soils to classes of high susceptibilities is also supported by results gained from laboratory experiments. In doing so Torrent et al.[14] found evidence that the neoformation of ferrimagnetic minerals is linked to the pedoclimate and the degree of weathering. This is maintaining the assumption that higher susceptibilities are to be expected in the soils denominated above. Further validation on the general relationship between soil development and the increase of magnetic properties is provided by recent field investigations from e.g. Van Dam et al.[15] and Torrent et al[16].

Fig. 2 is conceptually designed to use information from existing soil maps for a rough assessment of soil magnetic susceptibility. The first and most important information is knowledge about the rock type acting as parent material. The additional factor that is provided by the soil map is the soil type i.e. the degree of weathering. From all 32 soil groups as provided by the WRB system 3 soil groups are extracted and classified as possibly influencing metal detectors because of magnetic susceptibility increased during their pedogenesis. The relative ranking of these three selected soil groups in relation to all remaining soil groups is indisputable but the assignment to quantitative susceptibility classes is only based on expert knowledge and is therefore hypothetic. The proposed classification scheme in Fig. 2 should be regarded as a semi-quantitative approach. Especially the assessment of *Acrisols* still has to be verified by further measurements.

A general soil map of Angola at a scale of 1 : 3,000,000 was compiled and published by order of the Portuguese Ministério do Ultramar[17]. Within the Food Security Programme of the Southern African Development Coordination Conference[18] units of this map were relabelled and translated into the FAO classification system[10]. The resulting draft map at a scale of 1 : 2,000,000 from 1991 is available for download from the homepage of the International Soil

Reference and Information Center (ISRIC) in Wageningen, Netherlands (http://eusoils.jrc.it/esdb_archive/EuDASM/africa/lists/cao.htm) and was generalized in Fig. 3. For this, the map was downloaded from the ISRIC website. Georeferencing and the subsequent illustrations were compiled with the programme ArcGiS 9.2.

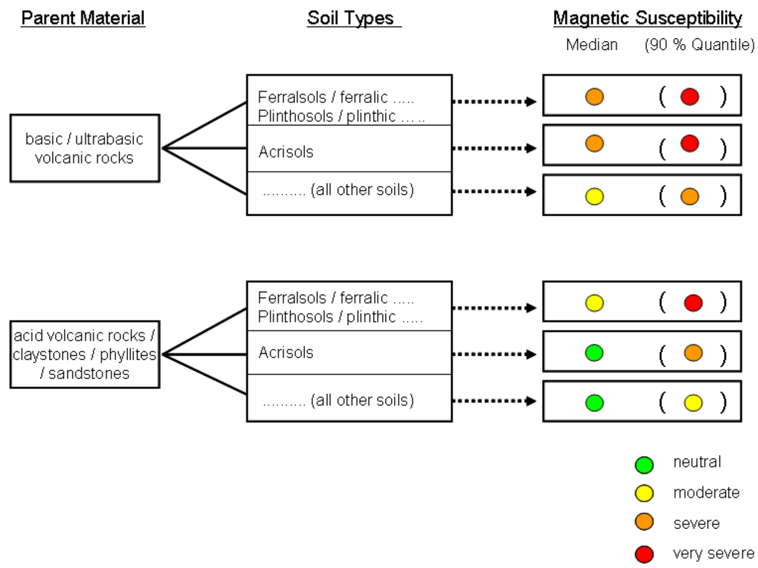

Fig. 2. Classification scheme for predicting soil susceptibility of soil types of the Angolan soil map. The four classes represent the likelihood of the impediment of the performance of metal detectors. There are finally two large groups of parent rock and 3 degrees of weathering.

The assessment scheme of Fig. 2 was applied to this map, leading to predicted medians of susceptibilities (Fig. 4) and predicted 90 % quantiles of susceptibilities (Fig. 5). In Fig. 6, also mine affected communities as surveyed by SAC[2] are plotted.

5. LANDSCAPE AND SOILS OF ANGOLA

A brief description of the natural landscape of Angola is helpful to understand the distribution of soil types throughout the country.

Angola is located in Southwestern Africa between 4°21´S and 18°02´S, including the Northern exclave Cabinda, and between 11°38´E and 24°03´E. Neighbours in the North are Congo, and Zaire and Namibia in the South. The coast line with the Atlantic Ocean is about 1,650 km long and with an area of 1,247,700 km² it is one of the biggest African countries.

On a large scale Angola is divided into 5 large geographic subterritories:

A narrow coastal belt at the Atlantic has a maximum width of 150 km. The coast is a graded shore line with a northbound sediment displacement due to the Benguela current. Elevations are up to 200 m with a rise in Eastern direction.

The Atlantic escarpment abruptly adjoins the coastal belt toward the East. It rises in several steps and has the highest elevations with up to 2,610 m.

The inner continental Highland of Middle Angola (Planalto) consists of high plains ranging from 1,000 to 2,000 m above sea level. Part of the Highland is the Lunda ridge. It runs more or less in West-Easterly direction. This is the main watershed in Angola and source of all major rivers.

The Highland is bounded by expanded depressions. These are the Congo basin North of the Lunda ridge and the Zambesi and Kalahari basin in the East of the Highland.

5.1 Soils

The soil map of Angola reflects the influence of soil forming factors such as geology, relief and climate. The areal distribution pattern is primarily a function of the parent material and secondarily influenced by the length of the rainy season and the amount of annual precipitation. The overall pattern follows the general structure of major geomorphological units: The transition zone along the escarpment and the ancient plateau in the Western half of the country made of crystalline bedrock of Precambrian age, is characterized by intensively weathered and deeply developed soils such as *Lixisols, Acrisols* and *Ferralsols* (Fig. 3). The lowlands in the Eastern part of the country lie buried under Tertiary deposits of windblown Kalahari sands and *Arenosols* are the predominant soil type (Fig. 3). Less frequent are several soil types that form a complex pattern in the coastal belt as well as *Fluvisols* that occur in the valleys of the main rivers. From SE to NW the duration of the rainy season and the degree of climatic humidity increase; accompanied by an increased intensity of chemical weathering and leaching processes trends towards soils that represent final stages of soil development. *Acrisols* are strongly weathered acid soils that have higher clay contents in the subsoil than in the topsoil as a result of pedogenetic processes, especially clay migration. *Ferralsols* represent the classical red or yellow soils of the humid tropics. Deep and intensive weathering has resulted in a residual concentration of resistant primary minerals alongside sesquioxides and kaolinite. Their occurrence is restricted to old, stable surfaces and perhumid or humid climatic conditions.

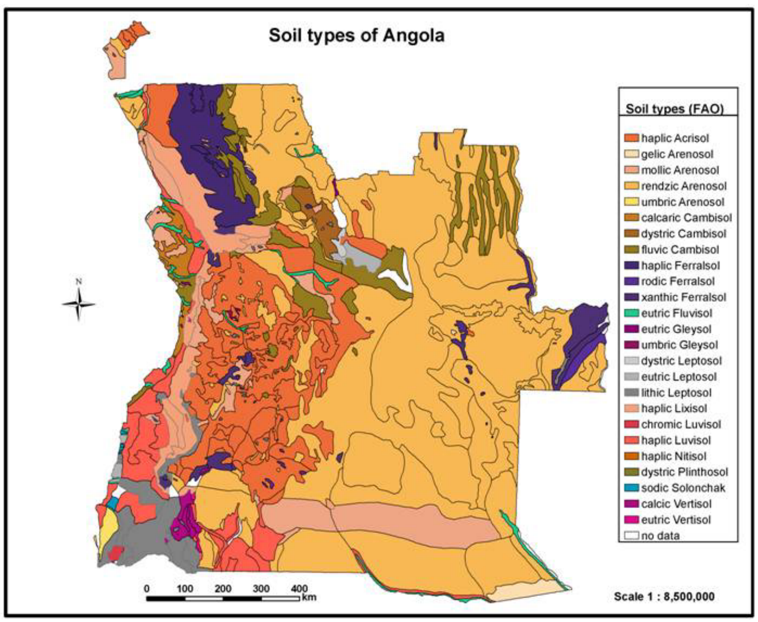

Fig. 3. Soil map of Angola based on the FAO system as available at ISRIC Wageningen at the original scale 1 : 2,000,000.

6. RESULTS AND DISCUSSION

Results of the classification of the Angolan soils are depicted in Figs. 4 and 5. The maps can be used as tools for predicting the likelihood of a specific category of susceptibility values. Fig. 4 shows the resulting map based on the medians of susceptibility values as given in Table 3. This map is a source of information on what to expect on average. Fig. 5, on the other hand, shows a classification derived from the 90 % quantile which is close to the highest values that can be expected in some places. This map may be seen as a source of information for the worst case scenario, which is probably the better choice to meet the requirements of a demining organisation. This is because safety regulations have a high priority when carrying out landmine clearance operations. High soil susceptibilities coupled with high frequency dependencies can make the operators' tasks more difficult or render a metal detector useless in extreme cases (cf. Das et al.[4]). Because the map in Fig. 5 is thought to be the more suitable way of displaying the results, we chose to add the mine affected communities as surveyed by the Survey Action Center[2]. This extended version of the map is more useful for demining purposes (see Fig. 6).

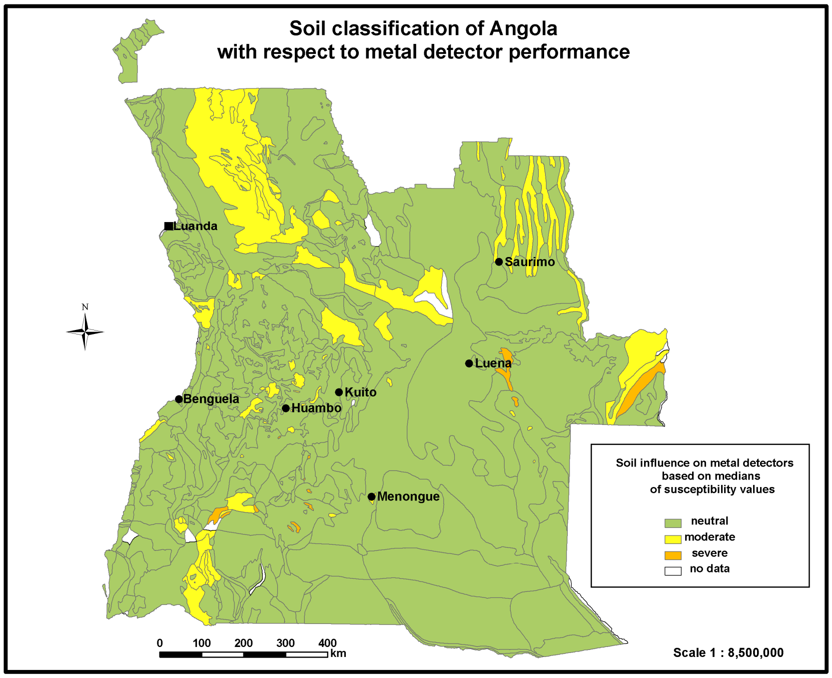

Fig. 4. Predicted soil susceptibilities of Angola based on the medians of susceptibility data in Table 3

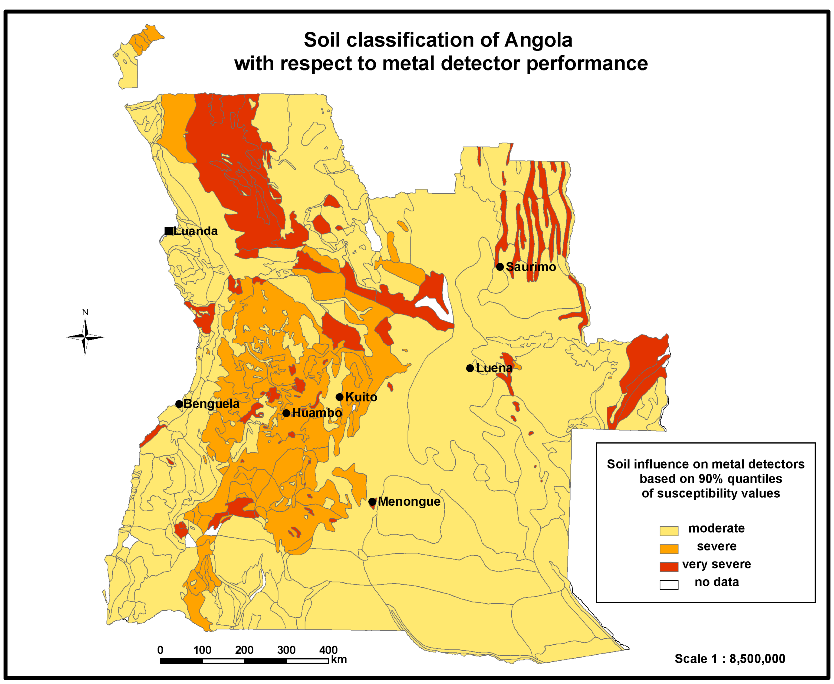

Fig. 5**.** Predicted soil susceptibilities of Angola based on the 90 % quantiles of susceptibility data in Table 3.

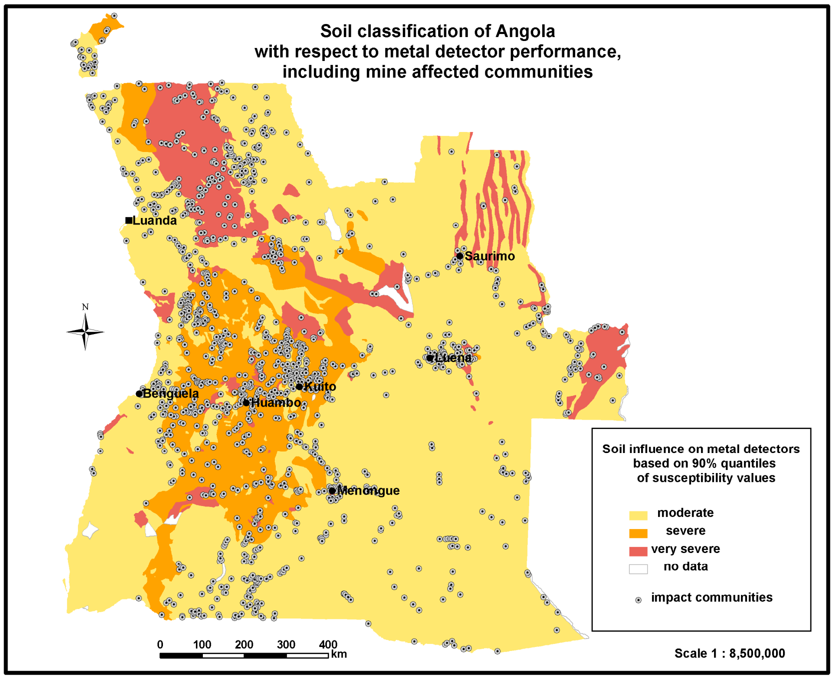

Fig. 6. Predicted soil susceptibilities of Angola based on the 90 % quantiles of susceptibility data including mine affected communities as surveyed by the SAC (2007).

Very severe limitations can occur in some cases over wide areas in the Northwest of the country, in the transition zone between the coastal belt and the Congo basin. This region suffers from a high impact of landmines. *Ferralsols*, derived from Proterozoic magmatites are the prevalent soil types here. The same soil types appear in a large area in the Zambesi basin in the very East where *Ferralsols* are developed on rocks of the Archean and Paleoproterozoic basement complex. Smaller stretches of land with *Ferralsols* that are likely to cause problems are found in the Western half, in the region of the Atlantic escarpment and in the Highland. Both regions are heavily affected by the dissemination of landmines. *Arenosols* on highly metamorphic rocks are the main soil types in these landscapes and they also can cause very severe limitations in places according to the worst case scenario in Fig. 5.

Other seriously critical zones in spacious extent are regions where *Plinthosols* formed of magmatic rocks are predominant. These are areas in the North Western transition zone, Eastwards adjacent to the widespread appearance of *Ferralsols*.

The Southern margin of the Congo basin and several locations in the Atlantic escarpment and the Highlands are further problematic territories where severe limitations are to be expected. The linear North by South directed structures in the Northeast, in the Congo basin are also dominated by *Plinthosols* developed on the basement complex. Hence they are also classified to cause very severe problems for metal detectors locally.

Recapitulating, the following detailed combinations of parent rock and soil type for Angola lead to a classification of soil influence as ‘very severe’ (cf. Figs. 3, 5): On basic and ultrabasic volcanic rocks this can issue from *rhodic* and *xanthic Ferralsols* while *ferralic ...sols, Plinthosols, plinthic ...sols* and *Acrisols* are not developed on this kind of parent material. On all other parent rocks the occurrence of *Ferralsols, ferralic Cambisols* or *Plinthosols* can be responsible for this assessment.

Completely different results are found for the coastal belt and especially in its Southern part. In the South, *Nitisols* and *Leptosols* on Mesozoic and Cenozoic sediments are prevailing which are classified as “moderate”. A similar situation applies to almost the entire Eastern half of Angola. The largest fraction of that area is likely to cause only a moderate soil influence on metal detectors, even in a worst case scenario. Soils with these moderate magnetic properties are *Arenosols* developed on Kalahari sands.

When interpreting the map it must, however, always be remembered that its large scale is associated with generalisation effects. Information on small-scale outcrops of parent rock that may cause higher soil susceptibilities is lost. In particular the outcrop of some Cretaceous basic igneous rocks within the Kalahari sand area as depicted in the Geological map at the scale 1 : 1,000,000[19] is not being reproduced in the underlying soil map at the scale 1 : 2,000,000 used here[18]. With the help of a more small-scale database the extensive classification of the *Arenosols* as "moderate" in the Eastern and South Eastern area of Angola would be more often interrupted by islands classified as "severe" (cf. Fig. 3).

The assignment of individual soil types, especially the *Acrisols*, to a certain degree of weathering and thus to a range of soil susceptibility should be matter of further investigations. However, the expert based classification done here gives confident ranges of soil magnetic susceptibilities since it is drawn up in a conservative manner. This is why it is based at first on the parent rock of the soils and their classification according to measured data. A modification is done by the combination with degrees of weathering which is also supported by the underlying data set. At least the assignment of soil types to degrees of weathering is carried out by means of pedological experience and interpretation and this is of course an arguable approach. Hence, this step had been carried out carefully and it was made sure the assignment of highly weathered tropical soils to a high degree of weathering was only made when justified.

The next step is to verify our concept with field investigations. Yet the shown approach can already be used by landmine clearance organisations as a decision support tool. In Angola this may be especially useful since efforts for landmine clearance have increased in recent years. In addition, the presented method can be applied to other mine affected countries in the tropics.

In total, our approach is an easy tool and a universal approach to predict magnetic properties of tropical soils. Thus, for the first time mine clearing organisations which usually do not have detailed geoscientific expertise can use existing FAO soil maps to predict the order of soil susceptibility magnitude and hence of metal detector performance. Furthermore, the approach does not require regionalisation of data since it can be deployed using existing and easily available soil maps which implies a reduction in potential sources of error.

REFERENCES

[1] ICBL International Campaign to ban Landmines, http://www.icbl.org/problem/what (2008).

[2] SAC Survey Action Center, "Surveys – Completed Survey – Angola," http://www.sac-na.org/surveys_angola.html (2007).

[3] Das, Y., "Effects of soil electromagnetic properties on metal detectors," IEEE Transactions on Geoscience and Remote Sensing 44(6), 1444 – 1453 (2006).

[4] Das, Y., McFee, J.E. and Cross, G., "Soil properties database for humanitarian demining: A proposed initiative," Paper presented to the Council of the International Union of Soil Science at the 17th World Congress of Soil Science, Bangkok, Thailand, 14-21 August 2002, ftp://ftp.fao.org/agl/agll/docs/wcss.pdf (2002).

[5] Mullins, C.E., "Magnetic susceptibility of the soil and its significance in soil science - a review," J. Soil Sci. 28, 223-246 (1977).

[6] Singer, M.J. and Fine, P., "Pedogenetic factors affecting magnetic susceptibility of Northern California soils," Soil Sci. Soc. Am. J. 53,1119-1127 (1989).

[7] Dearing, J.A., Hay, K.L., Baban, S.M.J., Huddleston, A.S., Wellington, E.M.H. and Loveland, P.J., "Magnetic susceptibility of soil: an evaluation of conflicting theories using a national data set," Geophys. J. Int. 127, 728 – 734 (1996).

[8] Hanesch, M. and Scholger, R., "The influence of soil type on the magnetic susceptibility measured throughout soil profiles," Geophys. J. Int. 161, 50-56 (2005).

[9] Hannam, J.A. and Dearing, J.A., "Mapping soil magnetic properties in Bosnia and Herzegovina for landmine clearance operations," Earth and Planetary Science Letters 274(3-4), 285-294 (2008).

[10] FAO Food and Agriculture Organization of the United Nations, "FAO-UNESCO Soil Map of the World (Revised Legend)," FAO World Soil Resources Report No. 60, (1988).

[11] Preetz, H., Altfelder, S. and Igel, J., "Tropical soils and landmine detection – an approach for a classification system," Soil Sci. Soc. Am. J. 72, 151–159 (2008).

[12] CEN European Committee for Standardization, "CEN workshop agreement (CWA) 14747:2003 - Humanitarian mine action - Test and evaluation - Metal detectors," http://www.gichd.ch/fileadmin/pdf/publications/CWA_metal_detectors1.pdf (2003).
[13] WRB, "World reference base for soil resources - a framework for international classification, correlation and communication," World soil resources reports 103, 128 p., Rome. http://www.fao.org/ag/Agl/agll/wrb/doc/wrb2006final.pdf (2006).
[14] Torrent, J., Barron, V. and Liu, Q., "Magnetic enhancement is linked to and precedes hematite formation in aerobic soil," Geophys. Res. Letters 33, 1–4, DOI:10.1029/2005GL024818 (2006).
[15] Van Dam, R.L., Harrison, J.B.C., Hirschfeld, D.A.., Meglich, T.M., Li, Y. and North R.E., "Mineralogy and magnetic properties of basaltic substrate soils: Kaho´olawe and Big Island, Hawaii," Soil Sci. Soc. Am. J. 72, 244–257 (2008).
[16] Torrent, J., Liu, Q., Bloemendal, J. and Barron, V., "Magnetic Enhancement and iron oxides in the Upper Luochuan loess-paleosol sequence, Chinese Loess Plateau," Soil Sci. Soc. Am. J. 71, 1570–1578 (2007).
[17] Ministério do Ultramar, "Carta generalizada dos solos de Angola (3. Aproximação), Escala 1:3 000 000 (Generalised soil map of Angola, scale 1:3 000 000)," Junta das Missões Geográficas e des Investigações do Ultramar, Missão de Pedologia de Angola e Moçambique & Centro de Estudos de Pedologia Tropical (1965).
[18] SADCC Southern African Development Coordination Conference, "Soil map of Angola 1 : 2 000 000. Draft (Revised legend FAO-UNESCO 1988)," Food Security Programme, regional inventory of agricultural resource base; Harare. http://eusoils.jrc.it/esdb_archive/EuDASM/africa/lists/cao.htm (1991)
[19] Carvalho, H. de, "Notice explicative préliminaire sur la géologie de l'Angola (Preliminary explicative note on the geology of Angola)," Garcia de Orta: Serie de geologia / Revista do Instituto de Investigaçao Científica Tropical 6(1/2), 15–30 (1983).