ECONOMICS OF SITE SPECIFIC LIMING - COMPARISON OF ON-THE-GO AND GRID-BASED SOIL SAMPLING TO DETERMINE THE SOIL PH

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ABSTRACT

An important basis for adequate liming is the recording of the soil pH. Several studies indicated a large heterogeneity of soil pH within fields. Recent technological improvements facilitate an on-the-go determination of the soil pH in a much higher sampling density compared to the conventional, time-consuming and costly laboratory method. The Veris Soil pH Sensor allows georeferenced on-the-go mapping of the soil pH. However, the Veris Soil pH Sensor and the widely accepted laboratory method differ in their measuring principles. Hence, it is necessary to adjust the results of the pH sensor to the results of the laboratory method.
The economic potential of high resolution soil sampling strategies compared to the conventional soil sampling strategies is determined by four effects: the costs of applying the technology, the cost savings resulting from the reduction of over-fertilisation, the improved exploitation of phosphate (which will become plant-available due to small scale pH management) and the expected increase in yield (and thus revenues) resulting from a better lime distribution. To quantify the four effects, on-farm experiments were carried out, and the results of which are presented. In the on-farm field trials four different soil sampling approaches were compared: (1) one-ha fixed grid, (2) five-ha fixed grid, (3) “intelligent” apparent electrical conductivity homogenous sampling zones, (4) high resolution soil sampling. The impact of the four approaches on profitability was calculated for a six-year crop rotation. The costs of the technology, the cost savings resulting from the reduction of over-fertilisation and the improved exploitation of phosphate occur only once within the six years. The expected yield effects, however, must be taken into consideration six times within the crop rotation.
The analysis of the field trials shows that sampling density is crucial for the reduction of oversupplied and undersupplied zones. According to the conventional sampling method (5-ha fixed grid), approx. 32 % of the area was over-fertilized and approx. 38 % under-fertilized. The “intelligent” soil sampling showed similar results. The reduction of over-fertilisation was equal to a value of approx. 20 € ha^{-1}, which can be saved or better distributed. An improved lime distribution resulting from high resolution soil sampling increases the amount of

plant-available phosphate and leads to an increase in yield. Corresponding savings amount to approx. 32 € ha^{-1} for the phosphate which must not be applied. The increase in yield generates increased revenues of approx. 15 € ha^{-1} (annually). The costs for applying technology add up to 20 € ha^{-1} for the pH sensor, whilst the conventional procedures (fixed grids) cause costs between 2 and 13 € ha^{-1}. In short, the field trials indicate an annual economic advantage of 15 – 30 € ha^{-1} of the high-resolution soil sampling compared to conventional soil sampling.

Keywords: precision agriculture, Veris-MSP, economic comparison, soil pH, on-the-go soil sampling, site specific liming

INTRODUCTION

An important basis for lime fertilisation is the knowledge of the existing soil pH. Several studies have shown that the soil pH can vary greatly on a small scale (Bianchini and Mallarino, 2002; Lauzon et al. 2005). With the development of sensors (e.g. the Veris-MSP (Lund et al., 2004)) it has become possible to determine the pH value cheaply in a much higher sampling density than with the time and cost intensive laboratory method. Both methods differ in their measurement principles. The results of the pH sensor must be adjusted to the results of the laboratory method. Then it is no problem to compute lime doses by means of well-introduced fertilizing rules ("code of good practice"). A suitable algorithm for the calibration of the on-the-go recorded soil pH data has been evaluated and presented by the authors (Leithold et al., 2012).

With the high-resolution soil pH map it is possible to carry out site-specific lime fertilisation of a field in order to establish a uniform optimal soil pH. In contrast to this, lime fertilization using conventional sampling methods would lead to sub-fields being oversupplied or undersupplied. The expected agronomic effects of variable rate liming in contrast to uniform liming were evaluated for a simulated trial period of six years.

MATERIALS AND METHODS

The investigation of high-resolution soil sampling was carried out using the Veris-MSP pH Manager on three fields (see table 1). The measurement principle is based on the removal of a soil sample, which is then analyzed online through two pH sensitive electrodes within a few seconds to obtain the pH value (Lund et al., 2004). The interpolated soil pH maps (according to the pH sensor) then serve as the basis of the simulated soil sampling.

Table 1. Description of the experimental sites

Field	1	2	3
Size (ha)	45.31	28.08	116.27
longitude/	11.046278/	12.467478/	11.948912/
latitude	51.775511	50.764906	51.619575
Textural class[1]	Silt loam	Sandy loam	Silt loam
Date of soil sampling	16.9.2011	24.7.2011	20.9.2011
Crop 2011	Winter wheat	Winter barley	Winter wheat

[1] (FAO, 2006)

Conventional soil sampling was computed in fixed 1-ha and 5-ha grids as well as according to homogeneous apparent electrical soil conductivity zones (EC_a). For the simulation, we used ArcGIS (Esri, 2009). The apparent electrical conductivity of the soil was recorded with a frequency of 1 Hz during the soil pH measurements by the Veris-MSP. For each of the three variants (1-ha grid, 5-ha grid and homogenous electrical conductivity zones) a sampling pathway was determined. Then the 15 nearest probes along this sampling pathway were combined as a mixed sample to compute the average soil pH of the grids and the zones respectively. Finally, the results of the four variants

- high-resolution soil mapping
- 1-ha grid soil mapping
- 5-ha grid soil mapping and
- soil mapping according to homogenous EC_a zones

were compared using the following four parameters:

- procedural costs
- incorrectly allocated liming costs
- exploitation of the phosphate effect and
- the expected effects on yield.

Procedural costs

The procedural costs include the costs for taking and analyzing the soil samples. Furthermore, the procedural costs also include the costs for the procurement and preparation of the data of the apparent electrical conductivity of the soil.

Incorrectly allocated liming costs

The incorrectly allocated liming costs were calculated as the difference between the optimally distributed liming application map according to the pH sensor and the liming application map of the conventional methods. The decision rules of the VDLUFA are used (von Wulffen et al., 2000) in order to create the liming application maps. The over-fertilized amount of lime is multiplied by the lime price and results in the incorrectly allocated liming costs.

Exploitation of the phosphate effect

Kerschberger (1987) developed a rule of thumb from long-term lime fertilization trials; describing the interaction between the soil pH and the phosphate solubility available to plants in the soil. It states that with an increase in the soil pH of one pH unit, phosphate solubility increases by 1 mg P per 100 g of soil. In order to obtain a comparable increase of the phosphate content with mineral fertilization, a fertilization of 100 kg P ha^{-1} would be necessary. The rule of thumb is only true for the suboptimal soil pH area, which depends on soil texture and humus content.

Due to the varying informational density of the sampling methods investigated, different results can occur in the spatial distribution of the soil pH. As a result, the liming application maps differ in that the expected soil pH development in the fertilization planning period progresses differently according to the sampling method. The following assumptions are made for this:

1. Fertilization period: 6 years
2. Fertilizer application once in the first year
3. Complete conversion of the lime fertilizer: 2 years
4. Annual pH-change through external influences such as soil acidification, acidifying fertilizer, nutrient removal: - 0.1 pH-units (Rowell, 1997)
5. Price of lime: 21.33 € CaO^{-1} t^{-1} (AMI, 2010 – 2013)
6. Price of phosphate: 434.22 € P^{-1} t^{-1} (AMI, 2010 – 2013)

Figure 1 shows the temporal course of the soil pH with liming and with no liming based on assumptions 3 and 4.

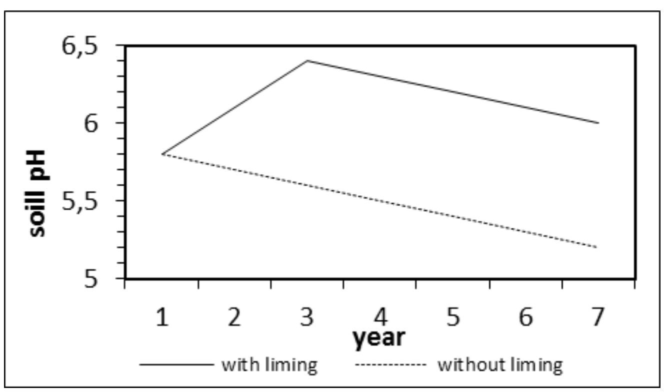

Figure 1. Temporal development of the pH value with/without influence of liming

The expected effects on yield

The different developments of the expected temporal pH values can occur suboptimally such that yield depressions must be expected. It is also known that crops have different lime requirements. A differentiation is made between high and low lime-demanding crops (Schilling, 2000). The literature analysis of long-term lime fertilization trials leads to no clear yield-soil pH relationships within the high and low lime-demanding crops. There are trials with less strong effects on yield (Cifu et al., 2004, Merbach et al., 1999, Pagani et al., 2009) as well as trials with a strong effect on yield (Cifu et al., 2004, Liu et al., 2004). A scenario calculation is suitable for this type of vaguely defined parameters, which spans an expected range for the economic evaluation from a worst-case scenario up to a best-case scenario. In figure 2, the dotted lines show the boundaries of the worst-case and best-case scenarios.

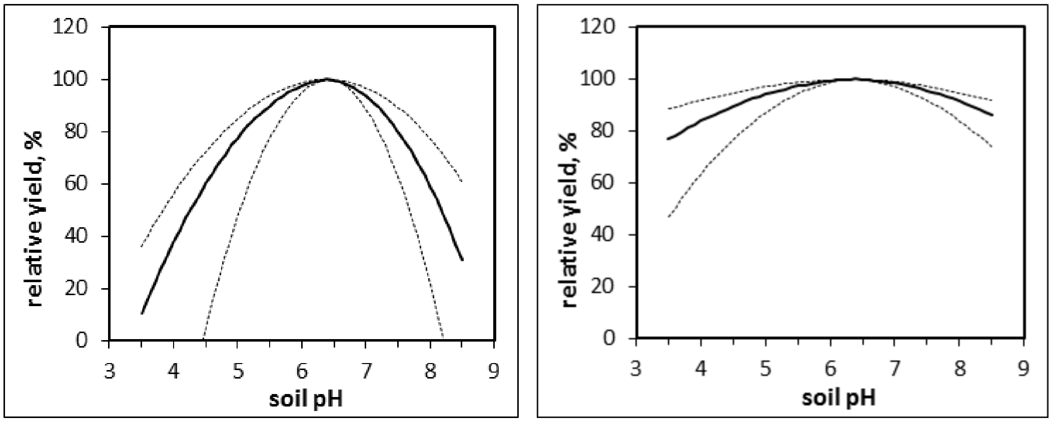

Figure 2. Average expected relative yield and boundaries of the relative yields for high lime-demanding (left) and low lime-demanding (right) crops

The following crop rotation is assumed for all trial fields for the scenario calculations, the expected yields and the respective product prices of the crops are shown in table 2:

sugar beet – winter wheat – winter barley – canola – winter rye – summer barley.

Table 2. Expected yields and product prices considering the locational characteristics

	Expected yield[1] ($t\ ha^{-1}$)		Product prize (€ t^{-1})
crops	field 1	fields 2, 3	(3 years average)
Summer barley	5,00	6,50	19,89[2]
Winter barley	6,50	8,50	15,69[2]
Canola	3,80	4,50	34,94[2]
Winter rye	7,00	9,00	19,17[2]
Winter wheat	7,00	8,50	18,45[2]
Sugar beet	60,00	70,0	4,40[3,4,5]

Sources: [1] Personal interviews with the farm manager, [2] Hamm et al. (2013), [3] Beil (2010), [4] Beil (2011), [5] Beil (2012)

For the economic evaluation the procedural costs and the incorrectly allocated liming costs can be seen as **costs**. The exploitation of the phosphate effect and the expected yield depressions do not express costs per se, but should be interpreted as **lost income**. The farm manager expects a yield from the crops sown that cannot be realized, however, due to the suboptimal soil pH distribution.

RESULTS

With an increasing sampling density, the understanding of the "true" spatial soil pH distribution increases. Even clearer pH differences can be observed within 1-ha parcels through the much higher sampling density of the pH sensor. The comparison of the resulting lime application maps of the sampling procedure shows that ca. 12 – 26 % of the lime fertilizer used could have been saved or better distributed on other places within the fields. According to the sampling methods investigated, an over- or under-fertilization of lime occurred on ca. 70 % of the areas (table 3).

Table 3. General results of the sampling methods investigated

	site	Veris-MSP	1-ha-grid	5-ha-grid	EC_a-grid
Sampling density ($n\ ha^{-1}$)	1	15.80	0.84	0.22	0.53
	2	21.41	1.18	0.21	0.50
	3	14.62	1.01	0.23	0.46
pH_{MEAN} (pH_{MIN} / pH_{MAX})	1	6.45 (4.99/7.25)	6.48 (5.28/7.17)	6.43 (5.82/6.88)	6.45 (5.51/7.08)
	2	5.57 (4.23/6.38)	5.63 (5.30/6.20)	5.58 (5.41/5.85)	5.67 (5.46/5.90)
	3	5.99 (4.81/7.53)	5.99 (5.25/7.01)	6.01 (5.65/6.80)	5.99 (5.37/7.11)
recommended amount of lime (CaO t)	1	62.13	46.49	50.11	50.97
	2	46.39	43.61	47.72	37.40
	3	365.14	361.33	337.29	368.34
over-fertilized amount of lime (CaO t)	1	0.00	7.67	16.32	14.14
	2	0.00	8.40	12.18	6.02
	3	0.00	57.28	57.19	66.16

The soil pH map for field 1 generated by the measurements of the Veris-MSP is presented in figure 3. The interpolated map is based on the soil pH of 720 sampling points (~16 sampling points ha^{-1}). The variation of the soil pH is considerably high, even within short distances. At the first glimpse, it becomes clear, that a more roughly fixed grid sampling cannot reflect those differences of the soil pH. The fixed grid sampling hits the "true" mean soil pH of the Veris-MSP pretty well, but is not able to reproduce the whole range of the "true" measurements by the Veris-MSP (table 3, pH_{MEAN} and pH_{MIN} / pH_{MAX}).

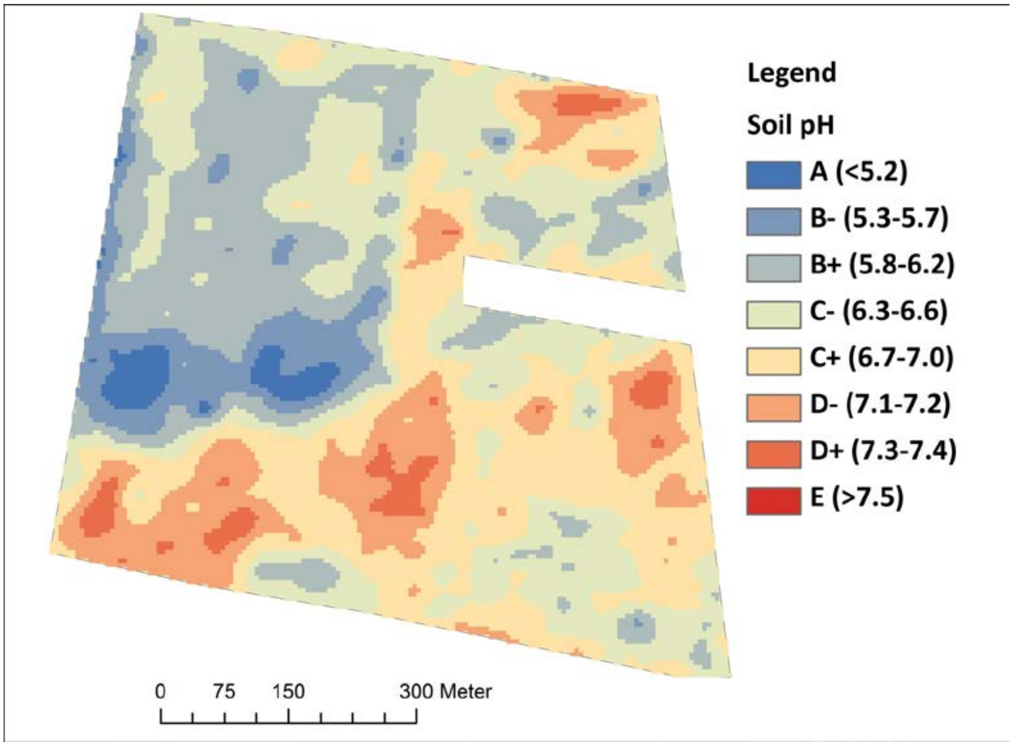

Figure 3. Soil pH map for field 1 generated by the measurements of the Veris-MSP (interpolated, 720 sampling points)

The result of the economic evaluation according to the four criteria mentioned above is shown in figure 4. All values are based on the annual costs or the annual lost profits of the sampling methods. The pH sensor shows the highest procedural costs, which, however, turn out to be very low with an annual sum of 3.33 € ha^{-1}. Through the optimal distribution of lime, no areas are supplied with too much or too little lime, so that no misallocated lime costs occur. Similarly, the phosphate effect is completely exploited through the optimal lime distribution and no mineral compensatory fertilization is necessary, unlike in the other sampling methods.

Despite the optimally distributed amount of lime, yield depressions must be expected for the pH sensor. The reasons for this are, on the one hand, a poor nutrient supply of the current state during sampling, which was first remedied after two years through the complete implementation of the lime fertilization. On the other hand, falling soil pH are to be expected through natural soil acidification and through other soil acidifying factors, which can lead to suboptimal soil pH in the simulated investigation period of six years. The average annual expected yield depression amounts to about 17 to 19 € ha^{-1} y^{-1} for the pH sensor; this is equal to 85 % of the total costs. Overall, the sum of the annual costs and the lost profits amounts to 20 € ha^{-1} y^{-1} to 23 € ha^{-1} y^{-1} for the pH sensor for all the locations.

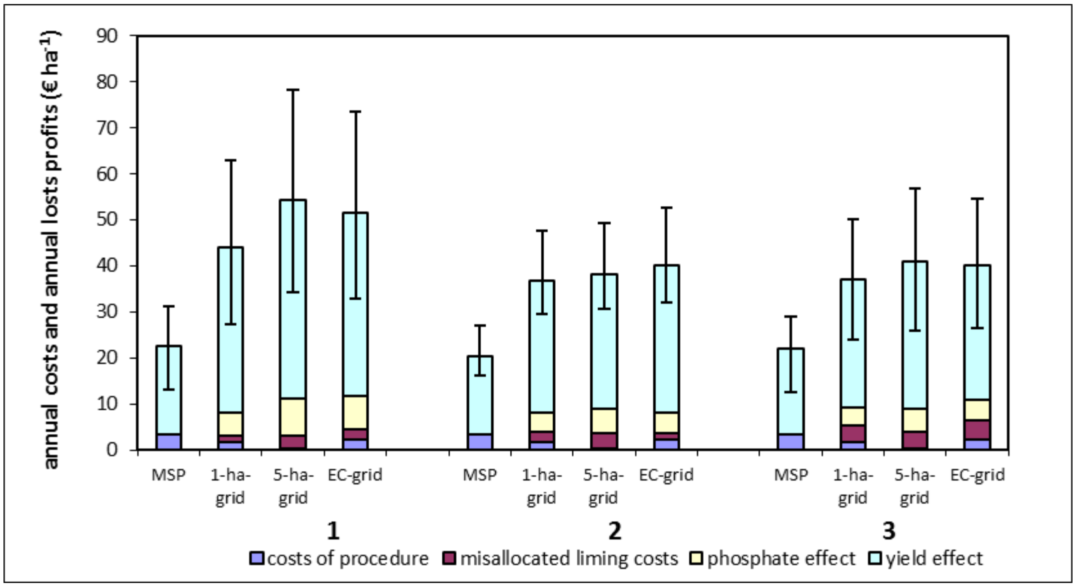

Figure 4. Annual costs and annual lost profits of the sampling methods (boundaries of the yield effect portray the worst-case and best-case scenarios respectively).

Small-scale soil pH heterogeneities are lost through the low sampling density of conventional sampling methods. Despite lower annual procedural costs (0.38 € ha^{-1} y^{-1} to 2.18 € ha^{-1} y^{-1}), the negative effects of the lower sampling density prevail. The largest proportion is borne by the average expected yield depressions with ca. 73 % to 82 % or 31 € ha^{-1} y^{-1} to 35 € ha^{-1} y^{-1}. Annual sums of between 1 € ha^{-1} y^{-1} to 5 € ha^{-1} y^{-1} occur for the incorrectly allocated liming costs, whilst the lost profits of the phosphate effect lie between 4 € ha^{-1} y^{-1} and 8 € ha^{-1} y^{-1}.

No positive economic effects can be achieved with the approach of delineating homogeneous conductivity zones for nutrient homogenous zones compared to the strict grids.

The economic comparison between the high-resolution soil sampling with the pH sensor and the conventional sampling method leads to an annual total potential of 17 € ha^{-1} y^{-1} to 22 € ha^{-1} y^{-1} for the use of the Veris MSP.

DISCUSSION

Adamchuk et al. (2004), Ericksen (2004) and Olfs et al. (2012) report on the positive economic effects of the use of the Veris-MSP, the economic potential of which lies in a region of between 5 to 10 € ha^{-1} y^{-1}. The economic evaluation of the named working groups is based on the procedural costs, the liming costs and the expected increase in yield. The interaction between the soil pH and phosphate availability was not taken into account.

The results presented are based on a model in which the yield is only dependent on the soil pH. It is known, however, that on the one hand the yield is dependent on several factors and that interactions between the factors must be taken into account. On the other hand, interactions do not only exist between the soil pH and phosphate availability, but also between the soil pH and other pH dependent nutrient availabilities, e.g. Cu, Zn and Mn (Rengel, 2002). Thus the presented simulated economic evaluation shows a range of results which, taking into account other complementary effects, for instance in micro-nutrient fertilization, could lead to an even higher economic potential than presented in this study.

Targeted soil sampling on the basis of homogenous zones according to the apparent electrical conductivity of the soil (Corwin and Plant, 2005) does not provide an alternative on the trial fields under investigation in comparison to the conventional fixed grid. The higher sampling density of the 1-ha grid leads to a much higher gain in information than the EC_a grid.

CONCLUSIONS

With a high-resolution, sensor-based soil pH measurement, notable economic advantages of variable-rate technology can be expected. A much higher density of information is characteristic of this technology, which is able to reveal small-scale soil pH heterogeneities. The profitability of a higher density of information does not reflect so much on the savings in fertilizer but rather on increased yields and a better utilisation of the interaction between the soil pH and phosphate availability.

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