Creating soil texture maps for precision liming using electrical resistivity and gamma ray mapping

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Abstract

This paper shows the first results of the EU-funded research project ‘pH-BB: Precision liming in Brandenburg’. The project aims to develop innovative solutions to adapt the current practice of pH management to the demands of a modern, resource-efficient and yield-optimized agricultural production. In the project, proximal soil sensors are used to rapidly generate high-resolution and cost-effective spatial datasets of soil parameters (i.e., soil pH, soil texture, soil organic matter) relevant for agricultural liming. Sensors include: (i) the Geophilus proximal soil sensing system to map apparent electrical resistivity (ERa) and natural soil-born gamma (γ) emissions, (ii) the Soil pH Manager (Veris Technologies) to measure the active soil acidity. The derivation of soil texture maps based on ERa and γ data and first results that are important for a precise liming application are presented in this paper.

Introduction

Liming is necessary for good nutrient availability and crop growth in acidic soils (Tunney et al. 2010). Acidification of soils is caused by natural processes (carbon, nitrogen and sulphur – C, N, S cycles) and human activities (Holland et al. 2018) and leads to a number of negative effects on yield, as for example shown in Goulding (2016).

A study by Zimmer & Ellmer (2012) showed that only 26% of 56,320 soil samples taken in the state of Brandenburg between 2006 and 2009 have an optimal pH value, while 38% were too low (acidic) and 36% were too high (alkaline). These numbers indicate that, at present, the lime management on farms in Brandenburg is not sufficient. The problems farmers are facing include high soil pH variability based on a high soil heterogeneity within field sites, expenses and time required for soil sampling, uncertainties concerning the interpretation of soil information and fertilization decision making as well as problems related to the availability and handling of appropriate fertilization technology.

Based on the official guidelines of the Association of German Agricultural Investigation and Research Institutions (VDLUFA) (von Wulffen et al. 2008), liming requirements are usually derived from 1 mixed soil sample per management unit of 3 ha. The mixed soil samples are tested for the current pH value and soil texture is derived by experts using a quick field texturing method. Based on this information, the liming requirement is defined by a look up table system for each management unit of 3 to 5 ha. However, this method implies several problems:

i. The average soil pH and soil texture as representation for the management unit neglect the variation of these parameters within the management units.
ii. The field texturing method is less accurate than a lab analysis on soil texture, which can lead to uncertainties in defining the target pH value.
iii. The soil texture classes in the VDLUFA system are rather coarse, distinguishing only 5 mineral soil texture classes and one class for peat soil, which can lead to unrealistic and severe differences in lime application recommendations of neighboring management units.

With respect to this and with regard to precision farming, farmers are confronted with the lack of high-resolution field maps of soil physical parameters as needed for decision support in acidity management. Publicly available soil information still does not reflect the small spatial variability of the soil properties present within the fields.

The European Innovation Partnership (EIP) AGRI funded project “pH-BB” aims to enhance soil acidity management on farms in Brandenburg. In the pH-BB project, mobile soil sensors are applied to enable fast and cost-effective assessments of soil parameters like texture (sand, silt, clay content), soil organic carbon (SOC), and current pH value at high spatial resolution.

Therefore, two mobile multi-sensor platforms were used:

i. Soil texture information were derived based on data of the Geophilus system which measures the electrical resistivity (ERa) at 6 depths up to 1.5m and the total counts of the natural gamma (γ) activity in the soil.
ii. The mobile sensor platform (MSP) manufactured by Veris technologies was used to spatially derive the current soil pH, with the soil pH Manager.

The aim of the present study was to develop a method that allows an easy and automated generation of top soil texture maps based on mobile soil sensing data, which furthermore can be used for a lime management that respects the natural soil variability in a high level of detail and improves the currently available best practice as described above.

Materials and methods

In the project pH-BB, the mobile sensor based soil mapping and precision liming approaches were tested in collaboration with three agricultural farms in Brandenburg. In 2017 and 2018, several fields have been mapped. For this paper, field 6 of Komturei Lietzen has been chosen as a representative example of the pH-BB procedure.

Study area

Field 6 of the Komturei Lietzen (E 52.451551, N 14.135066) is located about 50 km east of Berlin in the state of Brandenburg and has an area of 74 ha. Climatically, Brandenburg is located in the transition zone of the humid oceanic and the dry continental climates. The annual mean temperature is 9°C; minimum temperatures are reached in January and maximum temperatures in July. The mean annual precipitation sum is 550 mm. Soil genesis is strongly affected by different ice ages. The test site is located in the young moraine landscape of the Weichsel glaciation and soils in this area are commonly characterized by well-established sand layers over loam (clay leaching) over marl (MUGV 2011).

Applied Sensors

Most commonly used soil sensors map the bulk electrical conductivity (ECa), its reciprocal the electrical resistivity (ERa) or sample the soil's natural variation in γ activity. The soils ECa or ERa are affected by texture, water content, mineralogy, porosity, salinity, temperature, organic matter and bulk density (Corwin and Lesch 2005). The influence of the soils' current moisture content, which has on the one hand a strong influence on the soils' conductivity and resistivity, has on the other a very limited influence on the γ activity. Thus, a multiple sensor approach of ECa/ERa and γ measurements can improve the discrimination of different soil properties (Castrignanò et al. 2012) and may provide significant advantages when compared to other proximal soil sensing methods (Mahmood et al. 2013).

The applied experimental Geophilus-System (Lueck & Ruehlmann 2013; Fig. 1a) is a multiple sensor system that maps simultaneously the electrical resistivity (ERa) and the γ activity. It consists of seven rolling electrode pairs (one sending and six receiving) and measures the electrical resistivity in six layers from the soil surface up to a depth of 1.5 m. The attached γ probe measures soils γ activity (γ natural total counts) approximately in the upper 0.3m layer. The system logs the sensor values each second at a preferred speed of 10 km/h. A DGPS is used to geo-reference (incl. elevation) each logging.

The soil's current pH values were mapped using the *Soil pH Manager (MSP)* Veris technologies, (1925 Clay Ridge Ct. Salina KS USA). The pH values are derived from electrical voltage measurements of two ion selective antimony electrodes. A DGPS signal is logged to determine the exact measurement locations. Further information can be found in Schirrmann et al. (2011).

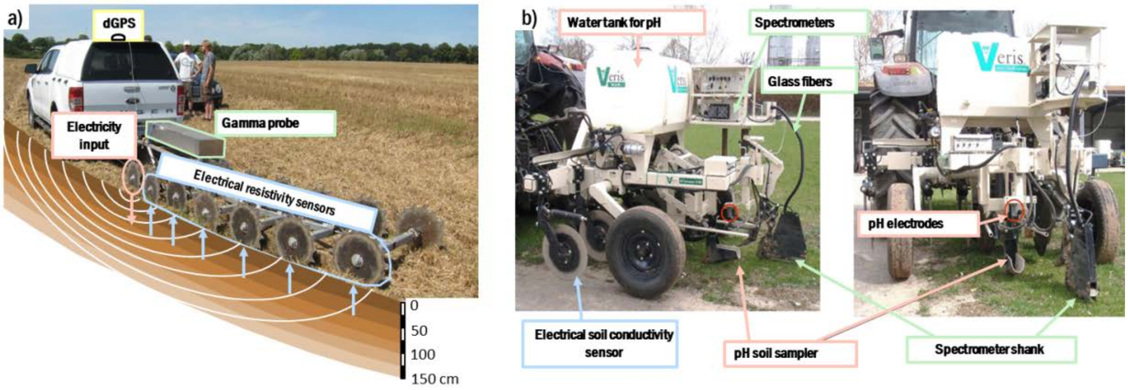

Figure 1. a) The Geophilus system with 7 rolling electrode pairs and γ probe b) *Mobile Sensor Platform (MSP) by Veris technologies* with pH-manager, *VIS-Nir spectrometer* and *OpticMappe*r (not shown).

Reference soil sampling

At 33 reference locations, soil samples (0-0.15 m depth) were taken and lab-analyzed for pH values, soil texture and soil organic carbon (SOC). Half of the sampling locations were chosen based on the pH mapping results and the other half based on the Geophilus mapping results. Reference samples were used to calibrate the MSP soil pH measurements and to regionalize soil textures using the Geophilus mapping results as covariables in multi-linear regression models.

Interpolation of ERa, γ and elevation data

The Geophilus system generates about 200 point measurements per hectare, which makes the interpolation with geostatistical methods like Kriging computationally very demanding and this method needs expert knowledge in the data preparation that farmers usually do nott have. Instead an inverse distance weighting (IDW) interpolation model (Shepard 1968) was applied to the mapped ERa, γ and elevation point data to generate raster datasets. This technique has been widely used in the past and is probably one of the oldest spatial prediction methods (Hengl 2009), it is computational less demanding and needs little expert knowledge. Raster datasets were created with a spatial resolution of 2 m for each parameter. Finally the dimensionless γ/ERa index **(**γEI**)** was calculated:

$$\gamma \mathrm{EI} = \gamma / ERa_{(\mathrm{Rho1})} * 1000 \qquad (1)$$

where γ is the γ raster dataset and $ERa_{(\mathrm{Rho1})}$ the electrical resistivity raster of the smallest dipol array with an exploration depth of about 0-0.25m.

The interpolated raster datasets were afterwards used as covariables for the regionalization of the soil textures.

Regionalization of soil textures

Raster values of the interpolated ERa, γ, γEI and elevation dataset were extracted at the reference locations of the 33 lab-analyzed soil samples, and values were added to the soil texture table. Based on this table, multi-linear regression (MLR) models were created, in a backward stepwise procedure. The prediction performance of applied MLR models was tested against the sampled soil physical properties. The model performance was assessed using a leave-one-out cross-validation (Isaaks & Srivastava 1989) and the accuracy of each model was determined by the root mean square error (RMSE).

The German KA5 soil texture classification system (Eckelmann et al. 2005) was applied to the raster datasets of clay, silt and sand content to create classified soil texture maps.

Regionalization of pH values

The mapped and calibrated soil pH values were regionalized using the Thiessen polygon method also known as the Voronoi diagram method. This regionalization method was applied and preferred over others like IDW or Kriging since extreme values fully remain within the regionalized result raster dataset. The extreme pH values are especially important for a precise acidity management that tries to improve the pH value at every location in the field towards its pH optimum.

Calculation of CaO amounts

The official German liming guideline of the VDLUFA (von Wulffen et al. 2008), is a look up table system that allows farmers to determine a optimum pH value based on the individual soil texture and organic matter (OM) classes present in the management unit. In comparison to the current pH status of the management unit, farmers can determine the application amount of CaO needed to change the pH-value towards the optimum.

In pH-BB this lookup table system was used in a slightly modified approach with an automated R script to calculate the CaO application amount for every pixel of the result raster data sets (Fig. 4 and 5). The modification implied the replacement of the soil texture and OM classes with clay and OM content.

Results

The field survey of the Geophilus-System and the Veris MSP was conducted at Field 6 on August 7th 2017. The interpolated mapping results are shown in Fig. 2a-d and Fig. 5a. The range in elevation is 18 m between the lowest point (66m) in the southeastern part and highest point in the southwestern part (84m) of the field (Fig. 2d).

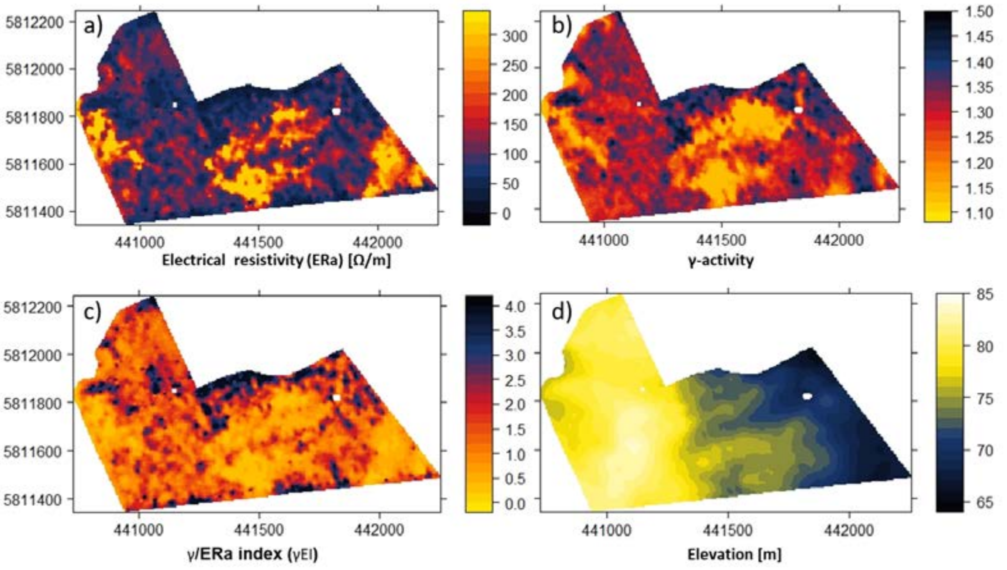

Figure 2. Mapping results of the Geophilus-System a), electrical resistivity of the first channel (Rho1; 0-0.25m) [Ω/m], b) γ activity, c) γ/Era index [dimensionless], d) digital elevation model [m] recorded with DGPS.

The yellow (bright) colored areas of the resistivity map > 300 Ω/m (Fig. 2a) represent very dry and/or very sandy areas while blue colors <50 Ω/m indicate areas with a high soil moisture content and/or high clay content. More or less corresponding to low-resistivity areas are the areas with a low γ activity (Fig. 2b). Differences between the patterns of the two maps can be explained by the different soil moisture sensitivity of the two sensors. As a result, the γ/ERa index map (Fig. 2c) may be interpreted as a soil moisture index map with yellow (bright) colored dry areas, blue (dark) colored moist areas and intermediate moisture in orange colored areas. The results of the 33 lab-analyzed soil samples (Fig. 3) show that sand is the dominating fraction with a mean of 74% and a range between 59 and 84%, while the clay content shows the lowest values with a mean of 5% and a range between 2 and17%. The silt fraction reaches values between 12 and 28% and a mean of 21%. Field 6 is characterized by a low SOC content with a mean of 0.82% and a range between 0.5 and 1.3%.

The derived multi-linear regression models in Eqs. 2-4 show a good relationship between covariables and the target variables with a good adjusted R^2 between 0.64-0.70.

Multi-linear regression equations:

$$Clay[\%] = -5.84 + (253.4 * \gamma\mathrm{EI}) + (0.11 * \mathrm{Elevation}) \tag{2}$$

adj. $R^2 = 0.64$; $\alpha = <0.001$; RMSE=1.94

$$Silt\ [\%] = -49.05 + (33.76 * \gamma + 0.035 * \mathrm{Elevation}\ ) \tag{3}$$

adj. $R^2 = 0.64$; $\alpha = <0.001$; RMSE=2.92

$$Sand\ [\%] = 116.00 + (-555.53 * \gamma\mathrm{EI}) + -0.46 * \mathrm{Elevation}) \tag{4}$$

adj. $R^2=0.70$; $\alpha = <0.001$, RMSE=3.7
where α is the significance level.

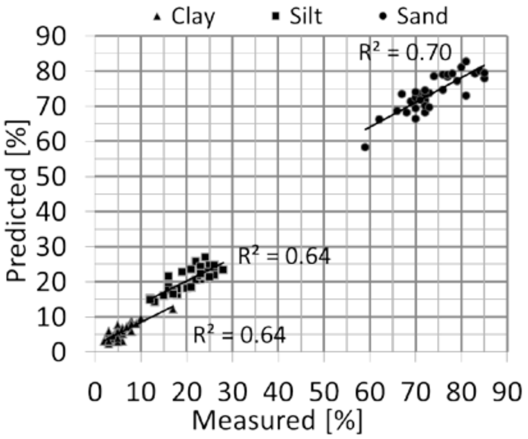

Figure 3. Scatterplots of the lab-analyzed reference soil texture samples and the predicted soil texture fractions clay, silt and sand.

The RMSE is low for all fractions with values of 1.9 (clay), 2.9 (silt) and 3.7 (sand) and indicate a good prediction performance of the models. Derived regression models were afterwards applied on the interpolated Geophilus raster datasets and soil texture fraction were predicted for the entire field (Fig. 4).

The predicted spatially distributed soil texture maps and the location of the 33 reference points are shown in Figure 4a-c with the same color range. The points are in good correspondence with the predicted soil texture maps. At the moment, the number of reference samples taken for the soil texture prediction is very high.

The project aims to reduce this number to a maximum of 5 reference samples, while keeping reliable prediction accuracy. The classified soil texture map in Figure 4d shows that the classes according to German KA5 system slightly silty sand (Su2) and slightly loamy sand (Sl2) cover the widest area of the field. The distribution of the class medium loamy sand (Sl3) is patchy but especially in the northern center and in the northwestern part bigger areas of this class can be identified. The classes of highly loamy sand (Sl4) and medium silty sand (Su3) are only visible in tiny patches of <0.03ha.

The calibrated and interpolated pH values of the Veris MSP mapping are shown in Fig. 5a. The results of the soil texture and pH mapping now allow different approaches to calculate liming recommendations.

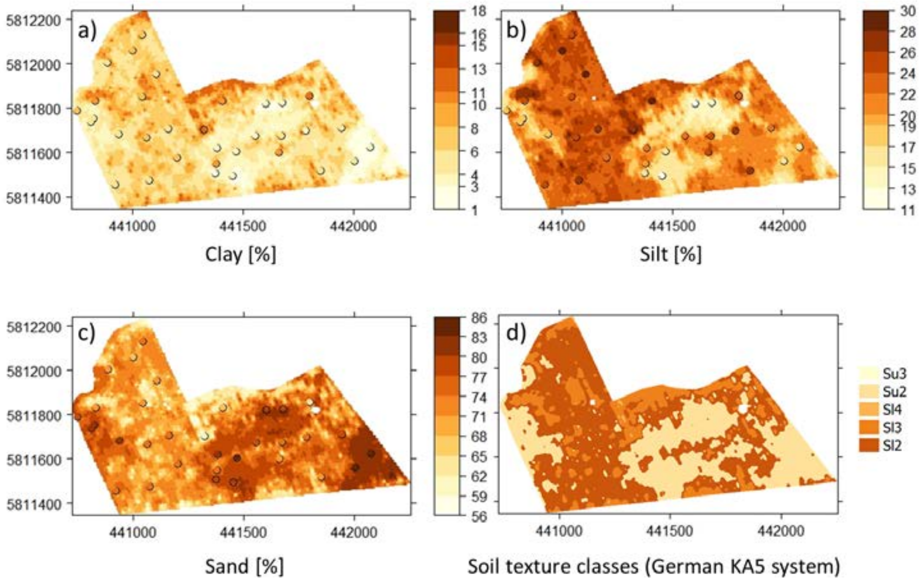

Figure 4. Predicted soil texture with reference soil sampling points, a) clay content [%], b) silt content [%], c) sand silt content [%], d) soil texture classes after the German KA5 system.

Figure 5b shows the final CaO application amounts calculated based on the soil texture in Figure 4 and the current soil pH value in Figure 5a (at OM < 4 % assumed). CaO data was aggregated on a 12*40m polygon raster in management direction (Fig. 5b). Based on the CaO application map (Fig. 5b) precise liming was applied with Granukal® lime using an AMAZONE ZA-TS with Amatron terminal on April 9th 2018.

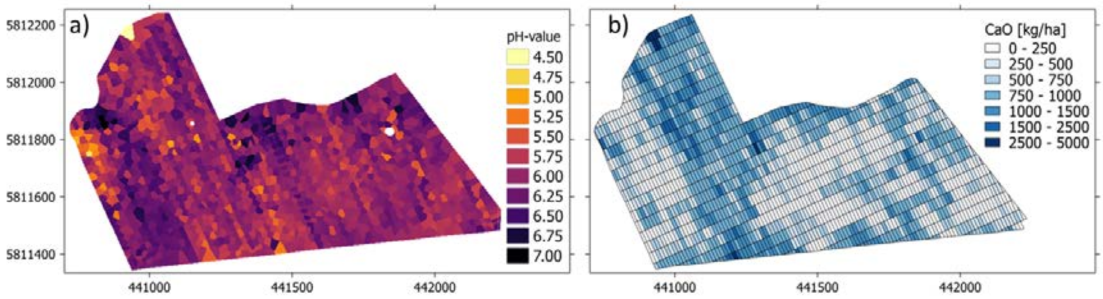

Figure 5. a) MSP mapped pH values and b) the CaO application amounts calculated for field 6 of Komturei Lietzen based on soil texture (Fig 4) and pH (Fig 5a) derived from proximal sensor data and aggregated to 12m x 40m management units.

Conclusions

This paper shows how mobile sensor data of the Geophilus system together with mobile soil pH measurements of the Veris MSP system can be used to acquire spatially distributed precise soil texture and soil acidity maps. The developed regression models allow a soil texture prediction based on ERa and γ data with a high accuracy (RMSE< 3.7) for all soil texture fractions. Therefore, these data can be used to calculate liming requirements that respect small scale soil and pH variabilities. The success of the precise liming will be controlled by repeated MSP pH mapping in the ongoing project.

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