# Variable-rate-fertilization of phosphorus and lime – economic effects and maximum allowed costs for small-scale soil analysis

**Soeren Schulte-Ostermann, Peter Wagner**

Martin-Luther-University Halle-Wittenberg, Institute for Agricultural Economics, Karl-Freiherr-von-Fritsch-Steet 4, 06099 Halle (Saale), Germany

**A paper from the Proceedings of the**
**14th International Conference on Precision Agriculture**
**June 24 – June 27, 2018**
**Montreal, Quebec, Canada**

---

The authors are solely responsible for the content of this paper, which is not a refereed publication.. Citation of this work should state that it is from the Proceedings of the 14th International Conference on Precision Agriculture. Schulte-Ostermann, S. & Wagner, P. (2018). Variable-rate-fertilization of phosphorus and lime – economic effects and maximum allowed costs for small-scale soil analysis. In Proceedings of the 14th International Conference on Precision Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture.

**Abstract.** *The pH values and macro nutrient contents are characterised by considerable variance within a field. A constant-rate-fertilization, which is practiced at most farms, does not reduce this effect, it may even boost variance. Besides the suboptimal nutrient supply, the site-specific yield potential is not exploited. Constant-rate-fertilization and liming results in an inefficient utilisation by over- and undersupply of most of the areas within a field. Fertilization with lime and phosphorus causes high costs and therefore solution concepts should be adapted continuously to increase efficiency. In this context, high-resolution soil information is essential to develop an ideal fertilization strategy. Results could justify costs for small-scale soil analyses and identify break-even for information acquisition. The analysis, presented in this paper, is based on long-term data within the scope of "on-farm-research". The constant fertilization strategy reveals a suboptimal application of resources, which generates unnecessary costs and does not exhaust yield potential. However, this does not mean that in the short-term a variable-rate-fertilization is less cost intensive. Though in the long-term view, possibly higher costs are legitimated due to higher yields. After achieving sufficient nutrient contents in undersupplied zones, these costs will no longer incurred in the future and an ideal nutrient level will be achieved. At the end, the whole potential of each field can be exploited in the context of nutrient supply and yield. To sum it up, the paper demonstrates maximum allowable costs of a detailed / small-scale soil analysis. This is compared with negative effects of a constant-rate-fertilization.*

**Keywords.** *Precision Farming, Economic Efficiency, Macro Nutrients, Soil Analysis, Break-Even*

# Introduction

Over the next years the world population will significantly increase. Changing food demand with rising amount of meat and climate change make it difficult to secure food supplies. Nevertheless, the agricultural sector - farmers - has to ensure food safety and maximize productivity (Foley et al., 2011; Godfray et al., 2010; Tilman, 1999). In this context high-level yield locations need exploit potential. Precision farming strategies may provide a contribution to increase efficiency.

Small-scale soil analysis can identify a high nutrient-content heterogeneity in fields, amplifying the significance of site-specific fertilization. In Germany, many farmers apply constant rates of fertilizers, which may even boost negative effects. However, current practice of constant-rate-fertilization increases waste of resources and the yield potential is not exploited. An increased yield level would maximize profitability and may justify costs of detailed soil data acquisition. Furthermore, European legislation forces farmers to reconsider common fertilization strategies.

In addition, agriculture has formidable challenges in order to obtain higher yields and reduce environmental impacts. New technologies offer possibilities to improve effectiveness and exploit the yield potential (Auernhammer, 2001; Foley et al., 2011; Tilman, 1999). In this context, research has to address this issue and needs to reveal opportunities (Eastwood, Klerkx, & Nettle, 2017). With regard to lime and phosphorus application, basic need is an investigation in appropriate VRF experimental designs and continuous cost-intensive analytics. Variable-rate-fertilization (VRF) may be an approach to meet the increasing challenges.

The application of constant rates may even raise variance in the long-term for zones of high nutrient contents. In result, they are constantly oversupplied in contrast to the enduring zones of low nutrient content. At the start of the current project more than 65 % of the test field grids where over- or undersupplied with phosphorus in 2006. This indicates a high significance of the problem and the need for detailed field information.

Objectives of this study is long-term data collection to demonstrate costs, benefits and chances of new technologies (VRF, sensors) within the scope of on-farm-research (OFR). This economic analysis reveals the difference between a variable- and a constant-rate-fertilization. The detailed soil analysis demonstrates effects of the various fertilization strategies over time. Building on this, changes and development of fertilization costs are documented and results are outlined in comparison.

Furthermore, positive effects may outweigh high costs of analysis. VRF offers new opportunities to improve site-specific fertilization. Moreover, new machinery facilitates farmers participation at VRF and precision farming service providers improve machinery data exchange. The integration of measurement output in decision support systems is essential to encourage farmers for application (Daberkow & McBride, 2003; Gebbers & Adamchuk, 2010). However, in the future new innovative sensor technologies are required to provide affordable small-scale soil information, which is the basis for this comprehensive solution.

## Materials and methods

This analysis demonstrates effects of a long-term on-farm-research (OFR) project. In 2006 a practical experimental design has been adapted to a 65 hectare field in Goerzig, Sachsen-Anhalt. The design is conducted to the available machinery at the farm and therefore a 36 x 36 m (0,1296 ha) grid system (n = 508) has been adapted. Furthermore, the field is divided into three different strategies focusing on basal fertilization (Figure 1). The variable-rate-fertilization strategy concludes 159 grids, the constant-rate-fertilization 142 grids and the untreated strategy 147 grids. Besides, 60 critical boundary grids are excluded from analysis.

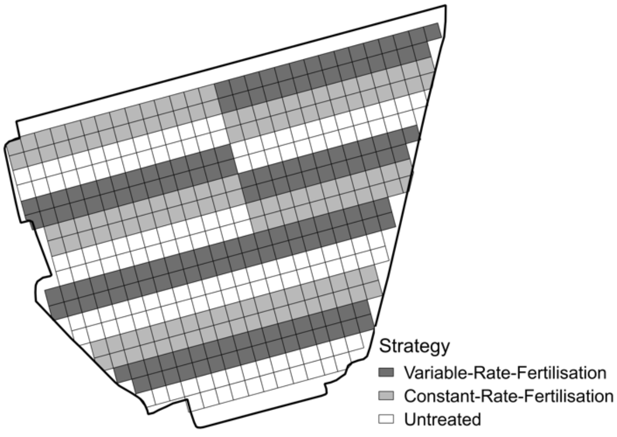


**Figure 1. Experimental design**

During the experimental period comprehensive soil analysis are implemented in 2006, 2011, 2015, 2016 and 2017 and in this study soil analysis of 2006, 2011 and 2017 are considered. Reliable and well-known methods (e.g. CAL-method for P-content measurements) for soil analysis are used for this experiment and therefore results are comparable over the years.

VDLUFA guidelines (Table 1) are the basis for measured phosphorus -classification 2015- and pH-values classification (VDLUFA, 2015; Wulffen et al., 2008). These classifications rest on many long-term field trials at different locations in Germany. Results enable conclusions about the ideal nutrient supply and take nutrient / pH levels in soil into account.

**Table 1. pH classification (Wulffen et al. 2008) and phosphorus classification (VDLUFA 2015)**

| Class | pH $CaCl_2$ | Phosphorus mg CAL-P / 100 g soil |
|---|---|---|
| A | <= 5,2 | < 1,5 |
| B | 5,3 - 6,2 | 1,5 - 3,0 |
| C | 6,3 - 7,0 | 3,0 - 6,0 |
| D | 7,1 - 7,4 | 6,0 - 12,0 |
| E | > = 7,5 | > 12,0 |

Calculations are related to a typical four varied crop rotation in Sachsen-Anhalt (middle of Germany) and the average yield is based on long-term experience at this location (Table 2). The presented figures represent the average phosphorus removal per annum of a four years planning period. Operating costs and discounting are not considered.

**Table 2. Crop rotation (assumptions)**

| Crop-Rotation | Yield dt/ha | Removal kg/dt | Phosporus Removal kg |
|---|---|---|---|
| Winter-Wheat I | 87 | 0,35 | 30,39 |
| Winter-Wheat II | 80 | 0,35 | 27,95 |
| Winter-Barley | 81 | 0,35 | 28,30 |
| Winter-Oilseed Rape | 40 | 0,79 | 31,44 |
| **Average of expected nutrient removal** | | | **29,52** |

A small-scale yield mapping system is the basis of yield effects calculation. Crop prices constitute on five-years average. Due to this, the assumed winter-wheat price is 17,62 €/dt, winter-barley 16,01 €/dt and winter-oilseed-rape 40 €/dt.

The assumed yield effects based on the particular phosphorus- and lime (pH) - supply represent a single nutrient approach with no interactions between them and other nutrients.

*Liming*

The VRF (variable-rate-fertilization) examines the individual pH value of each grid and, based on this, the recommended lime quantity is calculated. Moreover, soil type and humus layer are important for recommendations. The guideline classifies pH-value in five different classes and every pH-value requires a different CaO amount. This strategy is based on the small-scale data and lime is optimally applied according to the observed pH of each grid. Higher content classes (D, E) are oversupplied and no fertilizer will be applied anymore (LVLF, 2009; Wulffen et al., 2008).

In contrast, CRF (constant-rate-fertilization) strategy does not examine the individual pH-value of each grid. The pH mean of all grids within the CRF-treatment determines lime quantity.

This research assumes factor costs for the relevant elements of lime - CaO with 0,05 €/kg.

*Phosphorus*

The site-specific phosphorus application is combined with nutrient levels in soil and the presumed nutrient removal of crop rotation (Table 2). The VDLUFA classifies phosphorus contents in five different groups (Table 1) and an individual fertilization strategy is applied. For instance, the guideline recommends phosphorus fertilization in class “A” with 100 % more than the removal by yield and in class “B” with 50 % more than removal. In comparison, the guideline recommends no fertilizer in level “E” (VDLUFA, 2015).

However, CRF (constant-rate-fertilization) strategy does not consider the individual phosphorus content of each grid. The phosphorus content mean of all grids within the CRF-treatment determines phosphorus quantity.

This research assumes factor costs for phosphorus of 1,43 €/kg P. This is related to the available Triplesuperphosphat with an amount of 46 % $P_2O_5$ (20,07 % P).

# Results

## Coefficient of variation

Table 3 illustrates that the VRF results in a decreasing coefficient of variation (VK) with regard to soil-P-content and pH. After a period of five years, the VRF achieves a more balanced phosphorus supply and pH values. In particular, site-specific-fertilization reduces differences of nutrient contents/pH between grids. For instance, the pH VK in VRF grids decreased 43 %. Contents of phosphorus in soil is changing slower, than the pH-values in all strategies. Furthermore, VK of phosphorus increases from 2006 to 2011 in the CRF. For instance, the CRF also reduces effects of different nutrient contents/pH, but does not perform on the same level than VRF. Increasing variability of phosphorus contents characterize the untreated strategy. The development of contents -VRF and CRF- are shown in the appendix, Figure 3 and Figure 4.

**Table 3. Development of coefficient of variation between three strategies**

| | pH | | | Phosphorus | | |
|---|---|---|---|---|---|---|
| **Strategy** | **Coefficient of Variation** | | | **Coefficient of Variation** | | |
| | **2006** | **2011** | **2017** | **2006** | **2011** | **2017** |
| **Variable** | 0,076 | 0,046 | 0,033 | 0,471 | 0,442 | 0,342 |
| **Constant** | 0,083 | 0,059 | 0,045 | 0,534 | 0,616 | 0,468 |
| **Untreated** | 0,072 | 0,079 | 0,067 | 0,451 | 0,571 | 0,570 |

## pH – CaO

The attached tables demonstrate the development of lime fertilization costs over the period from 2006, 2011 and 2017. The average pH value of all grids is shown in the first row of the table. The last row of the table demonstrates the fertilizer amount and the related average costs of each strategy.

Calculation, based on soil analysis 2006, exhibits that most of CRF and VRF fertilization grids are undersupplied with lime. Table 4 illustrates, that there are 76 % (n = 108 / 142) of undersupplied grids in the CRF strategy with an area of 14 hectares (ha). The total 142 grids are characterized by an average pH of 5,9. Therefore, 900 kg/ha CaO have been applied at the CRF strategy. This generates costs of 43,55 €/ha. The quantity of fertilizer in VRF, using small-scale soil information, is 22 % higher than in the CRF. This generates higher average costs of 9,55 €/ha related to this experimental design.

**Table 4. Comparison of a constant- and variable-rate-fertilization of lime, based on soil analysis 2006**

| **pH - CaO** | | | Ø pH 5,9 | | | | Ø pH 5,8 | | |
|---|---|---|---|---|---|---|---|---|---|
| **2006** | **Grids CRF** | | **Constant-Rate-Fertilization** | | **Grids VRF** | | **Variable-Rate-Fertilization** | | *Difference* |
| | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *VRF - CRF* |
| *Class* | *n* | *ha* | *kg/ha CaO* | *€/ha* | *n* | *ha* | *kg/ha CaO* | *€/ha* | *€/ha* |
| A | 9 | 1,17 | 900,00 | 43,55 | 13 | 1,68 | 1911,54 | 92,49 | 48,95 |
| B | 99 | 12,83 | 900,00 | 43,55 | 128 | 16,59 | 1119,14 | 54,15 | 10,60 |
| C | 31 | 4,02 | 900,00 | 43,55 | 15 | 1,94 | 425,00 | 20,56 | -22,98 |
| D | 3 | 0,39 | 900,00 | 43,55 | 3 | 0,39 | 0,00 | 0,00 | -43,55 |
| E | 0 | 0,00 | - | - | 0 | 0,00 | - | - | - |
| **Ø/ha** | | | **900,00** | **43,55** | | | **1097,33** | **53,10** | **9,55** |

Within five years, in 2011 (Table 5) the pH value raised to 6,5 in both strategies. Soil analysis 2011 is the basis for the next planning period and thus the average lime quantities are lower compared to 2006. The reduced total quantities of lime decrease expenses of the CRF to 20,56 €/ha and of the VRF to 21,56 €/ha.

Around 31 % of the CRF grids are still over- or undersupplied. Based on these content levels, grids in class “B” would require an adjusted amount of lime. The VRF strategy considers those challenges and an amount of 563,16 kg/ha CaO is applied. This generates financial expenses of 27,25 €/ha. In class “C” 425 kg/ha are necessary in both strategies with 20,56 €/ha.

The differences between strategies are negligible 0,69 €/ha.

**Table 5. Comparison of a constant- and variable-rate-fertilization of lime, based on soil analysis 2011**

| **pH - CaO** | | | Ø pH 6,5 | | | | Ø pH 6,5 | | |
|---|---|---|---|---|---|---|---|---|---|
| **2011** | CN2:CV11 | | **Constant-Rate-Fertilization** | | **Grids VRF** | | **Variable-Rate-Fertilization** | | *Difference* |
| | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *VRF - CRF* |
| *Class* | *n* | *ha* | *kg/ha CaO* | *€/ha* | *n* | *ha* | *kg/ha CaO* | *€/ha* | *€/ha* |
| A | 0 | 0,00 | - | - | 0 | 0,00 | - | - | - |
| B | 34 | 4,41 | 425,00 | 20,56 | 38 | 4,92 | 563,16 | 27,25 | 6,69 |
| C | 98 | 12,70 | 425,00 | 20,56 | 114 | 14,77 | 425,00 | 20,56 | 0,00 |
| D | 9 | 1,17 | 425,00 | 20,56 | 6 | 0,78 | 0,00 | 0,00 | -20,56 |
| E | 1 | 0,13 | 425,00 | 20,56 | 1 | 0,13 | 0,00 | 0,00 | 0,00 |
| **Ø/ha** | | | **425,00** | **20,56** | | | **439,31** | **21,26** | **0,69** |

In 2017 (Table 6) the VRF realized an ideal pH-value in most of the grids. In favor of the VRF average costs are 0,75 €/ha lower. This is due to the 7 oversupplied grids in class “D” and “E”. In both classes no lime is recommended (Wulffen et al., 2008).

**Table 6. Comparison of a constant- and variable-rate-fertilization of lime, based on soil analysis 2017**

| **pH - CaO** | | | Ø pH 6,7 | | | | Ø pH 6,6 | | |
|---|---|---|---|---|---|---|---|---|---|
| **2017** | **Grids CRF** | | **Constant-Rate-Fertilization** | | **Grids VRF** | | **Variable-Rate-Fertilization** | | *Difference* |
| | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *VRF - CRF* |
| *Class* | *n* | *ha* | *kg/ha CaO* | *€/ha* | *n* | *ha* | *kg/ha CaO* | *€/ha* | *€/ha* |
| A | 0 | 0,00 | - | - | 0 | 0,00 | - | - | - |
| B | 7 | 0,91 | 425,00 | 20,56 | 3 | 0,39 | 600,00 | 29,03 | 8,47 |
| C | 116 | 15,03 | 425,00 | 20,56 | 149 | 19,31 | 425,00 | 20,56 | 0,00 |
| D | 18 | 2,33 | 425,00 | 20,56 | 6 | 0,78 | 0,00 | 0,00 | -20,56 |
| E | 1 | 0,13 | 425,00 | 20,56 | 1 | 0,13 | 0,00 | 0,00 | -20,56 |
| **Ø/ha** | | | **425,00** | **20,56** | | | **409,59** | **19,82** | **-0,75** |

## Phosphorus

The following tables illustrates the development of phosphorus fertilization costs over the period from 2006, 2011 to 2017. The average phosphorus content of all grids is shown in the first row of the table. The outpointed data at the end of each table explains the average costs of each strategy.

When starting the experiment in 2006 most grids are oversupplied with phosphorus (Table 7). Consequently the fertilization quantity of phosphorus is considerable reduced in the site-specific strategy and constant-rate-fertilization (based on average 7,9 CAL-P / 100 g soil). In the VRF an amount of 83 grids is in class “D” and half of the nutrient removal has to be applied. On all grids in class “E” no phosphorus need to be applied. The positive balance reflects higher costs of the VRF in contrast to the CRF. The average of 7,9 mg CAL-P / 100 g soil categories all grids into VDLUFA class “D” in CRF. Thus a quantity of 14,76 kg/ha P is applied.

**Table 7. Comparison of a constant- and variable-rate-fertilization of phosphorus, based on soil analysis 2006**

| **Phosphorus** | | | Ø P 7,9 mg P-CAL/100g soil | | | | Ø P 7,8 mg P-CAL/100g soil | | |
|---|---|---|---|---|---|---|---|---|---|
| **2006** | **Grids CRF** | | **Constant-Rate-Fertilization** | | **Grids VRF** | | **Variable-Rate-Fertilization** | | *Difference* |
| | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *VRF - CRF* |
| *Class* | *n* | *ha* | *kg/ha P* | *€/ha* | *n* | *ha* | *kg/ha P* | *€/ha* | *€/ha* |
| A | 0 | 0,00 | - | - | 0 | 0,00 | - | - | - |
| B | 1 | 0,13 | 14,76 | 22,04 | 0 | 0,00 | - | - | -22,04 |
| C | 60 | 7,78 | 14,76 | 22,04 | 62 | 8,04 | 29,52 | 44,09 | 22,04 |
| D | 66 | 8,55 | 14,76 | 22,04 | 83 | 10,76 | 14,76 | 22,04 | 0,00 |
| E | 15 | 1,94 | 14,76 | 22,04 | 14 | 1,81 | 0,00 | 0,00 | -22,04 |
| **Ø/ha** | | | **14,76** | **22,04** | | | **19,22** | **28,70** | **6,65** |

In 2011 (Table 8) soil analysis shows decreased phosphorus contents in both strategies. The demand-based VRF increased the amount of class "C" grids from 39 % to 80 % of all 159 VRF grids. In comparison, in 2011 70 % (n = 100) of all grids in the CRF attain the ideal nutrient level (2006 – 42 %). The phosphorus supply corresponds to the nutrient removal based on crop rotation. Hence, the VR application strategy generates costs of 40,07 €/ha (CRF 44,09 €/ha). The new planning 2011 would expect higher expenses of the constant rate strategy with a difference of 4,02 €/ha.

**Table 8. Comparison of a constant- and variable-rate-fertilization of phosphorus, based on soil analysis 2011**

| **Phosphorus** | | | Ø P 5,6 mg P-CAL/100g soil | | | | Ø P 5,2 mg P-CAL/100g soil | | |
|---|---|---|---|---|---|---|---|---|---|
| **2011** | **Grids CRF** | | **Constant-Rate-Fertilization** | | **Grids VRF** | | **Variable-Rate-Fertilization** | | *Difference* |
| | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *VRF - CRF* |
| *Class* | *n* | *ha* | *kg/ha P* | *€/ha* | *n* | *ha* | *kg/ha P* | *€/ha* | *€/ha* |
| A | 0 | 0,00 | - | - | 0 | 0,00 | - | - | - |
| B | 6 | 0,78 | 29,52 | 44,09 | 3 | 0,39 | 44,28 | 66,13 | 22,04 |
| C | 100 | 12,96 | 29,52 | 44,09 | 127 | 16,46 | 29,52 | 44,09 | 0,00 |
| D | 27 | 3,50 | 29,52 | 44,09 | 26 | 3,37 | 14,76 | 22,04 | -22,04 |
| E | 9 | 1,17 | 29,52 | 44,09 | 3 | 0,39 | 0,00 | 0,00 | -44,09 |
| **Ø/ha** | | | **29,52** | **44,09** | | | **26,83** | **40,07** | **-4,02** |

The current soil analysis in 2017 (Table 9) addresses more oversupplied zones with 7,52 ha in the CRF variant. The designated strategy CRF relates to VDLUFA class "D" and does not consider the number of 84 optimal supplied grids. At the end the VRF generates expenses of 37,16 €/ha, which is 15,11 €/ha more expensive than CRF.

**Table 9. Comparison of a constant- and variable-rate-fertilization of phosphorus, based on soil analysis 2017**

| **Phosphorus** | | | Ø P 6,3 mg P-CAL/100g soil | | | | Ø P 5,9 mg P-CAL/100g soil | | |
|---|---|---|---|---|---|---|---|---|---|
| **2017** | **Grids CRF** | | **Constant-Rate-Fertilization** | | **Grids VRF** | | **Variable-Rate-Fertilization** | | *Difference* |
| | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *Quantity* | *Area* | *Fertilizer* | *Costs/ha* | *VRF - CRF* |
| *Class* | *n* | *ha* | *kg/ha P* | *€/ha* | *n* | *ha* | *kg/ha P* | *€/ha* | *€/ha* |
| A | 0 | 0,00 | - | - | 0 | 0,00 | - | - | - |
| B | 1 | 0,13 | 14,76 | 22,04 | 0 | 0,00 | - | - | -22,04 |
| C | 83 | 10,76 | 14,76 | 22,04 | 112 | 14,52 | 29,52 | 44,09 | 22,04 |
| D | 50 | 6,48 | 14,76 | 22,04 | 44 | 5,70 | 14,76 | 22,04 | 0,00 |
| E | 8 | 1,04 | 14,76 | 22,04 | 3 | 0,39 | 0,00 | 0,00 | -22,04 |
| **Ø/ha** | | | **14,76** | **22,04** | | | **24,88** | **37,16** | **15,11** |

## Yield effects

As an example for yield effects, the following Figure 2 reflects the deviation of the ideal content class “C” with a maximum yield of 44,91 dt/ha. The lowest yield occurs in class “E” with 21,85 dt/ha. This substantial yield depression generates lower revenues. In the light of different nutrient sensitivity of crops, the yield effects arise variously.

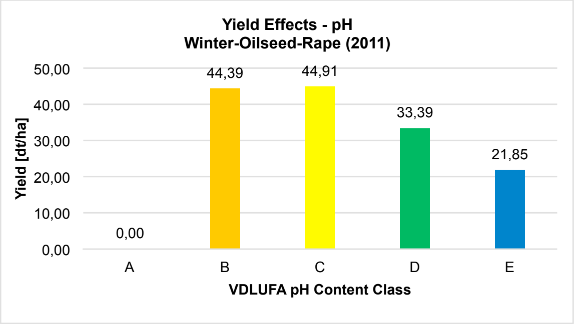


**Figure 2. Yield effects of suboptimal pH-value (winter-oilseed-rape)**

Table 10 and Table 11 outline negative yield effects based on a suboptimal supply of phosphorus and lime. The allocation of yield levels to the different classes is related to a soil analysis after the harvest.

Especially boosted pH values in soil (Table 10) reduces yield potential of oilseed rape between 11,52 dt/ha in “D” and 23,06 dt/ha in “E”. Analysis demonstrates, that every crop reacts differently. Thus a non-ideal pH reduces winter-barley yield in class “D” with 6,49 dt/ha and 3,68 dt/ha in class “B” in comparison to the ideal class “C”. At this test field the deviation of ideal content class “C” decrease average revenues of oilseed-rape by 30,99 €/ha winter-wheat by 15,55 €/ha and winter-barley by 14,79 €/ha.

**Table 10. Yield effects of a suboptimal pH-value: winter wheat, winter barley and winter oilseed rape**

| **pH** | **Winter Wheat** | | | **Winter Barley** | | | **Winter Oilseed Rape** | | |
|---|---|---|---|---|---|---|---|---|---|
| *Class* | *n* | *Deviation to "C" (dt/ha)* | *Less Yield (dt)* | *n* | *Deviation to "C" (dt/ha)* | *Less Yield (dt)* | *n* | *Deviation to "C" (dt/ha)* | *Less Yield (dt)* |
| A | 0 | - | - | 0 | - | - | 0 | - | - |
| B | 35 | -3,22 | -14,60 | 74 | -3,68 | -35,28 | 181 | -0,52 | -12,14 |
| C | 194 | 0,00 | 0,00 | 305 | 0,00 | 0,00 | 247 | 0,00 | 0,00 |
| D | 4 | -23,24 | -12,05 | 14 | -6,49 | -11,78 | 18 | -11,52 | -26,87 |
| E | 0 | - | - | 0 | - | - | 2 | -23,06 | -5,98 |
| **∅ Reduced Proceeds €/ha** | | | **-15,55** | | | **-14,79** | | | **-30,99** |

A similar pattern in documentation of phosphorus contents characterizes yield effects of non-ideal phosphorus levels in soil (Table 11). The yield decreased significantly in class “B” in contrast to the ideal content class “C”. Winter wheat is 4,55 dt/ha lower and winter-barley 4,25 dt/ha. A yield depression in class “D” and “E” is not expected. To sum it up, the analysis shows lower income for winter-wheat with 18,04 €/ha, for oilseed-rape with 17,92 €/ha and for winter-barley with the slightest yield depression of 13,41 €/ha.

**Table 11. Yield effects of a suboptimal phosphorus content: winter wheat, winter barley and winter oilseed rape**

| **P** | **Winter Wheat** | | | **Winter Barley** | | | **Winter Oilseed Rape** | | |
|---|---|---|---|---|---|---|---|---|---|
| *Class* | *n* | *Deviation to "C" (dt/ha)* | *Less Yield (dt)* | *n* | *Deviation to "C" (dt/ha)* | *Less Yield (dt)* | *n* | *Deviation to "C" (dt/ha)* | *Less Yield (dt)* |
| A | 1 | -2,08 | -0,27 | 1 | -10,48 | -1,36 | 1 | -3,93 | -0,51 |
| B | 52 | -4,55 | -30,65 | 75 | -4,25 | -41,30 | 76 | -2,59 | -25,50 |
| C | 83 | 0,00 | 0,00 | 206 | 0,00 | 0,00 | 280 | 0,00 | 0,00 |
| D | 89 | 0,00 | 0,00 | 98 | 0,00 | 0,00 | 77 | 0,00 | 0,00 |
| E | 8 | 0,00 | 0,00 | 13 | 0,00 | 0,00 | 14 | 0,00 | 0,00 |
| **∅ Reduced Proceeds €/ha** | | | **-18,04** | | | **-13,41** | | | **-17,92** |

**Sensor Costs**

The following Table 12 exhibits an approximate calculation of maximum allowable sensor costs for pH detection at this particular test field.

**Table 12. Maximum allowable sensor costs - pH**

| **Maximum allowable sensor costs** | | **pH** |
|---|---|---|
| Winter wheat I | (€/ha) | -15,55 |
| Winter wheat II | (€/ha) | -15,55 |
| Winter barley | (€/ha) | -14,79 |
| Winter oilseed rape | (€/ha) | -30,99 |
| **Average yield effects** | **(€/ha)** | **-19,22** |
| Reduction of yield effects per year | (%) | 12,50 |
| Interval to maximize yield | (years) | 8 |
| **Average yield effects incl. reduction** | **(€/ha)** | **-10,81** |
| Necassary soil analysis | (n) | 2 |
| Tolerance deduction | (%) | 15 |
| **Sensor costs for one soil analysis** | **(€/ha)** | **36,76** |
| **Maximum allowable sensor costs** | **(€/ha)** | **73,52** |

The average yield effects are based on the typical crop rotation. Moreover, this approach assumes decreasing negative yield effects by 12,5 % in 8 years. This means that the site-specific fertilization increases the pH values in soil and thus yields increase. The average reduced proceeds, based on low nutrient or lime supply, are estimated with 10,81 €/ha. However, to accomplish VDLUFA class “C”, it is necessary to conduct two small-scale soil analysis in the eight years. In this context, calculation determines maximum allowable pH sensor costs of 36,76 €/ha for one soil analysis including a 15 % tolerance deduction. In the eight years planning period, total costs of 73,52 €/ha are justifiable for two necessary pH analysis (Table 12).

**Table 13. Maximum allowable sensor costs - phosphorus**

| **Maximum allowable sensor costs** | | **Phosphorus** |
|---|---|---|
| Winter wheat I | (€/ha) | -18,04 |
| Winter wheat II | (€/ha) | -18,04 |
| Winter barley | (€/ha) | -13,41 |
| Winter oilseed rape | (€/ha) | -17,92 |
| **Average yield effects** | **(€/ha)** | **-16,85** |
| Reduction of yield effects per year | (%) | 12,50 |
| Interval to maximize yield | (years) | 8 |
| **Average yield effects incl. reduction** | **(€/ha)** | **-9,48** |
| Necassary soil analysis | (n) | 2 |
| Tolerance deduction | (%) | 15 |
| **Sensor costs for one soil analysis** | **(€/ha)** | **32,23** |
| **Maximum allowable sensor costs** | **(€/ha)** | **64,50** |

Table 13 illustrates an approximate calculation of maximum allowable sensor costs for phosphorus detection. This calculation specifies negative yield effects with 16,85 €/ha. This further analysis identifies average costs of suboptimal phosphorus contents in soil of 9,48 €/ha. Similar to the procedure in Table 12, the maximum allowable sensor costs for phosphorus are

32,23 €/ha. In the eight years planning period, total costs of 64,50 €/ha are justifiable for two necessary phosphorus analysis (Table 13).

To sum it up, this research specifies the break-even of small-scale sensor analysis around 32 €/ha to 37 €/ha for one soil analysis every 4 year. These calculations demonstrate, that sensor operating costs at this level or lower are justified.

## Conclusion

Small-scale soil analysis identifies a high heterogeneity at the on-farm-research field. This detailed information enables to adapt a site-specific high level farming strategy. It is particular interesting, that the test field is classified into a homogenous soil group 4, but it is characterized by different macro nutrient contents and pH-values. A constant-rate-fertilization would not ensure the ideal supply of phosphorus and lime. With reference to the demand-orientated lime application, the variable-rate-fertilization generates higher costs at the beginning in 2006. This expenses decrease over the time and will not arise anymore. Moreover, achieving the ideal pH-value would leads to other advantages related to nutrient interactions, which has not been detected in this study (Haynes, 1982; Jobbágy & Jackson, 2001; Tucher, Hörndl, & Schmidhalter, 2018).

The amount of VRF costs is depending on the identified soil contents. Many oversupplied zones lead to reduced costs and many undersupplied zones generates high costs to achieve the ideal nutrient level. Furthermore, initial higher costs of the VRF would not arise anymore in the long-term, after achieving the ideal nutrient/pH levels. For this reason, fertilization costs are not considered in calculation of maximum allowable sensor costs.

Research identifies sustainable sensor costs of 32 to 37 €/ha for one soil analysis at this particular field. Total expenses of 64 to 74 €/ha are acceptable in the eight years period to achieve the ideal nutrient/pH level. At other locations, with many undersupplied or oversupplied areas and significant negative yield effects, it may be higher. Nevertheless, the exploited yield potential justifies these costs after a short period.

Besides, detection of multiple nutrients and other soil parameters reduces analysis costs. However, the variability in yield levels depending on crop, nutrient content level or location exacerbate to calculate the break-even of sensor analyzation. Hence, more field experiments need to be accomplished to provide enough data and calculate the exact break-even.

### Acknowledgments

This study is financed by the BMBF and PTJ of Germany (Project BonaRes I4S). The authors would like to thank the supporting institutes.

# Appendix

**Figure 3. Development of pH-values between 2011 and 2017; VRF and CRF**

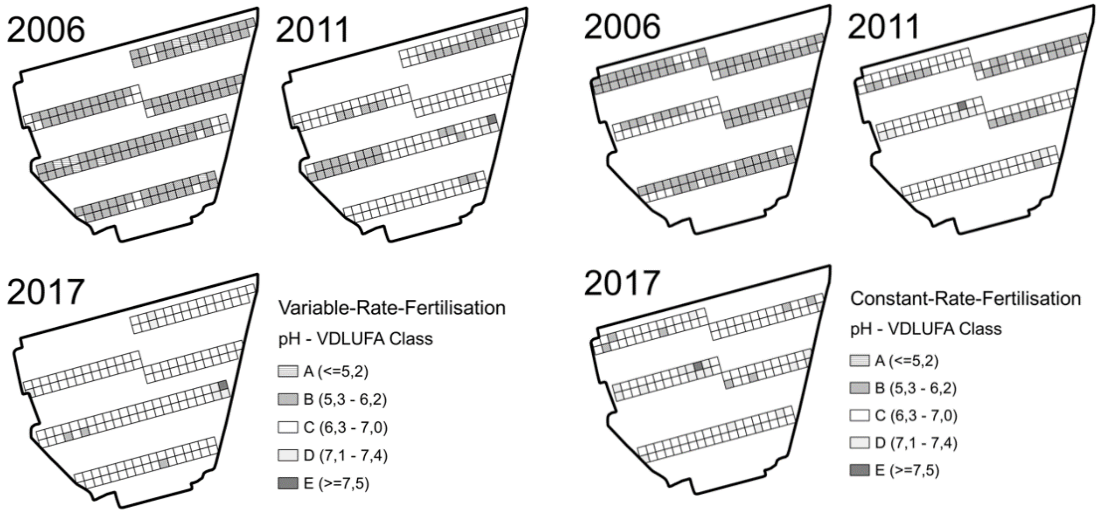
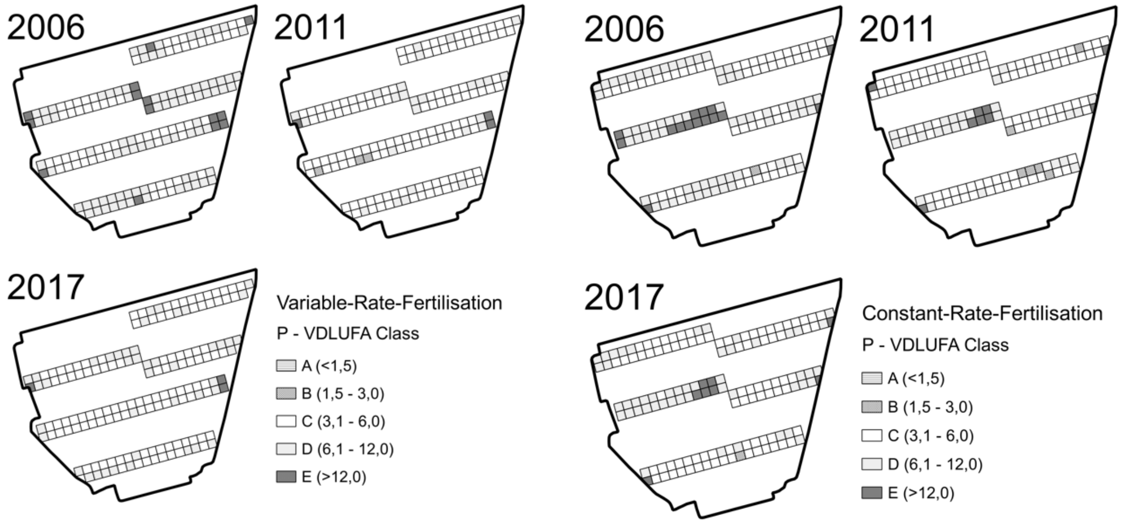


**Figure 4. Development of phosphorus between 2011 and 2017; VRF and CRF**



# References

Auernhammer, H. (2001). Precision farming - The environmental challenge. *Computers and Electronics in Agriculture*, *30*(1–3), 31–43. http://doi.org/10.1016/S0168-1699(00)00153-8

Daberkow, S. G., & McBride, W. D. (2003). Farm and operator characteristics affecting the awareness and adoption of precision agriculture technologies in the US. *Precision Agriculture*, *4*(2), 163–177. http://doi.org/10.1023/A:1024557205871

Eastwood, C., Klerkx, L., & Nettle, R. (2017). Dynamics and distribution of public and private research and extension roles for technological innovation and diffusion: Case studies of the implementation and adaptation of precision farming technologies. *Journal of Rural Studies*, *49*, 1–12. http://doi.org/10.1016/j.jrurstud.2016.11.008

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*, 337. http://dx.doi.org/10.1038/nature10452

Gebbers, R., & Adamchuk, V. I. (2010). Precision Agriculture and Food Security. *Science*, *327*(5967), 828 LP-831. http://science.sciencemag.org/content/327/5967/828.abstract

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., … Toulmin, C. (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science*, *327*, 812–817. http://web.mit.edu/12.000/www/m2019/pdfs/Godfray_2010_Science.pdf

Haynes, R. J. (1982). Effects of liming on phosphate availability in acid soils - A critical review. *Plant and Soil*, *68*(3), 289–308. http://doi.org/10.1007/BF02197935

Jobbágy, E. G., & Jackson, R. B. (2001). The distribution of soil nutrients with depth: Global patterns and the imprint of plant. *Biogeochemistry*, *53*(1), 51–77.

LVLF. (2009). *Hinweise zur Probenahme von Boden, Pflanzen und Düngemitteln*. *Gemeinsame Hinweise der Länder Brandenburg, Mecklenburg-Vorpommern und Sachsen-Anhalt*. http://www.isip.de/coremedia/generator/Inhalt/Nachrichten/Deutschland/Brandenburg/Fachinformationen_20D_C3_BCngung/Brosch_C3_BCren/Probenahme,property=Dokument.pdf

Tilman, D. (1999). Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. *Proceedings of the National Academy of Sciences*, *96*(11), 5995–6000. http://doi.org/10.1073/pnas.96.11.5995

Tucher, S., Hörndl, D., & Schmidhalter, U. (2018). Interaction of soil pH and phosphorus efficacy: Long-term effects of P fertilizer and lime applications on wheat, barley, and sugar beet. *Ambio*, *47*(Eurostat 2016), 41–49. http://doi.org/10.1007/s13280-017-0970-2

VDLUFA. (2015). *Positionspapier - Phosphordüngung nach Bodenuntersuchung - Anpassung der Richtwerte für die Gehaltsklassen ist geboten und notwendig*. *Verbands Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten*. Speyer. http://www.vdlufa.de/joomla/Dokumente/Positionspapiere/2015_Phosphordüngung-nach-Bodenuntersuchung.pdf

Wulffen, U., Roschke, M., Kape, H.-E., Holz, F., Greiner, B., Schulze, H., … Pöplau, R. (2008). Richtwerte für die Untersuchung und Beratung sowie zur fachlichen Umsetzung der Düngeverordnung (DüV). Bernburg, Güterfelde, Rostock: Land Sachsen-Anhalt.