Analysis of site-specific N-fertilization on-farm trials in cereals under assumption of spatial covariance structures

Heinrich Thöle[1*], Christel Richter[2], Bärbel Kroschewski[2] and Detlef Ehlert[1]

[1] Leibniz-Institute for Agricultural Engineering Potsdam-Bornim e.V., Max-Eyth-Allee 100, 14469 Potsdam, Germany

[2] Humboldt-Universität zu Berlin, Faculty of Agriculture and Horticulture, Institute of Crop Sciences, Department Biometry and Experimental Design, Invalidenstr. 42, 10115 Berlin, Germany

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Abstract - Kurzfassung

The application of real-time sensors provides the possibility of adapting nitrogen fertilization to requirements in heterogeneous cereal crops site-specifically. Efficient and environmentally sound fertilization strategies can be developed by the use of on-farm trials as a contribution to sensor-based farming. This paper assesses what agronomic effects can be found using the mechanical sensor "Crop-Meter" for nitrogen fertilization. On-farm trials were conducted to compare the application of uniform nitrogen rates with sensor-based site-specifically applied rates. As an example, an approach is demonstrated taking the crop heterogeneity into account as a factor of interest in the statistical analysis, whereas heterogeneity is often treated as undesired noise factor. To include the heterogeneity, yield data were classified by magnitude of the above-ground plant mass in order to create comparable conditions. Each class was analyzed by assuming mixed models taking into account spatial co-variance structures, which provided substantially better model fits than the classic ANOVA model. The trial considered showed that the reduction of nitrogen fertilizer in site-specific application (mean: 22 kg ha^{-1} N) caused no statistically significant yield differences by comparison with uniform application. Therefore, the spatial variation of nitrogen fertilizers seems a useful contribution to reducing direct cost of crop production and to decreasing environmental impacts.

Keywords: Site-specific nitrogen fertilization, auto-correlated grain yield data, mixed linear models, spatial co-variance structures

Räumliche Analyse systematischer Versuchsdesigns zur teilflächenspezifischen N-Düngung mittels Kovarianzstrukturen

Der Einsatz von Echtzeit-Sensoren bietet die Möglichkeit, in heterogenen Getreidebeständen die Stickstoffdüngung dem Bedarf teilflächenspezifisch anzupassen. Praxisversuche stellen eine Möglichkeit dar, effiziente und umweltschonende Düngungsstrategien als Beitrag zur sensorgestützten Bestandsführung zu entwickeln. Im vorliegenden Beitrag wird untersucht, welche agronomischen Effekte beim Einsatz des mechanischen Sensors "Crop-Meter" zur Stickstoffdüngung entstehen. Es wurden Praxisversuche zum Vergleich von herkömmlicher, flächeneinheitlicher N-Düngung mit sensorgestützter, teilflächenspezifischer N-Düngung in Getreide angelegt. Anhand eines Beispiels mit Wintertriticale wird erläutert, wie die Heterogenität eines Getreidebestands, die in der Regel als Störgröße betrachtet wird, in die statistische Auswertung gezielt einbezogen werden kann. Die Heterogenität wurde berücksichtigt, indem die Kornerträge nach Größe der Pflanzenmasse in Klassen eingeteilt wurden, um vergleichbare Bedingungen zu schaffen. Jede Klasse wurde auf Basis gemischter linearer Modelle analysiert, um räumliche Kovarianzstrukturen einzubeziehen. Diese brachten im Vergleich zum klassischen ANOVA-Modell deutlich bessere Modellanpassungen. Der Versuch erbrachte trotz Reduktion der Düngermenge in der teilflächenbezogenen Variante (Mittel: 22 kg ha^{-1} N) keine statistisch signifikanten Ertragsunterschiede. Damit kann in diesem Fall von einem teilflächenspezifischen Einspareffekt ohne Ertragsrückgang ausgegangen werden, was einen sinnvollen Beitrag zur Senkung von Kosten und Umweltbelastungen darstellt.

Schüsselwörter: Teilflächenspezifische N-Düngung, autokorrelierte Ertragsdaten, gemischte lineare Modelle, räumliche Kovarianzstrukturen

1 Introduction

Site-specific nitrogen fertilization aims to use fertilizers more efficiently than in present farm management to benefit farm income and environment. Uniform spreading of nitrogen fertilizers in cereal crops is currently common agricultural practice and meets legal requirements (MELFF M-V 2004). For uniform applications, mean conditions for sites and crop stands relating to entire fields are assumed, although within-field soil and crop variabilities are often known. Therefore, it seems reasonable to account for variabilities by applying fertilizers site-specifically to improve

* Corresponding author. Tel: ++49 (0) 331 5699 420; Fax: ++49 (0) 331 5699 849; E-mail: hthoele@atb-potsdam.de

nitrogen use efficiency (AID 2005). For this purpose in a first step, information about variability of soil or plant traits must be obtained by suitable and affordable measurement methods. In a second step, the measurements have to be interpreted agronomically for precision farming applications (Domsch 2004). Thus, a mechanical sensor (CROP-Meter) was developed to measure aboveground plant mass in cereals. Based on this measurement and application algorithms determined, nitrogen fertilizers can be spread site-specifically in real time (Ehlert & Dammer 2006).

In this study an on-farm experiment was conducted to compare the influence of site-specific fertilizer application (SSA) with CROP-Meter and uniform application (UA) on grain yields of winter triticale. This kind of on-farm trials is carried out on fields of farmers because crop stand heterogeneity is an essential prerequisite for practicable site-specific applications with the "CROP-Meter".

In the planning of agricultural trials replication, randomization and accounting for noise factors by blocking are the classic principles. Block design assumes homogenous experimental conditions within the blocks, while different blocks correspond to different levels of noise factors. In field experiments the block construction is primarily determined by soil characteristics and normally one block represents a spatial adjacent and uniform group of experimental units. However, in this study, heterogeneity represented by the crop stand before applying any different treatments is explicitly desired. Under these circumstances the creation of equal conditions for the treatments within blocks can hardly be guaranteed. Moreover, the different levels of crop heterogeneity do not have to be treated only as a noise factor, but can also be interpreted as different management zones or as a factor of interest in such experiments. Therefore, the main focus lies on the comparison of both fertilization treatments per management zone. As described below, we suggest one way of accounting for the inherent ambiguity of crop heterogeneity. Strata of equal crop stands are defined, which do not necessarily depend on spatial proximity, unlike blocks, and the treatments are compared per stratum. Finally, the way to obtain a total result for the given field is outlined.

In on-farm trials geo-referenced grain yield data are mostly affected by spatial autocorrelations and/or trends providing spatial co-variances unequal to zero. Assumptions of classic inferential methods such as analysis of variance cannot be met because the stochastic independence of residuals is not fulfilled. Thus, statistical approaches are necessary regarding spatial correlations. Several approaches are cited in literature regarding spatial correlations and/or trends: Mudra (1949) proposes linear adjustments by control treatments in standard designs. Thomas & Stressmann (1972) suggest adjusting the influence of soil trends by using polynomial functions. Another method is the Nearest Neighbor analysis based on an approach of Papadakis (Wilkinson et al. 1983; Bhatti et al. 1991). Moder (1998) compares Nearest Neighbor analyses with a special form of co-variance analysis. He concludes that in almost all cases co-variance models were superior to other methods. Hurley et al. (2004) and Lambert et al. (2004) test geostatistical approaches regarding spatial structures to estimate site-specific nitrogen crop response functions. Hong et al. (2005) develop guidelines for co-variance model selection in randomized complete block designs.

All these methods can be described by mixed linear models, including classic analysis of variance (ANOVA). Mixed linear models allow us to account for spatial co-variances (Littell et al. 2006). In matrix notation a mixed linear model is written as (Searle et al. 1992):

$$\mathbf{Y} = \mathbf{X}\beta + \mathbf{Z}\gamma + \varepsilon \qquad (1)$$

where **Y** denotes the vector of *n* dependent observations, **X** is a $n \times p$ design matrix of known coefficients of fixed effect parameters, and β is the *p* vector of unknown fixed-effects parameters**.** The vector ε of *n* error terms is assumed to be normally distributed with E(ε) = 0 and Var(ε) = **R**. The matrix **R** specifies the error variance. In our study, two assumptions for the matrix **R** are compared. In the first case, the matrix **R** corresponds to σ^2I under the assumption of identically and independently distributed residuals (*iid*), where **I** denotes the $n \times n$ identity matrix. In the second case, spatial variance-covariance structures of residuals are specified under assumption of auto-correlated errors.

Random effects, which are described by the $n \times q$ design matrix **Z** and the vector γ of *q* unknown effects, if applicable, are not included. To estimate the variance components, the Restricted Maximum Likelihood algorithm (REML) is used.

Many authors suggest REML algorithms to account for spatial correlation and/or trends: Robinson (1987) points out that efficient estimates of treatment effects as in variety trials are obtainable, whatever the field conditions are, if information about random error structure is considered. Mallarino et al. (1998) obtain more thorough comparisons of phosphorus fertilization practices by a combination of on-farm strip trials with precision farming technology. They account for spatial correlation of yield data by mixed models. Gilmour et al. (1997) attempt to recognize the sources of variation in plot experiments and conclude that no universally valid mixed model exists for every trial.

But an individual fitting of models to each "situation" is needed. Wolfinger & Chang (1995) recommend the comparison of several covariance structures in mixed models if observed values are correlated and exhibit heterogeneous variability.

This paper considers whether a correlated error approach represented by spatial co-variance structures or the classic ANOVA approach using the assumption of identically and independently distributed errors is more suitable for analyzing on-farm fertilization trials.

2 Material and methods

As an example, our approach is described by an on-farm fertilization strip trial, which was established on the field of a farmer in Wittbrietzen (Brandenburg, Germany). Wittbrietzen is located on a Cambic Podzol from dystrophic sand deposits. This site often suffers from early summer droughts. Therefore under climate conditions of Central Europe, Wittbrietzen can be characterized as marginal site for arable farming. Winter triticale (variety "Triamant") was sown on September 27th, 2005, with 300 seeds per m^2. The preceding crop was maize for silage. Grain was harvested on August 2nd, 2006.

The first nitrogen rate (70 kg ha^{-1} N) was spread uniformly in both treatments at start of vegetation. For the second nitrogen rate, the treatments were performed at the start of stem elongation with a centrifugal spreader. The uniform rate applied was 54 kg ha^{-1} N. The total uniform rate (124 kg ha^{-1} N) is geared to recommendations for wheat growers on marginal sites in Brandenburg (Adam & Fahlenberg 2004). The site-specific fertilizer application was carried out with the mechanical sensor "CROP-Meter" and a linear algorithm determined. The algorithm was based on the correlation of sensor deviation angles (ϕ) and plant mass density of cereal crops (Ehlert et al. 2003). The site-specifically applied rate (13.5…54.0 kg ha^{-1} N) increased with increasing aboveground plant mass according to equation 2. On average, the applied fertilizer amount was 22 kg ha^{-1} N less than in the uniform treatment. The algorithm was determined under the assumption that plant mass development in early spring is already an appropriate indicator for expectable soil water deficit on this sandy site. In parts of the fields with above average plant mass, a higher nitrogen rate (54 kg ha^{-1} N) would be used more likely by the plants than in parts of the field with below average plant mass indicating a higher level of soil water deficit (Ehlert et al. 2004).

$$\text{SSA rate }(\Phi) = \begin{cases} 13.5 & \text{for } \Phi < 15° \\ -27 + 2.7\Phi & \text{for } 15° \le \Phi \le 30° \\ 54.0 & \text{for } \Phi > 30° \end{cases} \quad (2)$$

The differently fertilized treatments were adapted to the tramline system of the field. One treatment or strip, respectively, consisted of two adjacent tramlines spanning the entire field and taking the triangular distribution pattern of the centrifugal spreader (working width: 27 m) into account. A site-specifically fertilized treatment always was performed next to a uniformly fertilized treatment. In Wittbrietzen five fertilization strips (10 trams) were arranged as a standard design (Fig. 1). In both treatments deviation angles and application rates were recorded with geographical positions in time intervals of 2 s.

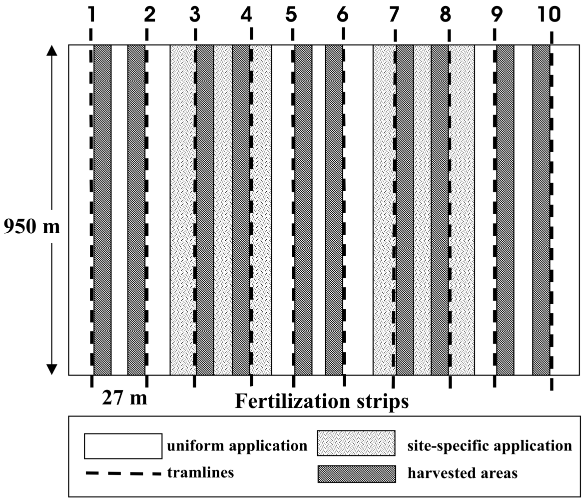

Fig. 1: Design of fertilization strip trial in Wittbrietzen

Grain was harvested in transects along the tramlines with a full cutting width of the combine harvester (width: 9 m). Two harvested transects were located between two adjacent tramlines of the same fertilization treatment. One harvested transect related to one tramline (Fig. 1). Grain yields were measured by a *Claas Quantimeter* system associated with a *Cebis* terminal and a dGPS receiver at time intervals of 5 s. The two outermost uniformly fertilized tramlines Nos. 1 and 10 were excluded, since the total number of observations for the treatments should be balanced at the very beginning. In Table 1, the grain yields (raw data) demonstrate that there are differences between the tramline means (5.11 t ha^{-1}… 5.76 t ha^{-1} for UA and 5.40 … 5.62 t ha^{-1} for SSA). The coefficients of variations (CV) range from 11.6 % to 18.8 % for UA and from 12.6 % to 18.3 % for SSA. The variations per tramline are caused by heterogeneous field conditions, the variations for SSA additionally by the potential effect of differentiated fertilization.

Unfavorable yield data positions are not identical to the positions of fertilization parameters. Therefore, raw yield data were interpolated with the program GS+ (Version 7.0, Gamma Design Software, Plain-

Table 1: Deviation angles and grain yields for tramline No. 2 to 9

		Deviation angles		Grain yield		
Tramline No.	Treatment	Means (°)	CV (%)	Means (t ha^{-1})	CV (%)	Variances
2	uniform	20.8	28.5	5.11	18.8	0.93
3	variable	21.6	27.9	5.40	18.3	0.98
4	variable	22.3	24.1	5.50	17.8	0.96
5	uniform	20.0	26.9	5.29	12.4	0.43
6	uniform	20.3	23.8	5.40	16.3	0.77
7	variable	22.7	18.1	5.62	12.6	0.50
8	variable	22.6	17.1	5.51	16.4	0.81
9	uniform	19.2	21.6	5.76	11.6	0.44

well, Michigan, USA) by block-kriging on the original locations of deviation angles to aggregate application and harvest data on identical positions. Therefore, data were only processed within an identically treated tramline to exclude the influence of neighbor tramlines.

Before the block-kriging was performed, variograms were estimated one-dimensionally in direction of the tramline up to only 50 m, because for kriging, the fit near the origin (short distances) should be as accurate as possible. The best fitted variogram models are given in Table 2. Since estimation of variograms was limited to shorter distances, the sill is smaller than the total variances mentioned in Table 1. Correspondingly, the kriging interpolation was carried out separately for the yield data within each tramline.

To assess the starting conditions for both treatments the crop stands before application of the second nitrogen rate were compared by means and coefficients of variation (CV) of deviation angles per tramline (Table 1). The overall means were 20.1° for uniform application and 22.3° for site-specific application. These different means were indicators that the starting conditions could not be assumed as homogenous for the both treatments. The coefficients of variation ranged from 17.1 % to 28.5 % and showed different variations within the tramlines.

According to the ambiguity of crop heterogeneity the total data set was subdivided into eight deviation angle dependent classes (class width: 2.5°) in order to create comparable experimental conditions before estimating effects of fertilization treatments. In the lower angle classes the number of observed values is larger for UA and in the upper angle classes for SSA. These different distributions would disadvantage UA if this fact were ignored. However, nearly the same experimental conditions exist within each class, so that treatments can be compared per angle class. These classes can be treated as management zones and correspond to the strata above mentioned. The kriged yield data were assigned to the classes. In doing so, the number of observations of the two treatments turned out to be unbalanced within the same class.

Following the analysis per angle class was performed. Kriged yield data correspond to the vector **Y** in equation 1, and the effects of the two methods SSA and UA are components of the fixed effect vector β. The **R** matrix was specified by 11 spatial covariance models (6 isotropic and 5 anisotropic models, SAS) and by the ANOVA model with co-variances equal to zero. All spatial approaches were analyzed with or without the addition of a nugget effect. In total, 23 models were fitted to each class. In view of the fact that the kriged yield data are predicted values and have different prediction errors, we specified the inverse of kriging variances as weight variable.

The analyses were realized by the SAS procedure MIXED (PROC MIXED) (Version 9.1, SAS Institute

Table 2: Variogram parameters for grain yield raw data

Tramline No.	Treatment	Model	Nugget	Sill	Range (m)	Residual sum of squares
2	uniform	spherical	0.0090	0.400	38.6	$2.98*10^{-5}$
3	variable	spherical	0.0010	0.393	47.7	$1.29*10^{-2}$
4	variable	spherical	0.0010	0.654	71.0	$6.03*10^{-4}$
5	uniform	spherical	0.0530	0.428	72.1	$5.35*10^{-3}$
6	uniform	spherical	0.0350	0.492	96.9	$5.85*10^{-3}$
7	variable	exponential	0.0048	0.224	56.1	$1.46*10^{-4}$
8	variable	spherical	0.0001	0.257	47.5	$1.42*10^{-3}$
9	uniform	spherical	0.0001	0.310	65.6	$2.62*10^{-3}$

Inc., Cary, NC, USA), which accounts for unbalanced data and co-variance structures of the **R** matrix. The normal distribution of the residuals was met as well as variance homogeneity for the two treatments per angle class. The Satterthwaite option was used to approximate degrees of freedom for covariance models (Hu et al. 2006).

In a last step an overall result for the whole field in Wittbrietzen is requested. For this purpose the numbers of observations per angle class were interpreted as fractions of the corresponding management zones on this field. Thereby is assumed that the fractions reflect a representative sample of the entire field.

Weighted with these fractions, a contrast was estimated for the difference between UA and SSA. As before, the best of all fitted models was used, but now fitted over all angle classes. Of course, this model would be also suitable for comparing the two treatments per angle class, but the analysis per angle class with the best fitted model was preferred to guarantee the best fit in each case.

3 Results and discussion

In Table 3 the results of model fitting per angle class and over all angle classes are given. The fitting of spatial models is described by Akaike's Corrected Information Criteria (AICC, Burnham & Anderson 1998). The AICC is a measure for the goodness of fit. The smaller the AICC the better the fit is. For all angle classes, the values of AICC from modelling spatial covariances are clearly smaller than the values from classic ANOVA.

Moreover, the model without correlation provided the worst fit compared with these spatial models, which converged and had significant covariance parameters. Additionally, for all classes the likelihood ratio test showed that all these spatial models were significantly superior to the model of classic ANOVA ($\alpha = 0.05$).

In Table 3 the best fitted spatial model and the model without correlation are given per angle class. Different spatial model types indicated the best fit in different angle classes. The addition of nugget effects had no additional benefit on model fitting for this data set. Hence, the variances can be explained completely by spatial correlations.

The final experimental results are given in Table 4. The least square grain yield means are compared per angle class using the respective best fitted model. For all classes the p-values of F-tests indicate no significant differences between uniform and site-specific nitrogen application.

Increasing angle class numbers represent better crop stand conditions at the start of stem elongation. Thus, yields of the UA treatment in higher classes are expected tend to be higher. Actually, the grain yield means show this tendency in Table 4, but the comparison over all angle classes requires a total analysis (two-factorial with the best "Over all" spatial model exp a). However, the results base on the analysis per angle class given in Table 4.

As an overall conclusion for the whole field, the test of the contrast between UA and SSA weighted with the corresponding management fractions of the field Wittbrietzen gave an estimate of 0.08 with a p-value of 0.455. That means that the chosen "SSA algorithm" in this special year and for this special field resulted in the same grain yield compared with UA.

As all management zones (angle classes) give the same result for this field, there is no conflict with the total result. In other experiments with inconsistent results in the angle classes, such a general conclusion for the whole field would be of interest.

Table 3: Model fitting criteria of the Wittbrietzen on-farm trial

Class	Range of deviation angles (°)	Range of 2nd variable N rate (kg ha^{-1} N)	n	Spatial model [1)] Model type	AICC	Model without correlation AICC
1	≤15.0	13.5	94	power	162.3	257.9
2	>15.0…17.5	>13.5…20.3	95	pow a	161.0	271.6
3	>17.5…20.0	>20.3…27.0	156	exp ga	237.1	375.0
4	>20.0…22.5	>27.0…33.8	184	exp a	279.8	466.9
5	>22.5…25.0	>33.8…40.5	198	exp a	196.8	470.1
6	>25.0…27.5	>40.5…47.3	113	matern	151.2	299.0
7	>27.5…30.0	>47.3…54.0	51	spherical	88.4	131.6
8	>30	54.0	35	spherical	31.7	62.4
Over all			926	exp a	366.5	2,336.6

[1)] notation in SAS version 9.1.3

Table 4: Comparison of N fertilization treatments per angle class

Class	Range of 2nd variable N rate [1)] (kg ha^{-1} N)	n	Grain yield UA (t ha^{-1}) LS Mean	SE	n	Grain yield SSA (t ha^{-1}) LS Mean	SE	F-Test p-value treatment
1	13.5	69	5.22	0.235	25	5.34	0.235	0.530
2	> 13.5…20.3	61	5.54	0.255	34	5.72	0.253	0.388
3	> 20.3…27.0	84	5.01	0.163	72	5.06	0.142	0.710
4	> 27.0…33.8	95	5.51	0.161	89	5.50	0.137	0.930
5	> 33.8…40.5	88	5.65	0.136	110	5.63	0.112	0.883
6	> 40.5…47.3	45	5.65	0.199	68	5.75	0.156	0.528
7	> 47.3…54.0	17	6.15	0.268	34	6.02	0.220	0.548
8	54.0	12	6.38	0.246	23	6.49	0.203	0.613

[1)] 2nd uniform N rate: 54 kg ha^{-1}

4 Conclusions

This paper describes an approach for applying the mechanical sensor "Crop-Meter" in site-specific N fertilization and for analyzing on-farm trials for the assessment of site-specific fertilization treatments. The comparison of grain yields per angle class (per stratum) is suitable for evaluating the treatments per management zone. The overall view gives the corresponding information for the entire field, taking into account different proportions of management zones.

For this field it can be stated that in every management zone negative influences on the grain yield can be excluded by deliberate site-specific reduction of nitrogen fertilizers. There is no conflict between total result and individual results in management zones. In this case the differentiated crop stand is obviously an appropriate indicator of different soil properties (water holding capacity) on this field. Therefore, the spatial variation and the directed reduction (on average: 22 kg ha^{-1} N) of nitrogen fertilizer seems a useful contribution to reducing the direct cost of crop production and to reducing environmental impacts.

Abbreviations

a	=	anisotropic
exp	=	exponential
ga	=	geometrically anisotropic
LS mean	=	least square mean
SSA	=	site-specific application
SE	=	standard error
UA	=	uniform application

References

Adam L. Fahlenberg, E. (2004): Weizenanbau unter Brandenburger Bedingungen. www.mluv.brandenburg.de/cms/detail.php/180733 (02.03.2007).

AID - Infodienst Verbraucherschutz, Ernährung, Landwirtschaft (2005): Landbewirtschaftung und Gewässerschutz. AID-Heft 1494. DCM Druckcenter, Meckenheim.

Bhatti A.U., Mulla D.J., Koehler F.E., Gurmani A.H. (1991): Identifying and removing spatial correlation from yield experiments. Soil Science Society of America Journal 55, 1523-1528.

Burnham K.P., Anderson D.R. (1998): Model selection and inference. A practical information-theoretic approach. Springer.

Domsch H. (2004): Entwicklung einer low-input Lösung für die teilflächenspezifische Bewirtschaftung im Betriebsmaßstab. Forschungsbericht des Leibniz-Instituts für Agrartechnik, Postdam-Bornim, 157 pp.

Ehlert D., Hammen V., Adamek R. (2003): On-line sensor pendulum-meter for determination of plant mass. Precision Agriculture 4, 139-148.

Ehlert D., Schmerler J., Völker U. (2004): Variable rate nitrogen fertilization of winter wheat based on a crop density sensor. Precision Agriculture 5, 263-273.

Ehlert D., Dammer K.H. (2006): Widescale testing of the Crop-Meter for site-specific farming. Precision Agriculture 7, 101-115.

Gilmour A.R., Cullis B.R., Verbyla A. (1997): Accounting for natural and extraneous variation in the analysis of field experiments. Journal of agricultural, biological and environmental statistics 2 (3), 269-293.

Hong N., White J.G., Gumpertz M.L., Weisz R. (2005): Spatial analysis of precision agriculture treatments in randomized complete blocks: guidelines for covariance model selection. Agronomy Journal 97, 1082-1096.

Hu X., Spilke J., Richter C. (2006): The influence of spatial covariances on the type I error and the power for different evaluation models. Biometrical Letters 43, 19-37.

Hurley T.M., Malzer G.L., Kilian B. (2004): Estimating site-specific nitrogen crop response functions: A conceptual framework and geostatistical model. Agronomy Journal 96, 1331-1343.

Lambert D.M., Lowenberg-DeBoer J., Bongiovanni R. (2004): A comparison of four spatial regression models for yield monitor data: A case study from Argentina. Precision Agriculture 5, 579-600.

Littell R.C., Milliken G.A., Stroup W.W., Wolfinger R.D., Schabenberger O. (2006): SAS for mixed models. 2nd edition. SAS Institute Inc., Cary, NC, USA.

Mallarino A.P., Wittry D.J., Dousa D., Hinz P.N. (1998): Variable rate phosphorus fertilization: on-farm research methods and evaluation for corn and soybean. Proceedings of the 4th International Conference of Precision Agriculture, July 19-22, St. Paul, minnesota. ASA-CSSA-SSSA. Madison, Wisconsin, p. 687-696.

MELFF M-V - Ministerium für Ernährung, Landwirtschaft, Forsten und Fischerei Mecklenburg-Vorpommern (2004): Düngung - Hinweise und Richtwerte für die landwirtschaftliche Praxis. Gülzow, 182 pp.

Moder K. (1998): Vergleich verschiedener statistischer Analysen zur Ausschaltung von Bodeneinflüssen in Feldversuchen. Die Bodenkultur 49 (1), 3-11.

Mudra A. (1949): Anleitung zur Durchführung und Auswertung von Feldversuchen nach neueren Methoden. Hirzel, Leipzig, 102 pp.

Robinson D.L. (1987): Estimation and use of variance components. The Statistician 36, 3-14.

Searle S.R., Casella G., McCulloch C.E. (1992): Variance components. John Wiley & Sons, Inc. New York, 536 pp.

Thomas E., Stressmann U. (1972): Auswertung von Standardversuchen mittels Ausgleichspolynom. Archiv für Acker- und Pflanzenbau und Bodenkunde 16 (9) 655-663.

Wilkinson G.N., Eckert R., Hancock T.W., Mayo O. (1983): Nearest Neighbour Analysis of field experiments. Journal of the Royal Statistical Society B 45, 151-211.

Wolfinger R., Chang M. (1995): Comparing SAS GLM and MIXED procedures for repeated measures. Proceedings of the 20th Annual SAS Users Group International (SUGI) Conference, Orlando, Florida, April 2-5.