The Relevance of Scale in Soil Maps

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Résumé: De l'importance de l'échelle concernant les cartes de sol

L'échelle a une influence décisive sur ce que nous pouvons déduire des cartes de sol. S'ajoute à cela les coûts très élevés de la récolte des données qui augmentent d'une façon exponentielle à mesure que l'échelle diminue. Dans cet article, nous discutons de l'importance de l'échelle en ce qui concerne l'interprétation des données du sol. Pour cela, nous avons comparé 3 cartes de sol à des échelles différentes (1:200000, 1:25000, 1:5000) pour la même région (bassin versant de Lippenrütibach et Grosse Aa, canton de Lucerne). Afin de quantifier cette comparaison, nous avons calculé la plage d'erreurs potentielles liées à la délimitation des polygones individuels et calculé le pourcentage de la surface représentée par les polygones complexes (avec des informations non-univoques et des données spatiales non-définies). Une surface importante de la région cartographiée est attribuée à des erreurs potentielles délimitant les polygones. A l'échelle de 1:200000, cela représente plus de 42% et à 1:25000 plus de 22% de la surface totale. A l'échelle 1:5000, cette proportion est supérieure à 15% de la surface totale. La carte à l'échelle de 1:200000 consiste uniquement (100%) en polygones complexes tandis que, à une échelle de 1:5000, cette part est réduite à 15%. Par conséquent, l'échelle de la carte est une donnée décisive à considérer vis-à-vis du contenu informatif et de l'utilisation pratique des cartes de sol. Même les cartes de sol avec une haute résolution spatiale contiennent toujours des incertitudes substantielles.

Zusammenfassung: Die Relevanz des Massstabs bei Bodenkarten

Der Massstab hat einen entscheidenden Einfluss auf das, was wir aus Bodenkarten herauslesen können. Bei Bodenkarten kommt speziell die Problematik hinzu, dass die Kosten für die Datenerhebung hoch sind und exponentiell mit der Verringerung der Massstabszahl ansteigen. In diesem Aufsatz diskutieren wir die Bedeutung des Massstabs für die Anwendung und Interpretation von Bodendaten. Dazu wurden 3 Bodenkarten mit unterschiedlichem Massstab (1:200000, 1:25000 und 1:5000) über dasselbe Gebiet (Einzugsgebiet Lippenrütibach und Grosse Aa, Kt. Luzern) miteinander verglichen. Um die Bedeutung des Massstabs grob zu quantifizieren, wurden die möglichen Fehlerbereiche bei der Grenzziehung zwischen einzelnen Polygonen und der Anteil an komplexen Polygonen (mit nicht-eindeutigen fachlichen und räumlichen Informationszuweisungen) berechnet. Ein beachtlicher Teil der gesamten kartierten Fläche entfällt in den Fehlerbereich der Grenzziehung von Polygonen. Bei einem Massstab von 1:200000 sind dies mindestens 42 % und bei 1:25000 immer noch ≥ 22 % der gesamten Fläche. Auch ein Kartierungsmassstab von 1:5000 enthält immer noch einen Fehlerbereich von mindestens 15 %. Die kleinmassstäbige Karte (1:200000) besteht nur aus komplexen Polygonen, währenddem bei 1:5000 dieser Anteil auf etwa 15% der Gesamtfläche reduziert wird. Der Massstab entscheidet vollumfänglich über den Informationsgehalt und den praktischen Nutzen von Bodenkarten. Selbst Karten mit einer kleinen Massstabszahl enthalten immer noch substantielle Unsicherheiten.

Keywords: soil map, scale, soil polygons, mapping soil, spatial planning

1. Introduction and Background

To satisfy the growing demand for (high-resolution) spatial soil information for environmental planning and modelling purposes, high-quality digital soil maps are needed (BEHRENS et al., 2005). Soil data provides information about the soil units or orders (e.g. Luvisol, Cambisol) and/or its characteristics (e.g. pH, organic carbon, etc.). This information is usually represented as a polygon on the map, showing which areas are covered by soils with similar properties. These multi-categorical soil variables display a complex spatial variation in general. Traditionally, the spatial variation in general. Traditionally, the spatial distribution of soil types and corresponding characteristics are documented by detailed field surveys. These field observations verify the interpretations made in the office using aerial photographs and topographic maps. Thus, soil maps are produced according to experts' empirical judgement based on these interpretations and surveys (MONMONIER 1991). More recently, mathematical models have been used as an alternative to the resource-intensive traditional methods to quantitatively characterise

the spatial distribution of soil variables (LI et al. 2004, MOURIER et al. 2008). The modelling approach is, however, not conventionally used for the production of soil maps.
The information on soil maps, their use and the data collection methods vary with the scale. Soil information systems (BURROUGH et al., 1997, MCBRATNEY et al. 2003) and experiments in collaborative geovirtual soil mapping (HODZA 2010, JACOBSON et al. 2009) can host multi-scale representations. In fact, the interactivity of such systems requires producing soil maps in multiple scales and levels of detail. Data collection, especially at a large scale (with a high spatial resolution), is very expensive (TOGNINA 2004) and producing soil maps 'is slow, tedious work' (MONMONIER 1991). Although methods exist, such as classification and regression tree analyses (KHEIR et al. 2010), neuronal networks (BEHRENS et al. 2005, 2010), Markov chain simulation (LI et al. 2004), geostatistical approaches (HENGL 2006, 2009), etc. which allow prediction of soil characteristics based on factors such as terrain and climate (BEHRENS et al. 2010, MCBRATNEY et al. 2003), these techniques are less accurate than the traditional soil mapping approach (UWE, 2010). To determine the accuracy of modelling results, they are often compared to existing soil maps because soil maps obtained from field surveys are considered as the 'ground truth' of the corresponding scale. In this paper, we would like to show that this 'ground truth' is also bound to a certain error range.
Whether we observe spatial patterns in environmental data depends on resolution, which is a direct derivative of the scale (OLIVER 2001). The scale of the soil map drives a number of decisions in the office and in the field such as the sampling scheme, frequency of and interval between samples and the possible interpolation between the data (OLIVER 2001). The larger the scale, the more profiles are necessary to assign correct soil characteristics and the more field work is required to verify the contours of the various soil polygons. However, even in detailed maps, the soil unit boundaries (marking the change from one soil unit to another) are approximations; soil characteristics rarely change abruptly. All thematic maps face the problem of drawing boundaries between classes (GOODCHILD et al. 1994). To reduce the problems associated with such abrupt boundary representations, cartographic solutions based on visual variables (MACEACHREN 1992, ROBINSON 2008) may be used. To further reduce boundary problems it has become common practice to map soil data one 'scale class' above the final map scale. For example, in Switzerland, a soil map with a scale of 1:5000 is surveyed at a scale of 1:2500 (LÜSCHER 2004). As the area of a map increases by the square of the scale, the level of detail (resolution of collected data) and therefore the production cost of a soil map would rise similarly (TOGNINA 2004). Due to this cost increase, soil maps are not always available at the necessary scale. Consequently, important environmental decisions are sometimes taken without having the appropriate soil data (KYRIAKIDIS and DUNGAN 2001, MONMONIER 1991).
Motivated by the facts and arguments above, we investigate the effects of scale on the represented level of detail (LOD) and accuracy of soil maps to identify the limitations encountered in using soil maps of various scales. We expect to show that a) errors in delineation of polygons are a function of the scale and that b) the use of multi-component mapping units becomes more frequent the higher the degree of generalisation.

2. Methods

Data Sources: We evaluated soil maps at three different scales (1:5000, 1: 25000 and 1:200000) covering an area in the northwest of Lucerne in central Switzerland. The smallest scale (1:200000) is the "soil aptitude map" of Switzerland. A first version of this map was produced in 1980 by the Swiss Federal Office for Spatial Planning. In 2000 it was geo-referenced and updated to its current digital format.The middle and large scale (1:25000 and 1:5000) soil maps cover the watersheds of Lippenrütibach and Grosse Aa. These two watersheds are in an agricultural area that is intensively used for animal farming. Due to this intensive land use, the area and nearby lakes (e.g., Lake Sempach) have been strongly influenced by eutrophication. The 1:25000 and 1:5000 maps were produced by the Department of Construction, Environment and Economics of the Swiss Canton of Lucerne when investigating phosphorus contamination of the area. The maps were digitised by the GIS section of Lucerne and have a relatively high spatial resolution, covering an area of approximately 1300ha each. We took the greatest common area of all three maps for a quantitative analysis.

Data Evaluation and Accuracy Assessment: We evaluated the soil unit accuracy in relation to the scale. The soil unit accuracy of the studied soil maps was estimated by

- analysing possible error ranges (area proportions of uncertainty ranges related to the whole mapping area) in delineating boundaries of soil units and
- calculating the proportion of areas having non-uniform data (P_{ND}) content (multiple-component mapping units) to the whole mapped area (A_M). This proportion is obtained by

$$P_{ND} = \frac{A_{ND}}{A_M}$$

where A_{ND} is the area of non-uniform data. These area proportions represent a measure of the uncertainty of a given soil map. Even though this is not a direct indicator of the map's accuracy, it gives the map user an idea of how trustworthy is the information presented on the map.

Polygon Boundaries In order to quantify the accuracy of a soil polygon we calculated the area covered by an uncertainty zone around the soil polygon margins of 1mm width (on the map). Additionally, the calculations were done for a 2-mm-wide buffer zone to demonstrate the drastic increase in uncertain assignment of a chosen area to a mapped polygon. The values of 1 and 2 mm were chosen under the following assumptions:

1) At a scale of 1:5000, a soil boundary has an error margin of approximately 2.5 to 5 m on either side. This assumption was based on FABO (2007) and BRUNNER et al. (1997) who stated that the delineation of the soil types that can be interpreted as being in the considered range can vary over several metres; and

2) The error margin increases linearly with scale. Similarly to HENGL (2006), we quantified the delineation errors using an imaginary grid of 1 cm^2 cells that was superimposed on the map (Fig. 1).

HENGL (2006) stated that it is a cartographic rule that there should be at least one and ideally four observations per 1 cm^2 (raster field) on the map. Any observation for a smaller area should be based on data that is obtained through interpolation between the sites where soil characteristics were determined in the field. For each raster field (grid cell) and for each scale (1:5000; 1:25000; 1:200000), the length of the borderlines between soil units was calculated to compute the area of the buffer zone. This area was divided by the whole mapped area to calculate the inaccuracy per grid cell.

Complex Soil Polygons A multiple-component mapping unit represents a group of too highly scattered, commonly-found soil classes. The smaller the area of a soil unit is, the higher the probability that it will be found in such a multiple-component unit (EGLI et al. 2004). Consequently, we can hypothesise that the use of complex soil polygons becomes more frequent with a higher generalisation degree of the map. However, even maps at a scale of 1:5000 may contain complex polygons. This means that not every polygon in the map contains the same type of information and level of detail because some polygons are

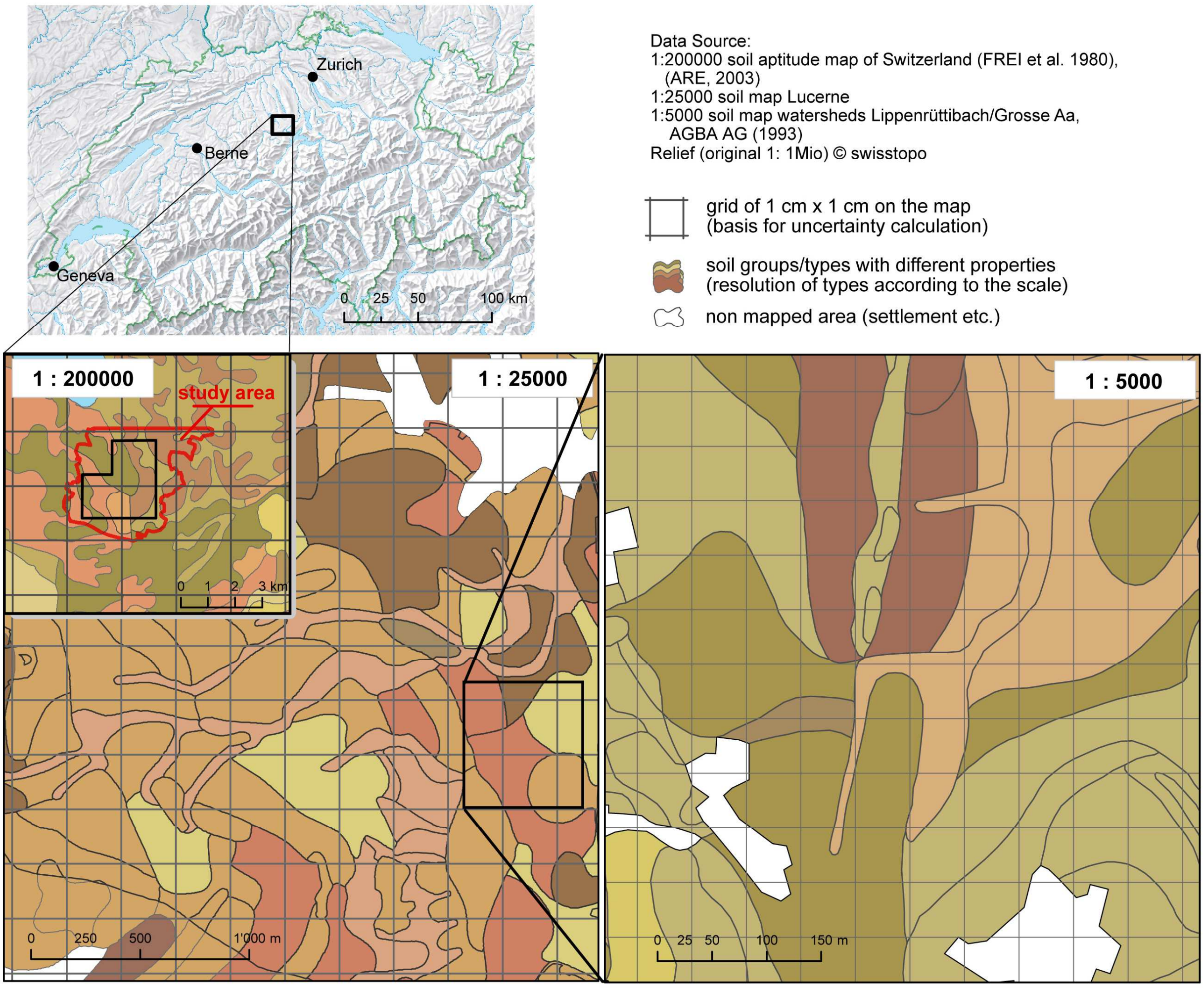

Fig. 1. Study area with details of the soil maps of the scales at 1:200000, 1:25000 and 1:5000.

aggregations of various soils (ORVEDAL et al. 1949). Complex polygons are less precise than single-component mapping units from the points of view of environmental legislation and land-use management. These polygons are directly identifiable in a soil map as they are labelled as such. The area covered by complex soil polygons is also an indication of the accuracy of the soil units on a map (in addition to the estimation based on polygon boundaries as introduced in the section above). Bearing this in mind, we calculated the total area of complex soil polygons and set them in relation to the total area of the map.

3. Results and discussion

Small Scale Map – 1:200000 The delineation errors of the soil entities at the 1:200000 scale were calculated on a relatively small area due to limited data availability on the middle and large scale maps (for comparison purposes the areas must cover the same spatial extent in all scales). The study area covers 3.32 cm^2 of the printed 1:200000 map (Table 1).

The buffer zones, using 1 and 2 mm, correspond to 200 and 400 m in reality (Fig. 1 and 2; Table 1). The relative area covered by these two buffer zones was in the range of 42 to 84 % of the total studied area. Consequently, minor errors in the delineation of polygons have a drastic effect on the precision of the map. The soil map 1:200000 gives a good overview of the pedologic conditions in Switzerland (FREI et al. 1980). Rather than giving a precise description, this map aims at giving some indications about the suitability of a particular area for certain usages. Thus, the possibilities for agricultural use as well as forest cultivation may be assessed over a larger area. Hence, a scale of 1:200000 does not allow a precise interpretation of the soil properties. Only general and rather vague information can be obtained. The studied soil map is reported to differentiate geomorphologic and pedologic entities: in total, the map has 144 units and according to their agricultural suitability and forestry use, these units are grouped into 18 different classes (FREI et al. 1980). FREI et al. (1980) used aerial photographs to divide the surface into geomorphologic units that were subsequently checked in the field. Some typical soil profiles were chosen according to their preliminary analyses and were checked in detail. The data collection in the field was optimised for a scale of 1:50000 and then generalised to 1:200000. Spatial variability of soil units is hardly taken into account and the degree of generalisation is very high (FREI et al. 1980). As a consequence, the map contains only complex polygons (100% of the studied area and also 100% of the whole of Switzerland) and no single-component mapping units can be found. The scale of this map and the subsequent size of polygons do not allow the soil chemical, physical, biological and ecological variations to be shown. This map has therefore almost no relevance for the implementation of environmental legislation and land-use management.

Table 1. Comparison of all three scale levels with respect to the delineation error (buffer zone) of 1 and 2 mm (and subsequent area on the map) and to the area covered by complex polygons.

Properties/scale	1 : 200k	1 : 25k	1 : 5k
Squares analysed [cm^2]	3.32	124	4723
Buffer zone of 1 mm (on plotted map)			
Width of buffer zone in reality [m]	200	25	5
Average area covered by buffer zone per cm^2	42.1%	22.3%	14.7%
Standard deviation	---	9.0%	9.9%
Maximum area covered by buffer zone per cm^2	---	45.7%	51.8%
Buffer zone of 2 mm (on plotted map)			
Width of buffer zone reality [m]	400	50	10
Average area covered by buffer zone per cm^2	84.3%	44.6%	29.3%
Standard deviation	---	18.0%	19.9%
Maximum area covered by buffer zone per cm^2	---	91.3%	100%
Complex polygons (multiple-component mapping unit)			
Area covered by complex polygons	100.0%	72.4%	15.0%

Middle Scale Map – 1:25000 The area on the printed 1:25000 map covers 124 cm^2. A grid cell of 1 cm^2 on the map corresponds to 62500 m^2 in reality. The average length of borderline per grid cell is 560 m in the field (Table 1). The width of the buffer zone along these borderlines is 25 to 50 m, which results in an area of 13900 to 27850 m^2 per unit area. Although a soil map of 1:25000 is usually considered quite precise, a remarkable amount of 22 to 44 % of the mapped area can be attributed to delineation uncertainties. Also the level of generalisation is quite high as the share of complex polygons is 72% (Fig. 2). This value (72%), however, might vary considerably from area to area as lower values in other areas are possible. The chosen area was, as mentioned, entirely due to the availability of digital datasets. It can be said, however, that assessments based on this scale (1:25000) should be regarded with caution and must be verified in the field. The production of this map was based on a detailed interpretation of aerial photos, geological-geotechnical and climate maps (EFLP 1988). Based on this information, sites were chosen for the detailed analysis of typical soil profiles and the delineation of the polygon boundaries was checked in field surveys (ground truth) using a hand-auger (EFLP 1988). The original soil map was produced at a scale of 1:10000 (data collection was optimised for this scale). The map was then reduced to the final scale of 1: 25000 as proposed by LÜSCHER (2004). In Switzerland, decisions concerning the implementation of environmental legislation are often based on this type of soil map (1:25000) because a better alternative is not available for most areas (AGROSCOPE 2010). The aim of this semi-detailed map is to allow assessments of soil quality and land use (e.g., agriculture and forestry). The map contains both an overview and important details of regional soil conditions (EFLP, 1988).

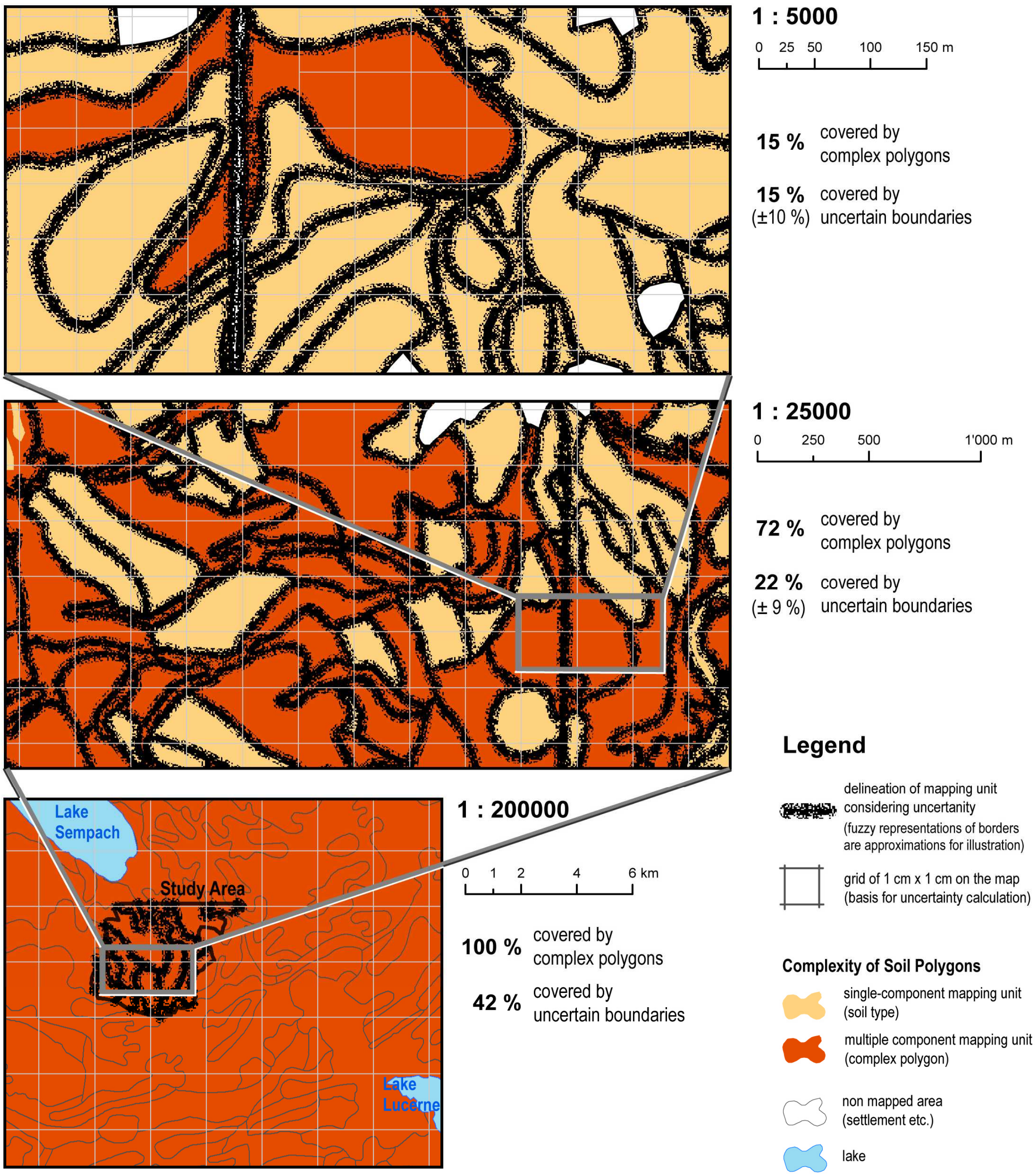

Fig. 2. Uncertainty visualisation at all three scales (1:200000; 1:25000; 1:5000). Complex polygons progressively cover the entire map.

Large Scale Map – 1:5000 The area on the printed 1:5000 map covers 4723 cm^2. A grid cell of 1 cm^2 corresponds to 2500 m^2. Possible errors in delineation were calculated using two buffer zones of 5 and 10 m width (i.e. 2.5 and 5 m to either side of the polygon boundary) corresponding to 1 and 2 mm on the map, respectively. Each grid cell has an average polygon boundary length of 73 m (±49.7 m). This results in an uncertainty area of 360 to 730 m^2 per grid cell and corresponds to about 14.7 to 29.3% of the total area. Although the map seems to have a high spatial resolution, the uncertainties attributed to polygon delineation are still substantial. Compared to the other maps, the share of complex polygons is reduced to 15%. This means that 85% of the polygons have single-component mapping units (Fig. 2). Both types of calculations showed that the soil map with a scale of 1:5000 does not fully meet the requirements for spatial planning as it still involves considerable uncertainty and error potential (LÜSCHER, 2004). More precise maps for large areas could be made available, but only at excessive cost. Compared to the other maps, this large-scale map integrates information not only about soil properties and the soil water regime but also about risks of nutrient losses (phosphorous) that were surveyed within the context of water eutrophication (AGBA AG, 1993). Similar to the 1:25000-scale map, the data were collected by interpreting available climate maps, geological maps and aerial photographs. Based on the profile examination and the produced concept map, the delineation of the areas having the same soil properties was determined by field surveys. The level of detail represented at this scale (1:5000) is greatly increased compared to the other maps. Soil maps at this scale and level of detail are typically used for large scale spatial planning, decisions concerning land use and landscape development, soil conservation, nature protection, water protection, agricultural consulting and research (FABO 2007, LÜSCHER 2004, VOL 2009).

4. Implications for Environmental Legislation and Soil Mapping

Soil maps contribute substantially to decision making regarding land-use and environmental protection issues such as planning irrigation systems, soil reforms, use of sewage sludge, site-adapted soil management, groundwater protection, etc. (BLUM et al. 2005, HERRERO et al. 2007). Bearing this in mind, the accuracy, the level of detail and possible errors in soil maps play a decisive role for environmental legislation. For example, in Austria, 30 ha of agricultural land are lost to non-agricultural purposes every day (BLUM et al. 2005). In Switzerland, these are 8 to 9 ha every day. Annually, 0.08 – 0.13% of the total area or 0.30 – 0.35% of the total agricultural land is lost to urbanisation (ARE 2003). This is likely to lead to a greater pressure on soils suitable for agriculture in the future. Therefore, we predict that a well-organised digital soil information system will be indispensable in the near future. As an input for soil information systems, aerial and point data for soils are essential to protect and conserve the soil and to sustain soil fertility. However, as demonstrated by our study, these methods will never be fully precise. To fill this gap, the geopedological approach in soil mapping tries to distinguish more homogeneous mapping units but is still not able to fully define and represent the variability and apparent chaotic nature of the soils (BORUJENI et al. 2009). Uncertainties in data lead to uncertainties in the results of analysis (LONGLEY et al. 2005). Therefore, it is understandable that web GIS browsers (BLW 2009, FABO 2007) restrict the scale ranges of the maps. Calculations and modelling of expected error ranges could help to tackle the ambivalence between mapping cost and decision-making. Visualisation techniques representing the accuracy of a soil map may be an essential tool for such an issue.

Different and improved techniques of stratifying the landscape are needed in order to better analyse and understand the soil-forming processes and soil variability and to improve sampling and mapping approaches. At the scale of the European Union, soil-quality maps are the main input-data source in the delineation process for 'less favoured areas' (LFA), which get special financial support. However, every EU member state uses its own national soil-map resources to derive soil-quality estimates; no uniform mapping scheme or map resources exist for the whole territory. These varying national mapping concepts do not seem to affect the accuracy very much, but methodological studies comparing national practices in soil mapping are rare and analysis about the comparability of these map resources is simply missing (DOBERS et al. 2010).

5. Conclusions

We investigated scale effects on soil maps of three different scales (1:200000; 1:25000 and 1:5000) representing the same area and tried to estimate the soil classification accuracy of these three different maps based on quantifiable criteria. Our research shows that soil maps at different scales may contain non-negligible error sources and uncertainties. These errors and uncertainties may cause great financial and social losses, because they have the potential to lead to misinformed environmental policy decisions. We found that the error that can be attributed to the delineation of polygons sharply decreases with increasing spatial resolution (scale) of the map: For the small scale map (1:200000) this error lies between 42 and 84%, while for a soil map of 1:25000 a remarkable amount of 22 to 44% of the mapped area can be attributed to delineation errors. These are rather high values. Although maps of this scale (1:25000) are usually considered to be quite precise and provide a general overview as well as important details of regional soil conditions, assessments based on these maps should be regarded with caution and must be verified in the field. As initially assumed, a higher degree of generalisation introduces more multi-component soil polygons in the map. The usefulness of multiple-component mapping units for land-use management and environmental protection is limited. The proportion of multiple-component mapping units on the total area is 100% for a scale of 1:200000 and c. 15% for a scale of 1:5000. This means that the small scale map (1:200000) consists purely of complex polygons and therefore only of aggregated information.

The content of a soil map definitely depends on its scale although the map production approach for all scales is similar. At the smaller scales the maps represent 'larger' categories (representing a broad overview of soil properties) whereas middle and large scale maps have a higher level of detail of soil characteristics (but are much more costly to produce). Soil maps with a scale of 1:5000 are, of course, much more suited as a basis for spatial planning and decision-making concerning environmental and agricultural issues.

Uncertainties due to delineation and aggregated information are, non-negligible. The discussion of scale is important not only for scientific reasons, but also because of possible financial consequences, e.g. in the context of subsidies for less-favoured areas, soil reforms, compensation etc. With this study, we clearly demonstrate that scale is crucially relevant for soil maps. Our hypotheses and calculations concerning the error ranges of different map scales should be, however, further verified with field work (FOODY 2002). Our findings can serve the community working with soil maps in research and in practice by showing that scale has a strong impact at all stages of soil mapping.

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