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Investigation and Modeling of the Optimization Potential of Adapted Nitrogen Fertilization Strategies in Corn Cropping Systems with Regard to Minimize Nitrogen Losses

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Table of Content

Tables

Figures

Abbreviations

A	Acre
APOLLO	Application of Precision Agriculture for Field Management Optimization
APSIM	Agricultural Production Systems Simulator
ASW	Available Soil Water
BSA	Bundessortenamt
bu	Bushel
C	Carbon
CERES	Crop Environment Resource Synthesis
CN	SCS Curve Number
CUM	Current Uniform Management
CV	Coefficient of Variability
DCP	Data Collection Points
DSSAT	Decision Support System Agrotechnology Transfer
C	Carbon
CP	Compensation Payment
dGPS	Differential Global Positioning System
DCP	Data Collection Point
DHP	Depth to the Hardpan or Restrictive Layer
DR	Drainage Rate
DSSAT	Decision Support System Agrotechnology Transfer
EC	Electrical Conductivity
EPIC	Environmental Policy Integrated Climate
ETDR	Effective Tile Drainage Rate
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
g	Gram
GDD	Growing Degree Days
h	Hour
HPF	Hardpan Factor or Restrictive Layer
IETC	International Environmental Technology Centre
IFA	International Fertilizer Industry Association
IfuL	Institut für Umweltgerechte Landbewirtschaftung
INRA	National Institute for Agricultural Research Institute National de la Recherche Agronomique
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
KAS	Kalkammonsalpeter
kg	Kilogram
km	Kilometer
L	Liter

lb	Pound
m	Meter
m^2	Square Meter
mg	Milligram
Mg	Magnesium
MNR	Marginal Net Return
mS	Milli Siemens
N/N_2	Nitrogen
N_2O	Nitrous Oxide
NH_4	Ammonium
NMF	Nitrogen Mineralization Factor
N_{min}	Soil Available Mineral Nitrogen
NO	Nitrogen Oxide
NO_2	Nitrate Oxide
NO_3	Nitrate
N_t	Total Nitrogen
OM	Organic Matter
OUM	Optimum Uniform Management
P	Phosphorus
ppb	Parts per Billion
PERFECT	Productivity Erosion Runoff Functions to Evaluate Conservation Techniques
PF	Precision Farming
R or r	Pearson's correlation coefficient
R^2 or r^2	Coefficient of Determination
RDRF	Root Distribution Reduction Factor
RMSE	Root Mean Square Error
SchALVO	Schutz- und Ausgleichs-Verordnung
SFF	Soil Fertility Factor
SHC	Saturated Hydraulic Conductivity of Deep Impermeable Layer
STICS	Simulateur Multidisciplinaire pour les Cultures Standard
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US/USA	United States of America
USDA-ARS	United States Department of Agriculture-Agricultural Research Service
VRM	Variable Uniform Management
WHO	World Health Organization
WMO	World Meteorological Organization

dedicated to the little humble-bee

1 Introduction

This dissertation "Investigation and Modeling of the Optimization Potential of Adapted Nitrogen Fertilization Strategies in Corn Cropping Systems with Regard to Minimize Nitrogen Losses" was embedded in the context of the Graduiertenkolleg (789) "Strategies to Reduce the Emission of Greenhouse Gases and Environmental Toxic Agents from Agriculture and Land Use" at the University of Hohenheim. The Graduiertenkolleg was established in 1996 at the University of Hohenheim with the objective to develop methods for quantifying and modeling the origin and the emission of greenhouse gases and environmentally toxic agents from agriculture and land use and for assess the economics of mitigation strategies (Graduiertenkolleg, 2004). Several projects were established, focusing on different aspects of greenhouse gas emission and environmental toxic agents arising from agriculture.

The aim of the study was to investigate the optimization of nitrogen fertilization strategies in corn production. Therefore the nitrogen management strategies of a current corn cropping system were considered with respect to the associated environmental impact, primarily on nitrate leaching. Based on the information of current nitrogen management strategies, the possibility to improve these strategies was tested. The potential to optimize nitrogen fertilization was simulated with a crop growth model with regard to minimize nitrogen losses.

The study was based on results of a 7-year period of continuous corn production in three farm fields in the Upper Rhine Valley. This region is characterized by intense continuous corn production and thus highly suitable for this study. Since 1998 the IfuL Müllheim (Institut für umweltgerechte Landbewirtschaftung) was in charge of conducting several studies on the optimization of corn cropping systems in the Upper Rhine Valley. A part of the data for this dissertation was collected by former projects carried out by the IfuL. Since 2003, another part of data was collected in cooperation of the IfuL and the University of Hohenheim.

1.1 Interest

The cultivation of corn (*Zea mays* L.) is characterized by an intense use of soil, water and fertilizers. In order to achieve the high yield potential of corn, a C4 plant, high input of nitrogen in the cropping systems in required, because nitrogen is the most likely yield-limiting factor. For corn, most of the nitrogen is taken up into the plant in the first two months of the growing season. However, corn plants can take up to 5 kg N ha^{-1} day^{-1} (Diepenbrock, 1996). Thus, during the growing season up to 180-200 kg N ha^{-1} can be taken up by corn plants. The current nitrogen application rates constitute about the same value, taking the mineralization potential and residual soil nitrogen into consideration. As the corn cropping system is characterized by a short growing season, followed by bare soil over the wintertime, nitrogen left in the soil after harvest has a high potential to leaching. During the first period of the growing season, corn covers only a small part of the soil, and thus, nitrogen losses could occur after heavy rainfalls. Because corn can be grown on the same field season after season, regions like the Upper Rhine Valley are often dedicated to continuous corn production. The combination of all these factors characterizing a corn cropping system lead to an increased risk of nitrogen losses in corn production (Ferguson et al., 2002). Thus, intense corn cropping systems may be associated with negative effects on the environmental quality due to nitrogen losses to groundwater and nitrogen losses to the atmosphere.

The quality of the groundwater is directly influenced by the land use, which in the Upper Rhine Valley is mainly agriculture with intense corn production (Umweltinformationssystem Baden-Württemberg, 2004). In 2001, an investigation of the groundwater quality in the Upper Rhine Valley was performed by the project Interreg II (BUND, 2003). The results indicated that the threshold of 50 mg NO_3 L^{-1} was exceeded by 15 % of the measurements analyzing the groundwater quality (BUND, 2003). At the same time about 75 % of the drinking water demand in the region between the Black Forest and the Vogesen were satisfied by the groundwater sources of the Upper Rhine Valley. More than three million people depend on the water resource of 45 billion m³ (BUND, 2003). In order to improve the water quality in the Upper Rhine Valley, areas were declared as water protection areas during the last decade. Thus, the producers had to adapt their nitrogen management in consideration of specified soil nitrogen thresholds and management strategies.

The urgency to optimize nitrogen fertilization strategies is strengthened by the fact that the nitrogen uptake within a field is not necessarily homogenous. The growth conditions in a field are influenced by many factors, and as a result, the nitrogen uptake could differ within a field. In current farming systems, nitrogen application strategies are uniform across a field, disregarding the underlying spatial variability within a field. Thus, uniform nitrogen applications could easily lead to overfertilization in one area and underfertilization in other parts of the field. However, overfertilization of a field should be avoided, because it increases the risk of nitrate leaching. In order to increase the water quality, the postulation for adapted nitrogen fertilization strategies must account for spatial variability within a field.

1.2 Aim

The aim of this dissertation was to determine if the existing nitrogen management strategies in a continuous corn cropping system in the Upper Rhine Valley could be optimized to reduce nitrogen losses, while maintaining the producers profits. The nitrogen loss due to leaching to the groundwater and to a lesser extent gaseous losses into the atmosphere were of special interest. This investigation was based on a 7-year data set (1998-2004) of continuous corn production in the Upper Rhine Valley, collected on three fields in Weisweil.

The objectives of the study was to investigate, if i) current corn cropping systems provide the possibility to further optimize nitrogen fertilizer strategies and ii) if a potential further optimization of nitrogen application could contribute to a reduction of nitrogen losses.

Thus, the specific objectives of this study were:

- to asses the spatial corn yield variability within three fields,
- to determine the underlying factors for spatial yield variability in the three fields,
- to use a crop growth model to estimate abiotic factors, and to understand the causes of spatial yield variability,
- to use a crop grow model to study optimum nitrogen fertilization strategies on field and site-specific levels,
- to estimate the optimization potential of site-specific nitrogen fertilization strategies with regard to nitrogen losses to groundwater (nitrate) and atmosphere (nitrous oxide).

1.3 Proceeding and Organization

This dissertation is a compilation of chapters describing basic information associated with the topic of this study, and chapters containing journal manuscripts submitted to refereed scientific journals. The manuscripts address specific objectives that were related to this study.

In order to investigate and model the optimization potential for adapted nitrogen fertilization strategies with regard to nitrogen losses, the following approach was followed.

1. The three farmer fields in the Upper Rhine Valley were investigated with regard to the nitrogen management and the resulting corn grain yield. At the same time, the spatial yield variability was measured within the fields, as well as temporal stability of yield pattern (Chapter 5). Spatial variability and temporal stability of yields are preconditions to adapt the nitrogen application rate on a spatial scale. In order to find explanations of the measured yield variability, correlations between yield-limiting factors and yield were tested (Chapter 5 and 7).
2. The identification of yield-limiting factors was performed by implementing simple mathematical regressions (Chapter 5) and crop growth models (Chapter 7). Compared to simple mathematical regressions that explain the spatial yield variability, a crop growth model can account for complex interactions between yield-limiting factors.

3. The crop growth model was calibrated for the spatial variability within the corn fields (Chapter 7). Afterwards the model was used to simulate different nitrogen application strategies, including the associated impact on the environment (Chapter 8). The different strategies were evaluated concerning nitrogen losses in terms of nitrate leaching and nitrous oxide emissions. As an outcome of the simulations, the optimization potential of variable-rate nitrogen fertilization strategies was determined (Chapter 9).
4. This study ends with a general discussion section (Chapter 9), which contains an estimation of the minimum potential nitrogen loss and ranks the results in the overall context. Additional recommended future work is included in the discussion section. The summary of the results completes the study.

2 Environmental Pollution by Nitrogen from Agricultural Land Use

This chapter addresses the problem of environmental pollution from agricultural land use. According to the topic of the study, it focuses on the importance on nitrogen. Thus this chapter covers the nitrogen cycle and nitrogen losses to the groundwater and the atmosphere.

2.1 Environmental Pollution from Nitrogen Application

It is well known that the current intense agricultural land use in the developed countries leads to environmental pollution. This is mainly caused the by increased input of nitrogen fertilizer into farming systems (Lægreid et al., 1999a). The input of nutrients and energy into the farming system is large compared to internal fluxes and cycling within the system (Haag and Kaupenjohann, 2001). However, the nutrient balances in the developing countries are still negative (Stoorvogel and Smaling, 1998), resulting in an imbalanced nutrient distribution on a global scale.

Nitrogen, which is essential for all life processes in plants and increases the plant growth and productivity, has been overused. In the developed countries where high crop yields are achievable and commercial sources of nitrogen are readily available, fertilizer application rates per year reach levels of up to 200 kg N ha^{-1} for cereals crops. Up to 400 kg N ha^{-1} is used for fodder grass and for silage (Hatch et al., 2002). Studies of International Fertilization Industry Association (IFA) and Food and Agriculture Organization of the United Nations (IFA and FAO, 2001) showed that during the growing season plants often take up only 50 % of the applied nitrogen, with the remaining nitrogen likely lost by emission or leaching. In 1985, the nitrogen surplus in Germany was calculated to be about 100 kg N ha^{-1} (Bach, 1987), and in animal farms, the surplus was computed to be up to 253 kg N ha^{-1}. On a European and global scale, the surplus of nitrogen still continues to be high (Behrendt et al., 2002; Krauss, 1999). Any remaining nitrogen in the soil, which is not immobilized by microorganisms or utilized by the plants, is a potential source of nitrogen pollution (Hatch et al., 2002). Publications of the FAO (1996) showed that in parts of Europe, nitrate contamination of groundwater has grown to an extent that more than 10 % of the population is exposed to levels that exceed the World Health Organization (WHO) guidelines for drinking water. To combat this problem, the European Union (EU) passed a law in 1991 designed to improve groundwater quality by providing incentives for producers to reduce nitrogen applications (EC-Council Directive, 1991).

In response to this legislation, the State of Baden-Württemberg (Southwest Germany) passed a law called “Schutzgebiets- und Ausgleichs-Verordnung” (SchALVO) in 1991. Since then the law has been changed and adapted several times, but the overall objective target has been kept. The SchALVO provides the basis for protecting the groundwater against pollution from agricultural sources, but focuses on the reduction of nitrogen losses to the groundwater (Schulze, 2001). Thus, existing pollutants of the groundwater should be reduced and further pollution should be avoided by following best management practices in water protection areas.

It is widely known that the intense nitrogen fertilization in agriculture led to increased nitrogen leaching and to increased nitrogen emissions (Haag and Kaupenjohann, 2001; Lægreid et al., 1999b). Thus, the United Nations Framework Convention on Climate Change (UNFCCC) has called the attention to the effect the global warming, which is the result of human activities (UNFCCC, 2004b). At the conference in Kyoto (Japan) on 11 December 1997, 185 parties acknowledged the existance of the global warming (UNFCCC, 2004b). The Kyoto protocol, which was adopted at this conference, set the stage to reduce the emissions of greenhouse gases worldwide (UNFCCC, 2004a).

Several studies indicated that current nitrogen application practices often increase the potential for contamination of the groundwater (Kanwar et al. 1993; Randall et al., 1997; Cambardella et al., 1999). In order to reach the objective targets of the EU and the Kyoto Protocol, agricultural practices need to be changed, especially in terms of nitrogen management. In this work, the main scope was focused on nitrate leaching to the groundwater and the minor focus was given to gaseous losses of nitrous oxide to the atmosphere. The effects of soil management (e.g. tillage effects) and crop production practices (e.g. crop rotation effects) on nitrogen transformation and movement in the farming system were beyond the scope of this work.

2.2 Nitrogen Cycle

Nitrogen is an incredibly versatile element, existing in both inorganic and organic forms, as well as many different oxidation states (Marschner, 1986). The principal forms of nitrogen in soil are ammonium (NH_4^+), nitrate (NO_3^-) and organic substances. The movement of nitrogen between the atmosphere, biosphere, and geosphere in different forms is described by the nitrogen cycle as shown in Figure 1.

Nitrogen enters a farming system, which is defined as an integrated set of farm management practices used for crop and livestock production, by atmospheric deposition, as fertilizer, by irrigation water, livestock production, feed, manures and by nitrogen fixation. Current rates of atmospheric nitrogen decomposition achieve a level of 25-100 kg N ha^{-1} $year^{-1}$ in Europe and the USA, which is 5-20 times more than in the pre-industrial times (Hatch et al., 2002).

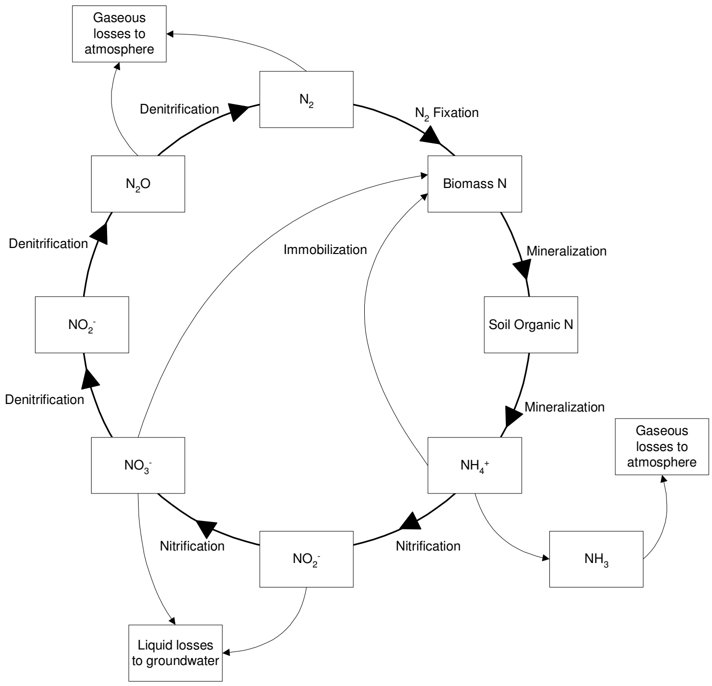

Figure 1. Nitrogen cycle (modified from http://bioag.byu.edu/aghort/514pres/denitrif/ sld002.htm, 2004).

Kanwar (1972) pointed out six basic reactions, which occurs to nitrogen in soil. Nitrogen could be utilized by crops in the form of ammonia or nitrate, incorporated into organic matter and thus be subject to immobilization, released from an unusable organic form into an inorganic form via mineralization, transformed into inert gas and lost through volatilization, lost out of the rooting zone of the plants by leaching or lost in surface runoff and soil erosion.

2.3 Nitrogen Losses to the Groundwater

In Central Europe, approximately 2000-9000 kg N ha^{-1} is stored in the organic matter of the upper horizon in the soil (Sattelmacher, 1990). The soil mineral pool is under a constant flux supplemented by the decomposition of soil organic nitrogen by the process of net mineralization. By the process of mineralization, the organic nitrogen is transformed into ammonia and converted into nitrite and nitrate via nitrification by microbes (Sieling et al., 1999). The net nitrogen mineralization ranges from 50-130 kg N ha^{-1} $year^{-1}$ for low organic cropped soils up to > 400 kg N ha^{-1} $year^{-1}$ under fertilized pastures (Jarvis et al., 1996). While organic fixed nitrogen is not mobile or leachable, some organic forms of nitrogen, which are soluble in water, like urea, amino acids and small proteins, are prone to leaching (Lægreid et al., 1999b). Because of its negative charge nitrate is not fixed to the sorption complex of the soil and therefore is highly susceptible to leaching.

2.3.1 Nitrate Leaching

Leaching is defined as the process where substances dissolved in fluid (i.e. water) are released from the soil, and are carried downward in the soil profile and lost out of the plant root zone. Leaching of nitrate causes eutrophication of rivers and lakes, which is followed by a gradual reduction in the number of species of plankton and diatoms, while epiphytes increase. The excessive biological growth results in hypoxia, the decrease of oxygen concentration in the water bodies (UNEP/IETC, 2002), which leads ultimately to the death of fish (Heathwaite, 1993).

Investigations of Werner and Wodsak (1994) have shown that the average nitrogen leaching rate from terrestrial ecosystems in Central Europe is 15 kg N ha^{-1} $year^{-1}$. In 1994 about 16 kg N ha^{-1} $year^{-1}$ were lost by leaching in Germany. Whereas Pedersen (2003) assumed a total average nitrogen leaching rate of 153 kg N ha^{-1} in arable farming. The nitrogen lost by leaching can be found in rivers and lakes. The EU has launched several directives to reduce water pollution caused or induced by nitrates from agricultural sources (EC-Council Directive, 1991). McKenna (1998) determined that the groundwater under about 22 % of the cultivated land in the EU showed a nitrate concentration above the threshold of 50 mg NO_3 L^{-1}. Similar results were found for 30-40 % of the lakes in the EU (Anon., 2002a). Results for the Midwest USA (Spalding and Exner, 1993) and the northern China (Zhang et al., 1996) confirmed this situation. Thus, a large proportion of nitrate in the groundwater is a result of agriculture. Currently, the objective underlying current agricultural practices in the EU is to meet the 1980 EC-Drinking Water Directive in shallow groundwater (maximum concentration of 50 mg NO_3 L^{-1}). In a current report provided by the German government, for most drinking water fountains, a reduction in nitrate concentration between 5-25 % was found across Germany due to these policies (Bundesregierung, 2004a).

2.3.2 Processes Influencing Nitrate Leaching

Leaching provides a way to regenerate groundwater (Sattelmacher and Stoy, 1990). Nitrate leaching occurs when the soil receives more water from infiltration than it can hold by capillary forces, and thus negatively charged nitrate is carried away with the water. Under German conditions, leaching mainly occurs during the wintertime. Verhagen and Bouma (1997) showed that nitrogen leaching during wintertime is linearly related to the residual soil mineral nitrogen concentration in the root zone at harvest. During the growing season the risk of nitrate leaching is reduced, due to an increased evapotranspiration and decreased water conductivity in the soil (Van der Ploeg et al., 1995). Empirical thresholds for levy-free nitrogen surpluses (e.g. 100 kg N ha^{-1} for arable land in 2008) are fixed at present values (Oenema et al., 1997), hereby neglecting the effect of soil heterogeneity. However, the lapse and magnitude of nitrate leaching is mainly influenced by site characteristics, like weather, soil and water conditions, and the soil cultivation system (Böttcher and Strebel, 1985).

2.3.2.1 Soil and Water Interactions

Soils differ in their natural content of carbon and nitrogen (Kuntze, 1983), which results in different behavior and intensity of the nitrogen mineralization (Table 1). Soils with a high C/N-ratio have a higher nitrogen mineralization potential.

Table 1. Carbon and nitrogen content (% of dry matter, dm), and nitrogen mineralization of different soil types, indicated by the German classification (modified from Kuntze, 1983).

Soiltype	C (% dm)	N (% dm)	N mineralization (kg N ha^{-1} $year^{-1}$)	
			1 %	2 %
Sand	2.58	0.14	60	120
Schwarzerde	3.10	0.28	110	220
Parabraunerde	1.17	0.11	46	92
Braunerde	1.55	0.15	63	126
Auenlehm	1.43	0.15	63	126
Niedermoor	57.1	2.98	450	900
Hochmoor	52.8	1.73	104	208

Both mineralization rate and the soil texture are important in determining nitrogen leaching. Soil texture mainly influences the water conductivity in the soil (Scheffer and Schachtschabel, 1989). In general, the water conductivity in the soil depends on the radius of the water-bearing pores, and on the continuity and network of the pores (Rambow and Schindler, 1994). The relationship between water content and soil-water tension for different soil types is shown in Figure 2. The soil-water or soil-moisture tension is lower in sandy soils compared to silty soils or clay soils, resulting in a higher potential for nitrogen leaching in sandy soil. The water movement in the unsaturated soil layers influences the infiltration, the capillary rise, the water storage, the regeneration of groundwater and the evapotranspiration (Rambow and Schindler, 1994). Therefore the water movement is responsible for the transport of nutrients, as well as harmful substances through the soil (Rambow and Schindler, 1994). Studies of Misra and Mani (1994) indicated that the risk of nitrate leaching is increased if water tables are shallow. Because of this, the weather pattern are also important in determining nitrate leaching. Addiscott et al. (1991) showed that nitrogen losses via leaching were directly related to rainfall in the three to four weeks following the fertilizer application.

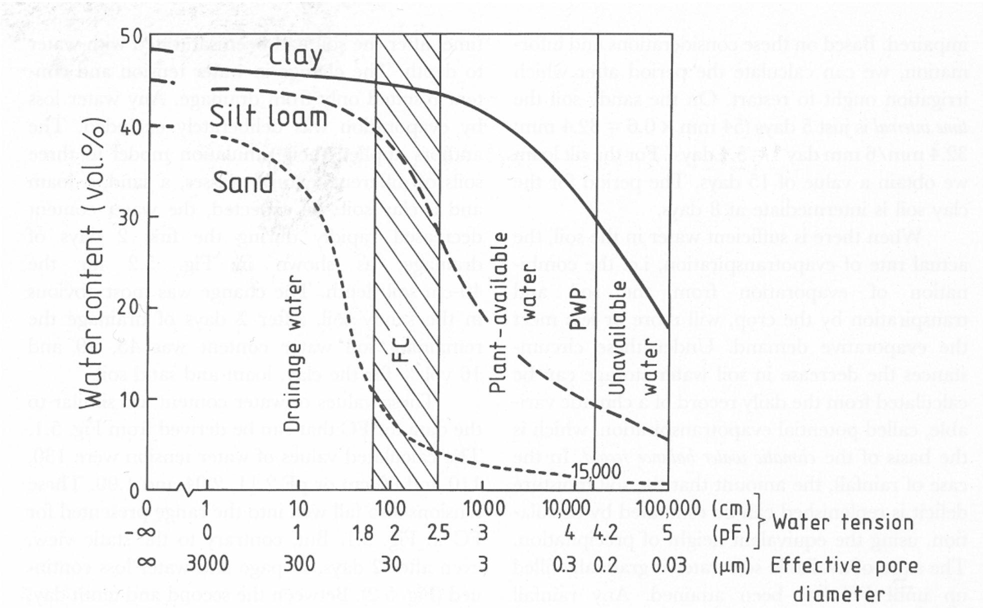

Figure 2. Relationship between water tension and water content (pF-curve) in the upper soil layer for a sand, a loam and a clay soil (taken from Ehlers and Goss (2003) based on Scheffer and Schachtschabel, 1998).

2.3.2.2 Crop Cultivation

Another important factor affecting nitrogen leaching is the cultivated crop. In general, a bare, fallow soil is more likely to leach nitrogen than a cropped soil because there are no plants present to take up any mineral nitrogen (Hatch et al., 2002). The earlier a crop emerges and the quicker it covers the ground, the more nitrogen is taken up and therefore the risk of nitrogen leaching is reduced (Hatch et al., 2002). Because of this, a high risk of nitrate leaching exists for corn crops. Due to continuous nitrogen mineralization and low nitrogen uptake at the end of the growing season, high amounts of nitrogen were generally found in the soil after corn production (Lambert et al., 2002). In most corn cropping systems the straw remains on the field. In contrast to wheat straw, with less content of nitrogen in the residue, corn straw contains more nitrogen in the residue and is therefore more susceptible for mineralization. Thus the potential for nitrate leaching is increased, when straw of crops, as legumes, oil rape, potatoes or corn, with a low or narrow C/N-ratio remains on the field (Claupein, 1994). In several studies continuous corn production has been identified as providing the greatest amount of nitrate into the groundwater through surface drainage (Kanwar et al. 1993; Weed and Kanwar, 1996; Randall et al., 1997) and consequently led to an increased nitrate concentration in the groundwater (Schröder et al., 1996; Van Dijk et al., 2004).

The major impact on the leaching potential is caused when the release of nitrogen from mineralization or application is not synchronized with the nitrogen uptake of the growing plant. This might happen by natural nitrogen sources, and by the application of mineral and organic nitrogen as fertilizer. Studies of Vinten et al. (1991) have shown that an increased application of mineral fertilizer enhances leaching, but leaching has been also associated with manure application and the incorporation of large amounts of crop residue (Torstensson, 1992; Jackson and Smith, 1997). Asmus (1993) showed that the application date for manure has a strong influence on the leaching potential. Thus, it is important to determine the actual amount of soil available nitrogen and to adapt the manure application rates to these amounts. In order to determine the susceptibility for leaching, Kues (1994) postulated to determine the depth of nitrate shifting for each soil type, climate and crop rotation. In studies of Ten Berge et al. (2004) a linear response of nitrate concentration in the groundwater to residual mineral soil nitrogen (N_{min}) was determined. Ten Berge et al. (2004) found that N_{min} (especially N_{min}-NO_3) was a much better predictor for estimating nitrate leaching on arable land, than nitrogen balance components like the nitrogen application rate or nitrogen surplus in a field (Van Dijk et al., 2004). Thus, the amount of soil available nitrogen should not be ignored when computing optimum nitrogen application rate.

2.3.3 Methods to Reduce Nitrate Leaching

Dampney et al. (2002) reviewed methods to decrease nitrogen losses into groundwater in Europe. Several studies exist, which indicate that the risk of nitrogen leaching could significantly be reduced, when the soil was covered with vegetation, e.g. cover crops (Lewan, 1994; Johnson et al., 1997). Evapotranspiration might be increased by cover crops and leaching prevented during the growing season by drawing the water from deeper layers to upper soil layers. The plants are able to reach nitrate that has been temporally out of reach (Kuhlman et al., 1989). In order to do so, it is important that the cover crops are planted early enough to develop fast and take up the nitrogen deep in the soil. While cover crops could cause reduced yields in the short-term (Wallgren and Lindén, 1994), they also may lead to an increased pool of mineralizable nitrogen in the soil (Jensen, 1992), especially in a continuous corn rotation, where the nitrate leaching level could be decreased to about 50 %, when a winter catch crop is grown (Schröder et al., 1996). The use of nitrification inhibitors could reduce the amount of nitrate leaching and nitrous oxide emissions as well (Di and Cameron, 2004). Gutser and Hauk (1994) showed that adding the straw of cereals to the field could reduce the nitrate leaching, due to an increased C/N-ratio and the subsequent immobilization of nitrogen. In their studies, between 30-50 kg N ha^{-1} could be immobilized when about 500 kg straw were broadcast per hectare.

However, the most important method to reduce nitrate leaching is the optimization of nitrogen application rates, which can ultimately be accomplished by matching crop nitrogen demand with the nitrogen inputs on a spatial scale. A more flexible and mechanistic approach to fertilizer management, applying knowledge of fundamental processes and considering different sources of variability, could increase control over nitrogen leaching and emissions. Precision farming offers great potential to match crop nitrogen demand with nitrogen application rates. The incorporation of spatial and temporal variability in nitrogen recommendations has the potential to increase fertilizer use efficiency and enable producers to stay within the limits imposed by current and future policies.

2.4 Nitrogen Losses to the Atmosphere

Because of the harmful impact on the environment, there was an international agreement that the emissions of greenhouse gases, including carbon dioxide, methane and nitrous oxides must be limited (UN, 1997). The Intergovernmental Panel on Climate Change (IPCC) has been established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) "to assess scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation" (IPCC, 2004). The UNFCCC was negotiated in 1992 (UNFCCC, 1992). The UNFCC postulated the stabilization of the greenhouse gas concentration in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate systems" (UNFCCC, 1992). At the Conference of the Parties to the UNFCCC in Kyoto in 1997, the basis was established to pass a law. In the Kyoto Protocol, the developed countries committed to reduce the overall emissions of the main greenhouse gases in the period from 2008 to 2012 under the level of the year 1990 (UNFCCC, 2004a). The government in Germany plans a reduction of emissions of about 21 % compared to the year 1990, while a reduction of 19 % was achieved in the year 2004 (Bundesregierung, 2004b). This equals a reduction of overall nitrogen emissions from about 1100000 t^{-1} $year^{-1}$ in the year 1985 to about 700000 t^{-1} $year^{-1}$ in the year 2000 (Bundesregierung, 2004a). The entry into force of the Kyoto Protocol was discussed at the 10^{th} Session of the Conference of the Parties to the UNFCCC in Buenos Aires from December 6-17, 2004. The Kyoto Protocol is scheduled to enter into force on February 16, 2005 (Bundesregierung, 2004c).

Although the nitrogen loss from agriculture through emissions is insignificant in terms of agronomy or economy, the emissions of nitrous oxide has an enormous environmental impact. Nitrous oxides is a greenhouse gas, as well as carbon dioxide, methane, halogenated fluorocarbon, perfluorocarbon and sulfur hexafluoride. Investigations of the IPCC have shown that the atmospheric concentration of greenhouse gases, like carbon dioxide, methane and nitrous oxide have increased by 31 %, 151 % and 17 %, respectively (Bouwmann et al., 2000; IPCC, 2001) within less than 150 years (IPCC, 2001). The atmospheric concentration of nitrous oxide has increased from 270 ppb at the preindustrial time to 314 ppb at present (IPCC, 2001), thus it causes between 5-6 % of the present global warming (Lægreid, et al., 1999a; IPCC, 2001). Today, there is no doubt that the change in atmospheric composition is mainly caused by human activities (Houghton, 1997; IPCC, 2001). The increase of nitrous oxide emissions is attributed to the increased nitrogen input in the biosphere (Mosier et al., 1998; IFA and FAO, 2001).

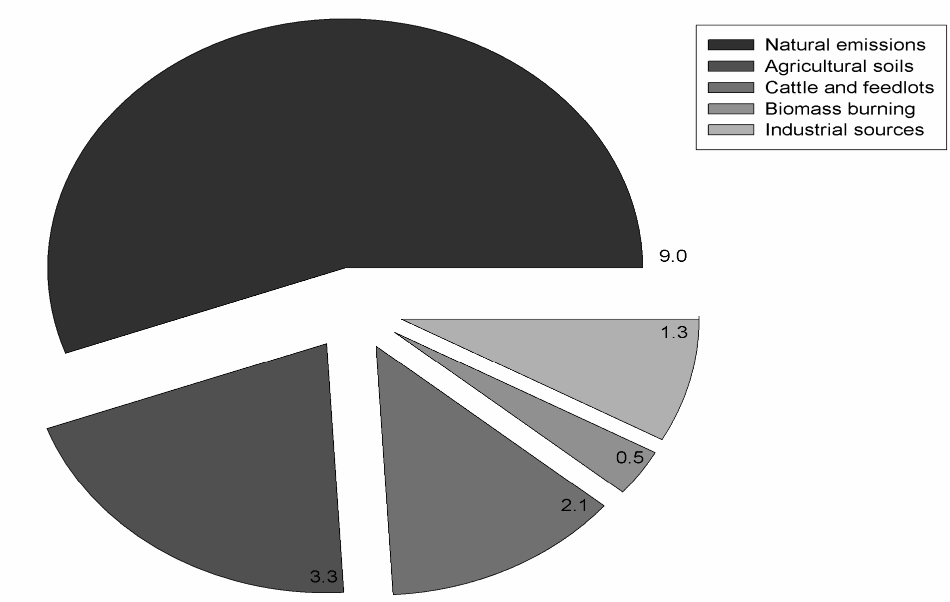

Figure 3. Natural and anthropogenic emissions of nitrous oxide (Mt N year^{-1}) worldwide (modified from Mosier et al., 1998).

Agriculture accounts for approximately half of the anthropogenic nitrous oxide emission in the EU (UNFCCC, 1998). On a global scale, 47 % of nitrous oxide emissions (IPCC, 2001) come from anthropogenic sources, particularly from the agricultural nitrogen cycle (Mosier et al., 1998). The nitrous oxide emissions caused by human activities are mainly due to tillage (44 %) and fertilization (22 %) on agricultural soils, followed by burning of biomass (9 %) and fossil fuels (10 %). The chemical production contributes 15 % to the nitrous oxide emissions (Figure 3). The high emissions from agricultural soils are mainly caused by the application of nitrogen fertilizer, which is transformed by nitrification and denitrification into nitrous oxide.

2.4.1 Formation of Nitrous Oxide

Nitrous oxide (N_2O) is generated by nitrification and denitrification when microbes transform inorganic nitrogen, including ammonia and nitrate (Firestone and Davidson, 1989; Granli and Bøckman, 1994; Hutchinson and Davidson, 1993). Both processes are governed by the soil water content. Nitrification mainly occurs when 30-60 % of the pore space is water-filled, and denitrification mainly occurs when 50-80 % or 60-90 % of the pore space is filled with water, depending on the soil properties (Bouwman, 1998).

2.4.1.1 Nitrification

Nitrification is characterized as the process in which ammonium (NH_4^+) is converted to nitrite (NO_2^-) and then nitrate (NO_3^-). This process naturally occurs in the environment, where it is carried out by specialized bacteria. The process is described by the following two equations:

$$NH_4^+ + 3/2\ O_2 \rightarrow NO_2^- + 2H^+ + H_20 \quad [1]$$

$$NO_2^- + 1/2\ O_2 \rightarrow NO_3^- \quad [2]$$

The process of creation, consumption and disposal of nitrous oxide is described by Firestone and Davison (1989) as the "hole-in-the-pipe" model (Figure 4).

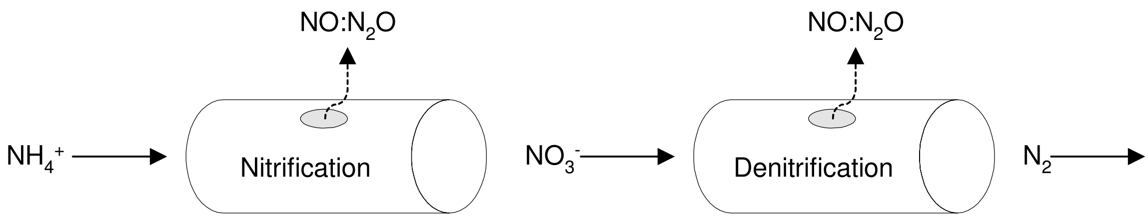

Figure 4. The "hole-in-the-pipe" model (modified from Firestone and Davidson, 1989).

In agricultural soils, the nitrification is mainly carried out by Nitrosomonas, Nitrosospira and Nitrobacter bacteria (Enquête-Kommission "Schutz der Erdatmosphäre" des deutschen Bundestages, 1994; Haynes, 1986). Soil water and oxygen content, as well as the macro pores, organic matter and pH in the soil mainly determine the development rate of nitrous oxide. The optimum condition for the nitrification in soil is at a water content of 60 %. When the water content is increased, the nitrification is limited by oxygen, and vise versa.

Between 1 % and 4 % of the nitrogen input is turned into nitrous oxide during the nitrification process (Enquête-Kommission "Schutz der Erdatmosphäre" des deutschen Bundestages, 1994), and about 0.5 % is turned into nitrogen oxide (Veldkamp and Keller, 1997).

2.4.1.2 Denitrification

Denitrification is defined as the reduction of nitrogen oxides (usually nitrate and nitrite) to molecular nitrogen or nitrogen oxides with a lower oxidation state of nitrogen by bacterial activity. "Nitrogen oxides are used by bacteria as terminal electron acceptors in place of oxygen in anaerobic respiratory metabolism" (www.soils.org/cgi-bin/gloss_search.cgi, 2004). Denitrification often occurs when the soil is wet or compacted or warm, because these are situations where oxygen is a limiting factor.

The denitrification is described by the following equation:

$$NO_3^- \rightarrow NO_2^- \rightarrow [NO] \rightarrow N_2O \rightarrow N_2 \qquad [3]$$

The bacteria that carry out the denitrification process are mainly Pseudomonas, Azospirillum (Enquête-Kommission “Schutz der Erdatmosphäre” des deutschen Bundestages, 1994) and Alcaligenes (Hutchinson and Davidson, 1993), but also fungi and yeasts are involved (Motz, 2002). During denitrification, nitrous oxide and nitrogen oxide are formed (Lægreid, 1999b). The rate of nitrous oxide can vary between 0 and 100 % in dependency of the availability of carbon and nitrogen, soil water and soil temperature (Focht, 1978; Arah and Smith, 1990). Decreasing oxygen content and increasing water content in the soil increases the process. The availability of organic matter and high temperature also speeds up the denitrification process (Enquête-Kommission “Schutz der Erdatmosphäre” des deutschen Bundestages, 1994). Between 0.5 % and 1.5 % of the applied nitrogen to agricultural soil may be emitted as nitrous oxide (McElroy and Woofsy, 1985).

2.4.2 Processes Influencing Nitrous Oxides Emission

The amount of nitrous oxide emission is mainly influenced by the nitrogen fertilization (Granli and Bøckman, 1994; Schmidt, 1998) as shown in studies of Schmidt and Bock (1998), who determined a strong correlation between nitrogen content in the soil and nitrous oxide emissions. The positive correlation between increased nitrogen input and increased nitrogen emissions (Bouwman, 1990; Eichner, 1990) provides the basis for estimating the impact of agriculture on nitrous oxide emissions on a global scale (IPCC, 1997). The emission factor is based on studies of Bouwman (1996) and is calculated by the following function:

$$EF = NI * 1.25 (+/-1) \% + BE \qquad [4]$$

Where EF = emission factor (kg N ha^{-1}), NI = nitrogen input (kg N ha^{-1}), and BE = background emission (kg NO_2-N ha^{-1}), which are normally set to 1.

Nitrogen that remains in the soil after harvest is the major source for nitrogen pollution of the groundwater (Van der Ploeg et al., 1995). At the same time, a substantial part of agricultural emissions is believed to be derived from nitrogen lost from agricultural land after leaching and run-off into drainage waters (Dowdell et al., 1979). This means reducing nitrate leaching would also reduce nitrous oxide emissions.

Verhagen and Bouma (1998) postulated that farm management should aim at a nitrogen profile in the fall that has a low risk of exceeding the present nitrate leaching limit during the wet season. In order to do so, the amount of nitrogen left in the soil after harvest needs to be reduced to a minimum value. This value might depend on natural soil characteristics as well as on local weather conditions. It is widely known, that those premises for nitrate leaching might vary spatially, not only on large but also on a small scale. This implies that the farm management should take this variability into account, and therefore, adapt the management strategies to the natural conditions. Thus, the nitrogen application should match the crop demand on a spatial and on a temporal scale.

3 Site Description

The area of investigation was located in the southwestern part of Baden-Württemberg (Germany), more precisely the Upper Rhine Valley. The Upper Rhine Valley spans the region between the Black Forest in the East, the Alps in the South, the Vogesen in the West and the Odenwald and the Pfälzer Wald in the North (Figure 5). The study was conducted on three fields near Weisweil (48° 19' N, 7° 67' E), which is located northwest of Freiburg, Germany.

3.1 Formation of the Upper Rhine Valley

The Upper Rhine Valley was evolved from the bulge and irruption of the Alps, 120 Mio and 45 Mio years ago, respectively (Huttenlocher, 1972; Friedmann, 2000). The Upper Rhine Valley is a sinking of the earths crust and was not formed by a river. The drawdown of the Upper Rhine Valley is up to 5 km deep and filled with tertiary and quaternary sediments. The whole valley is about 300 km in length and about 30-40 km in width (Friedmann, 2000). The structural salient was built of shifted parts of Paleogene and Mesozoic layers (Sick, 1994), which were formed by irregular bursts and gravitates of the clods (Friedmann, 2000).

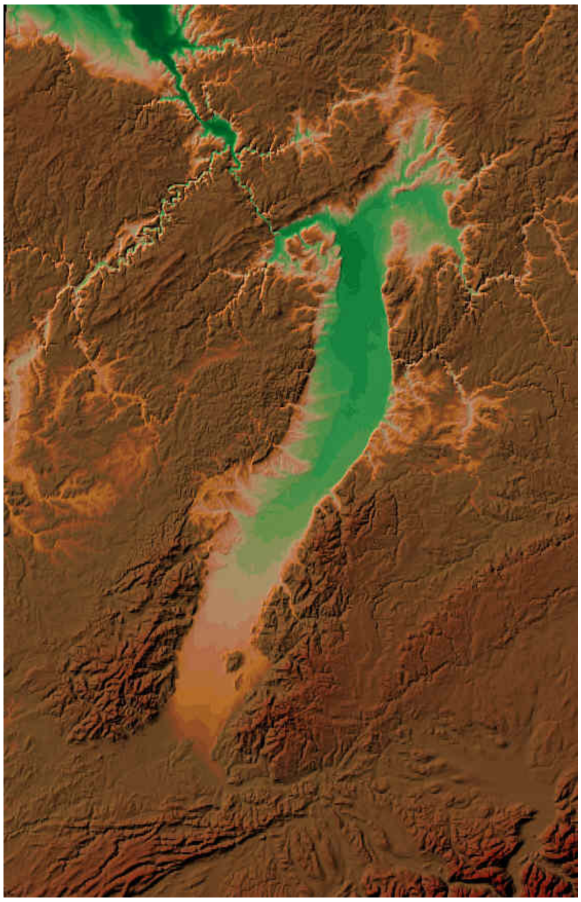

Figure 5. Relief of the Upper Rhine Valley, which is surrounded by the Black Forest, the Alps, the Vogesen, the Odenwald and the Pfälzer Wald (taken from http://oberrheingraben.de /Morphologie/Morphologie.htm, 2004).

During the time the dip of the Upper Rhine Valley was filled with roundabout 19.000 km^3 of sediments; mainly silt, sand, gravel, flint and marl were carried by rivers of the surrounding area (Figure 6). The accumulations reached a thickness of up to 3500 m at the estuary of the Neckar river into the Rhine River (Huttenlocher, 1972). After the Paleogene era, the Rhine flow through the Upper Rhine Valley and carried gravel and sand, which levelled the Rhine Valley.

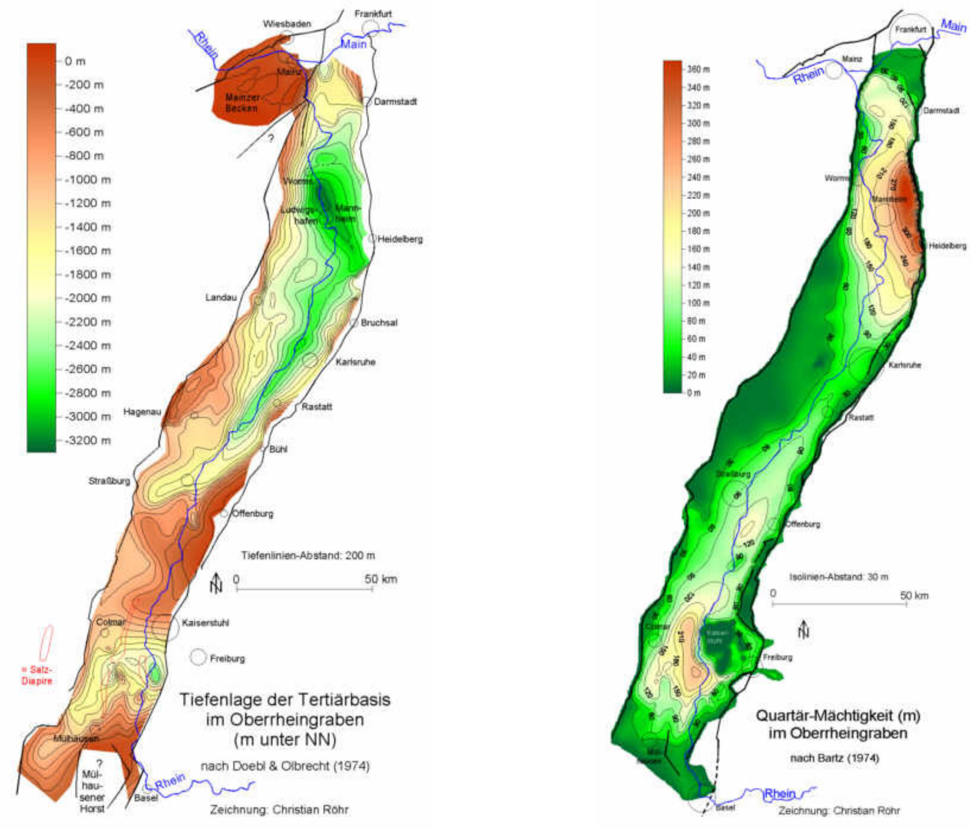

Figure 6. Depth of the base of the Upper Rhine Valley (left) and the thickness of the accumulations of sediments (right) in the Upper Rhine Valley (taken from http://oberrheingraben.de/ Grabenfuellung/ Grabenfuellung.htm, 2004).

The levelling process happened mainly during the summer, when the Rhine was filled with melting water. During the wintertime, fine loess was blown into the Rhine Valley and accumulated along the valley (Huttenlocher, 1972). After the last ice age gravel, flint and sand plateaus were formed, which were building a contrast to the loess layer.

3.2 Soil

In the Upper Rhine Valley, different soil types were developed in parallel on a very small scale, depending on the rock layer that was transformed into soil. In the Upper Rhine Valley itself, predominately brown soils of loamy sand and sandy loam, rich in nutrients were formed. However, alluvial soils consisting of sandy, silty and clayey loam were also formed in this region (Sick, 1994).

The predominant soil type in the area of investigation is terrestrial Parabraunerde and Pararendzina. Thus, the soil consists mainly of loamy soil (Götz and Fautz, 1962), which was developed from the sedimentations. The region north of the Kaiserstuhl is characterized by gravel or sand plateaus covered with loess (Huttenlocher, 1972) of a varying depth from 3-6 m (Mäckel, 1998). The plateaus were built out of gravel and flint carried by the Rhine, and is characterized by poor water availability (Mäckel, 1998).

3.3 Climate

The Upper Rhine Valley is characterized as one of the warmest (meanly 9.5° C) and sunniest (more than 1800 sunshine hours) regions in Germany. The precipitation in the Upper Rhine Valley is uneven, which means higher precipitation in the eastern part (west of the Black Forest) and lower precipitation in the western part (east of the Vogesen).

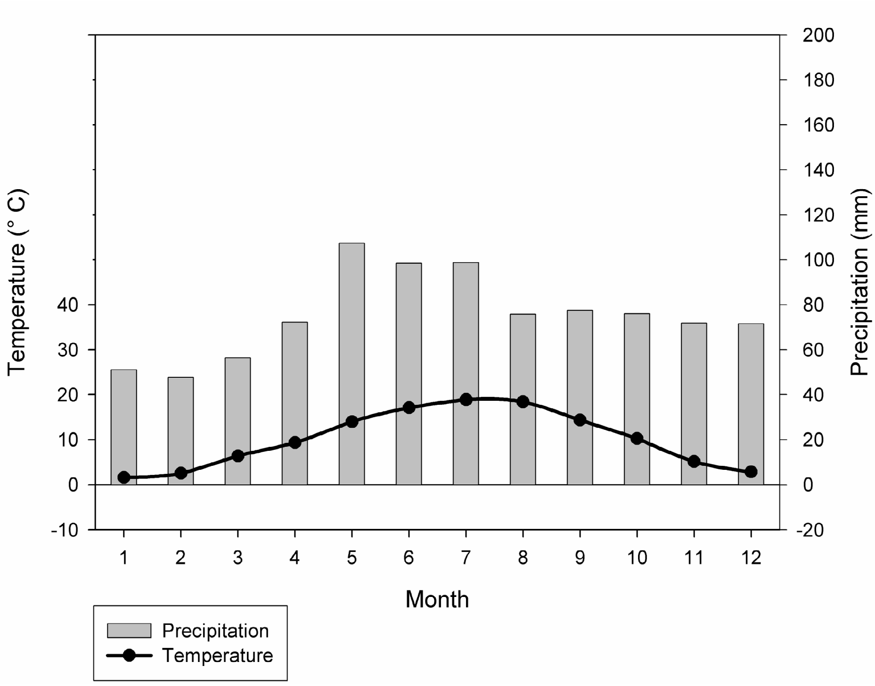

Figure 7. Monthly mean temperature and mean precipitation in the region around Weisweil over a 28-year period (1976-2003) collected from the weather station in Emmendingen-Mundingen, provided by the Deutsche Wetterdienst.

The weather data of the study area (Figure 7) were obtained at the weather station located at Emmendingen-Mundingen. Over the wintertime, the climate is mild, resulting in a mean temperature of about 9.5° C, which varies from a mean of 2.2° C in January to 19.7° C in August. The average total annual solar radiation in the Upper Rhine Valley is approximately 11390 kJ m^{-2}. The mean annual precipitation in this area is 910 mm, of which about 67 % occurs during the growing season (April – October).

3.4 Agricultural Structure and Land Use

In the region of the Southern Upper Rhine Valley, the agricultural land use area covers about 138460 ha. Small-scaled fields and heterogeneous land use characterize the whole region of the Southern Upper Rhine Valley.

Since 1979, the number of farms in the Southern Upper Rhine Valley has reduced from 19346 to 16478 farms in 1991 and to 12696 farms in 2003. In the Weisweil region, the number of farms has decreased from 63 farms in 1979 to 45 farms in 1991, down to 24 farms in 2003. At the same time, the proportion of professional framers decreased from 55.6 % in 1979 to 4.5 % in 2003 in the Weisweil region. In Figure 8 it is shown, that the numbers of farms for an agricultural land use area between 2 ha and 20 ha has been reduced dramatically.

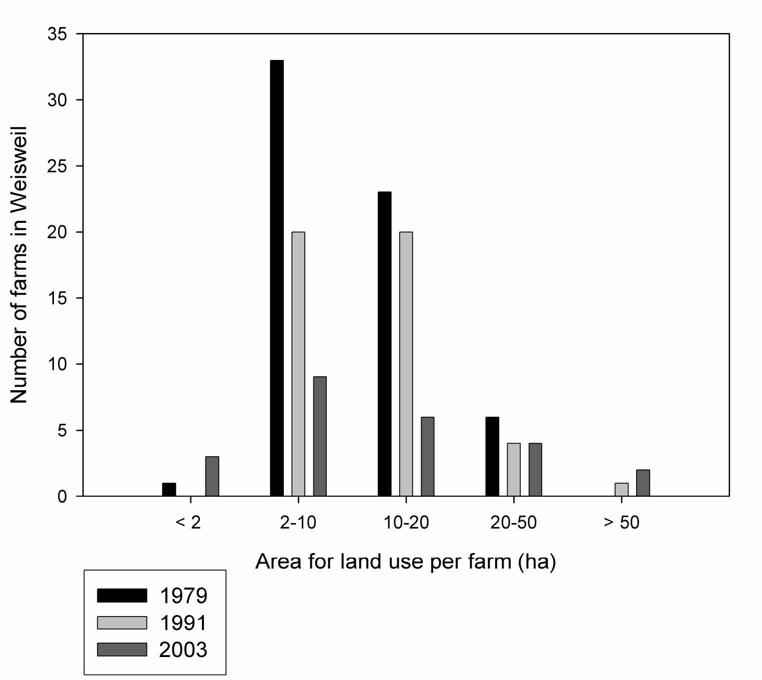

Figure 8. The development of the land use area per farm (ha) within the period from 1979, 1991 and 2003 for the Weisweil region (modified from www.statistik.baden-wuerttemberg.de, 2004).

In order to increase the economic feasibility of land cultivation in this region, the farmers have merged the small-scaled fields together and treated them as a single field.

The “Gewannebewirtschaftung” is typical for regions with small-scaled fields, like the Southern Upper Rhine Valley.

In 2003 about 43.5 % of this area was used as arable farmland, 44.1 % was used as permanent grassland, and 11.9 % was used for specialized crops such as fruits or tobacco (4.6 %) and wine yards (7.3 %). On 51.6 % of the arable farmland, corn was primarily grown for grain use followed by wheat that was grown on 10.8 % of the area. Compared to the year 1979 the fraction of corn increased by 139 %, whereas the fraction of wheat decreased by more than 66 %. The fraction of rye, triticale, winter and summer barley, oats, silage, potatoes, sugar beets and winter rape was less than 5 % of the farm land in the year 2003.

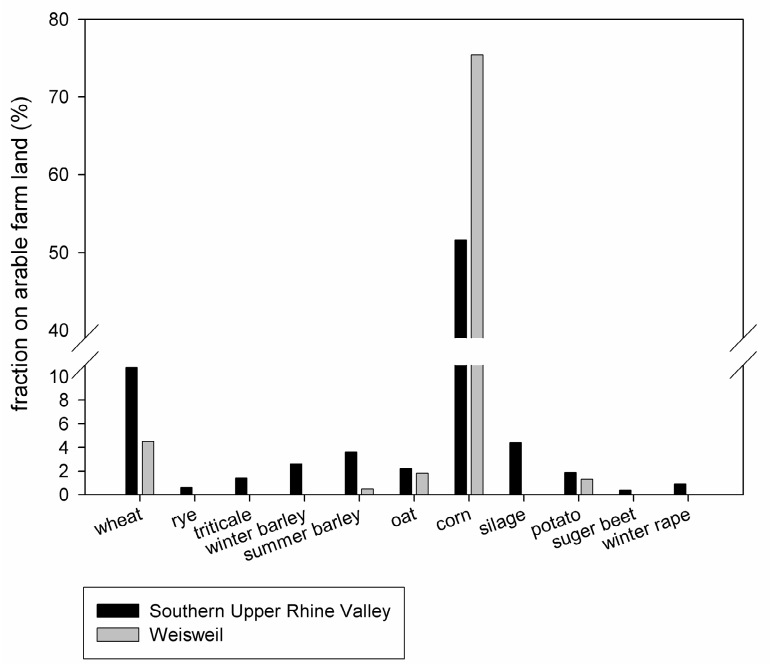

Figure 9. Fraction of different cultivated crops at the arable land in the Southern Upper Rhine Valley and Weisweil in the year 2003 (modified from www.statistik.baden-wuerttemberg.de, 2004).

In Weisweil, about 565 ha were used for agricultural production. A total of 88.4 % of the land was used for arable farmland, 10.4 % as permanent grassland and about 0.8 % as land for fruit growing. This means the land use around the community of Weisweil is dominated by the cultivation of corn, which was on 75.4 % of the arable farmland in 2003. Additionally, wheat (4.5 %), oats (1.8 %), potatoes (1.3 %) and summer barley (0.5 %) was grown on the farmland around Weisweil (Figure 9).

The increasing intensity of land use, especially the increasing area of corn production, was followed by an increase in nitrate in the groundwater. In intense corn production, high fertilizer inputs are common, but at the same time the fields are covered with crops from

April until October only, which leads to an increased risk of nitrate leaching. The threshold of 50 mg NO_3 L^{-1} set by the EC-Council Directive in 1991 was exceeded for most drinking water fountains in this region for a couple of years. Due to this situation, in 1993 about 20 ha in the community of Weisweil were declaimed as water protection areas.

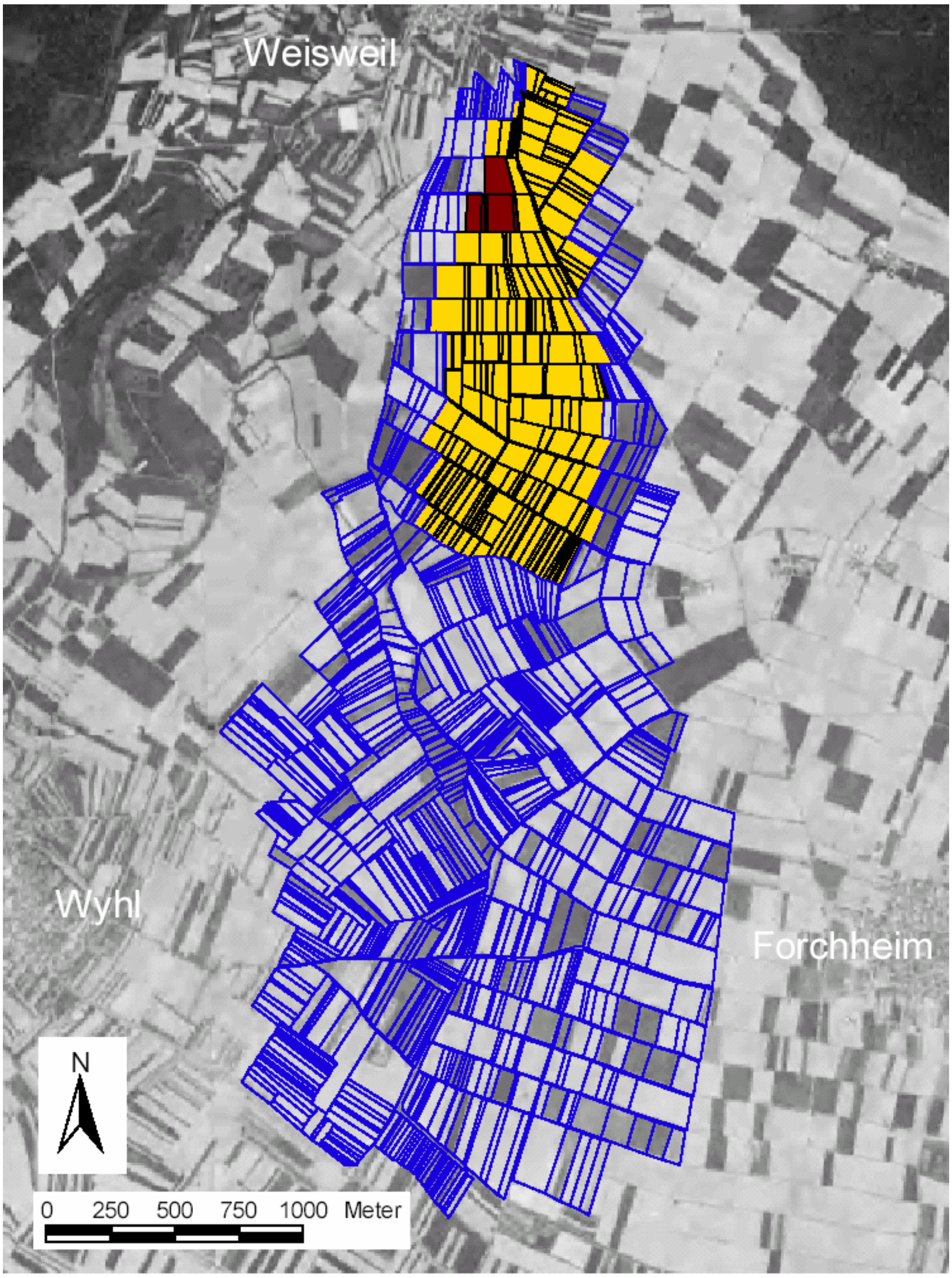

Figure 10. Water protection area around Weisweil including the core zone (yellow) with the three fields I1, I2 and I3 (brown) of this study (taken from Vetter et al., 2001).

In 1995, the water protection area was extended to about 550 ha (Rohmann and Rödelsperger, 1994). The extension of the water protection area and the location of the investigated fields (I1, I2 and I3) are shown in Figure 10 (brown area). In 2000, a new drinking water fountain was installed for the community of Weisweil and therefore Weisweil was taken out of the water protection area.

3.5 Experimental Sites

The region around Weisweil is dominated by small-scaled fields, with an average size of 1-2 ha (Figure 11). The research area for this study consisted of three farm fields (I1, I2 and I3), which covered about 5.5 ha in total (I1 = 1.8 ha, I2 = 1.2 ha, I3 = 1.5 ha). Although the three fields are located next to each other, each field belongs to a different farmer. However, all three fields were managed in cooperation by an over-operational service provider.

Since 1998, the fields were planted continuously with corn from April – October, with the exception of field I1 in 1999, where wheat was planted. Except for nitrogen application and harvest, each field was managed uniformly using the individual producer's current management practices. The fields were plowed in the spring and harrowed shortly before planting. Corn was planted with a four-row planter (0.75 m row spacing) near the midle of April with 85000 to 105000 kernel ha^{-1}. The corn cultivars varied over years and fields (Table 2).

Table 2. Corn cultivars planted on field I1, I2 and I3 during the 7-year period (1998-2002). K indicates the maturity classification based on BSA, 1998.

Field	1998	1999	2000	2001	2002	2003	2004
I1	Helix, K220	Soissons*	Marista, K400	Benicia, K250	Marista, K400	Peso, K290	Marista, K400
I2	Marista, K400	Helix, K220	Marista, K400	Peso, K290	Marista, K400	Peso, K290	Marista, K400
I3	Helix, K220	Helix, K220	Benicia, K250	Benicia, K250	DK514, K400	Peso, K290	DK514, K400

* In 1999 on field I1 wheat was grown

The major soil type of the three investigated fields was delineated by the State Soil Evaluation (1934) as a silty loam with 1.7-1.8 % organic matter (Figure 12). The upper soil layer (40-80 cm) consisted of loam and chalky silt. The soil layer underneath consisted of chalky sandy gravel. Based on the results of the State Soil Evaluation, no differences in elevation and soil water availability existed within the experimental area. The groundwater table was located at a depth of approximately 4 m. The field capacity on the sandy loam soil in the Weisweil region was determined by Rohmann und Rödelsperger (1994) to be 330 mm for the upper soil layer (0-90 cm).

Figure 11. Structure of the agricultural landscape south of Weisweil, including the field I1, I2 and I3 (left: section of a topographic map; right: aerial photography, modified from http://www.agrarprojekte.de/fotos-zf.htm, 2004).

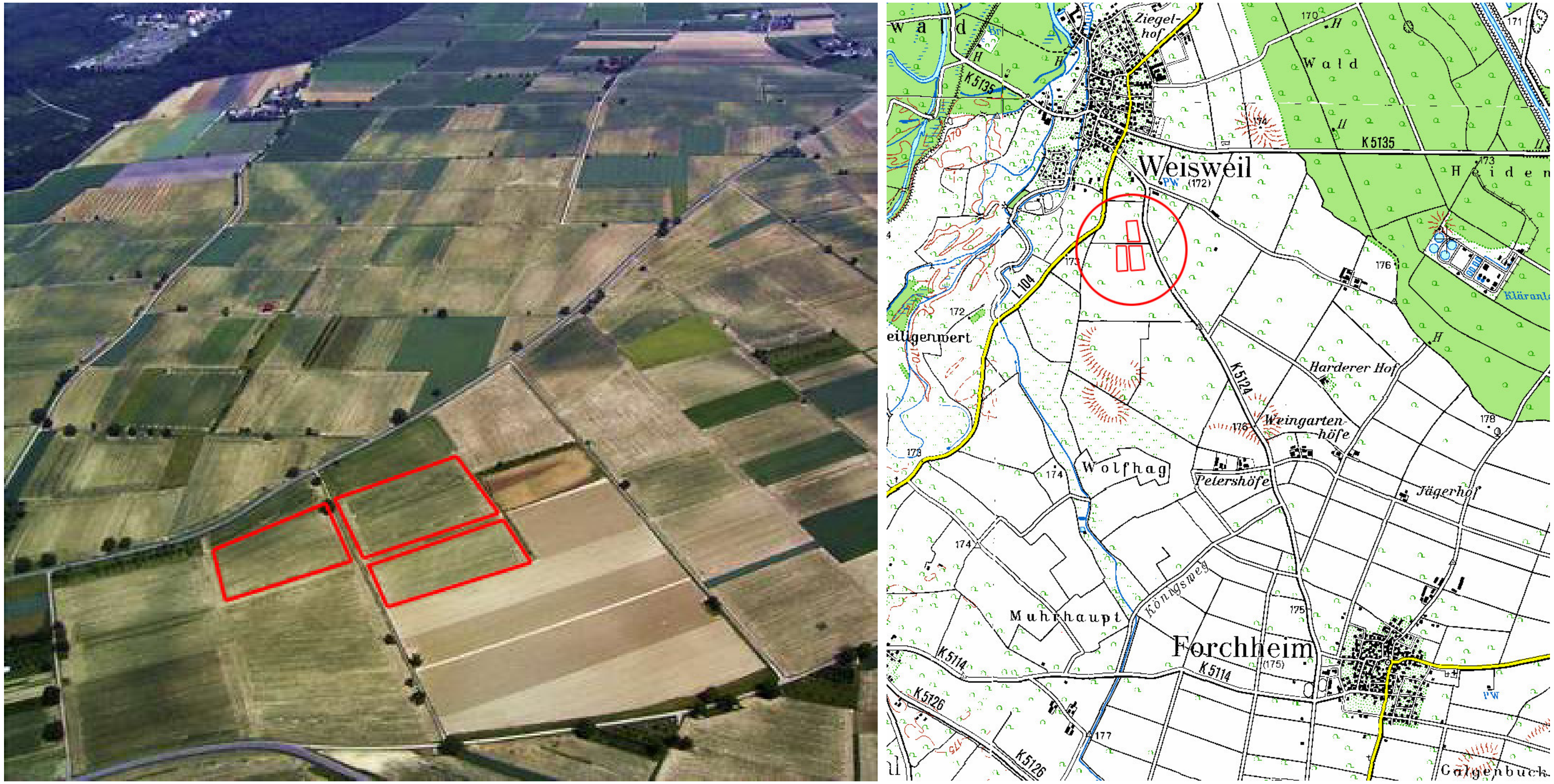

Table 3. Mean and range of soil characteristics and nutrient contents of field I1, I2 and I3.

Properties	Field	I1			I2			I3		
	(cm)	0 – 30	30 – 60	60 – 90	0 – 30	30 – 60	60 – 90	0 – 30	30 – 60	60 – 90
Clay	(%)	24.5 22.3 – 27.6	23 19.9 – 27.0	17.1 12.8 – 28.8	22.8 19.5 – 26.2	23.4 19.5 – 29.5	19.1 12.4 – 26.0	22.0 18.7 – 22.4	19.2 27.2 – 23.4	18.6 10.4 – 28.1
Silt	(%)	58.1 53.6 – 62.3	59.1 54.8 – 62.4	67.8 53.9 – 76.8	56.3 53.8 – 59.3	56.1 53.7 – 58.8	64.3 55.3 – 74.1	57.4 51.0 – 62.6	58 52.1 – 64.6	64.1 53.9 – 78.1
Sand	(%)	17.4 13.8 – 20.8	17.9 12.6 – 20.8	15.2 9.3 – 26.1	21.0 18.0 – 24.0	20.5 15.5 – 23.4	16.7 7.3 – 24.2	20.6 17.0 – 28.5	19.6 15.1 – 27.0	17.3 11.5 – 23.9
pH (CaCl)		7.5 7.4–7.5			7.3 7.2 – 7.5			7.4 7.3 – 7.5		
Organic matter	(%)	1.7 1.0 – 2.0			1.7 1.5–2.0			1.6 1.5 – 1.8		
Nitrogen	(%)	0.11 0.11 – 0.12			0.11 0.10 – 0.12			0.11 0.10 – 0.16		
Phosphorous	(kg P ha-1)	37.4 24.2 – 46.0	13.8 9.8 – 17.9	2.5 0.7 – 4.9	31.8 23.1 – 36.4	14.2 10.5 – 20.8	5.7 1.7 – 15.7	31.0 19.8 – 46.8	17.9 7.4 – 30.4	5.3 1.3 – 21.8
Potassium	(kg K ha-1)	43.8 28.7 – 55.1	21.6 12.0 – 30.3	10.3 7.0 – 15.9	36.0 27.9 – 49.5	20.4 12.9 – 32.4	10.7 7.0 – 14.6	35.2 22.0 – 48.2	22.0 14.8 – 36.6	10.3 6.0 – 15.4
Magnesium	(kg Mg ha-1)	8.2 7.0 – 11.0			9.6 7.0 – 12.5			8.2 7.0 – 11.0		
	(cm)	**0 – 30**	**0 – 90**		**0 – 30**	**0 – 90**		**0 – 30**	**0 – 90**	
Soil electrical conductivity	(mS m^{-1})	31.93 7.35 – 7.50	28.07 2.3 – 247.2		28.08 7.20 – 7.50	104.47 1.8 – 452.0		33.66 7.25 – 7.50	8.41 4.0 – 24.1	

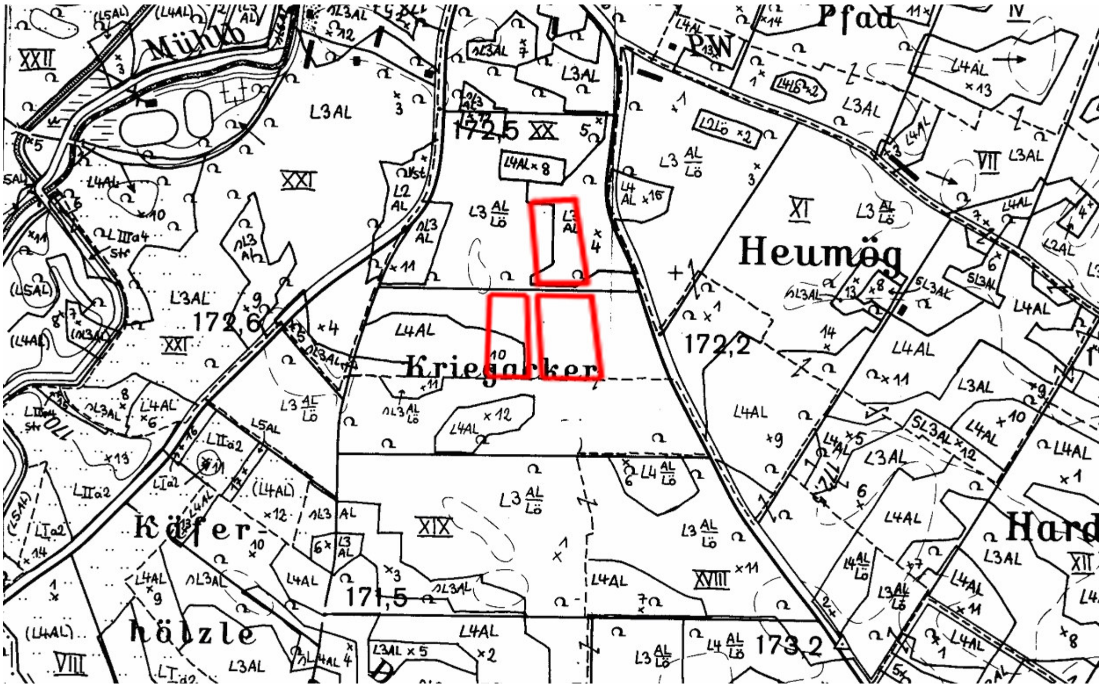

Figure 12. Soil map for the Weisweil region created during the State Soil Evaluation in 1934 (Geologisches Landesamt Baden-Württemberg), indicating different soil types including for the fields I1, I2 and I3 (red).

Figure 13 shows the spatial distribution of sand and clay content in the upper soil layers (0-30 cm). In field I2 and I3, the sand content over the whole field was above 20 %, whereas in parts of field I1 the sand content reached values below 20 %. The clay content varied between 21.5 % and 27.5 % in field I1 and I2. In field I3 the clay content in the upper soil layer did not exceed a value of 26.5 %.

The soil characteristics and nutrient content of the three fields in Weisweil determined in 2000 and 2003 are shown in Table 3. The pH value in the upper soil layer did not vary much within the three fields. Similar results were obtained for organic matter, nitrogen and magnesium content in the upper soil layer (0-30 cm). The content of phosphorous and potassium varied within the three fields. In the upper layer (0-30 cm), the phosphorous content was high and in the layer below (30-60 cm), the phosphorous content was optimal, only in the soil layer from 60-90 cm the phosphorous content was low. Concerning the potassium content in the soil, the upper soil layer (0-30 and 30-60) contained optimal or high amounts of potassium and still in the soil layer 60-90 cm the potassium content was adequate. This means that the soil content of phosphorous and potassium fall in the group D and E, and thus do not need additional fertilizer applications at this point in time. The results indicated that in all three fields, the nutrient supply needed to grow corn was adequate.

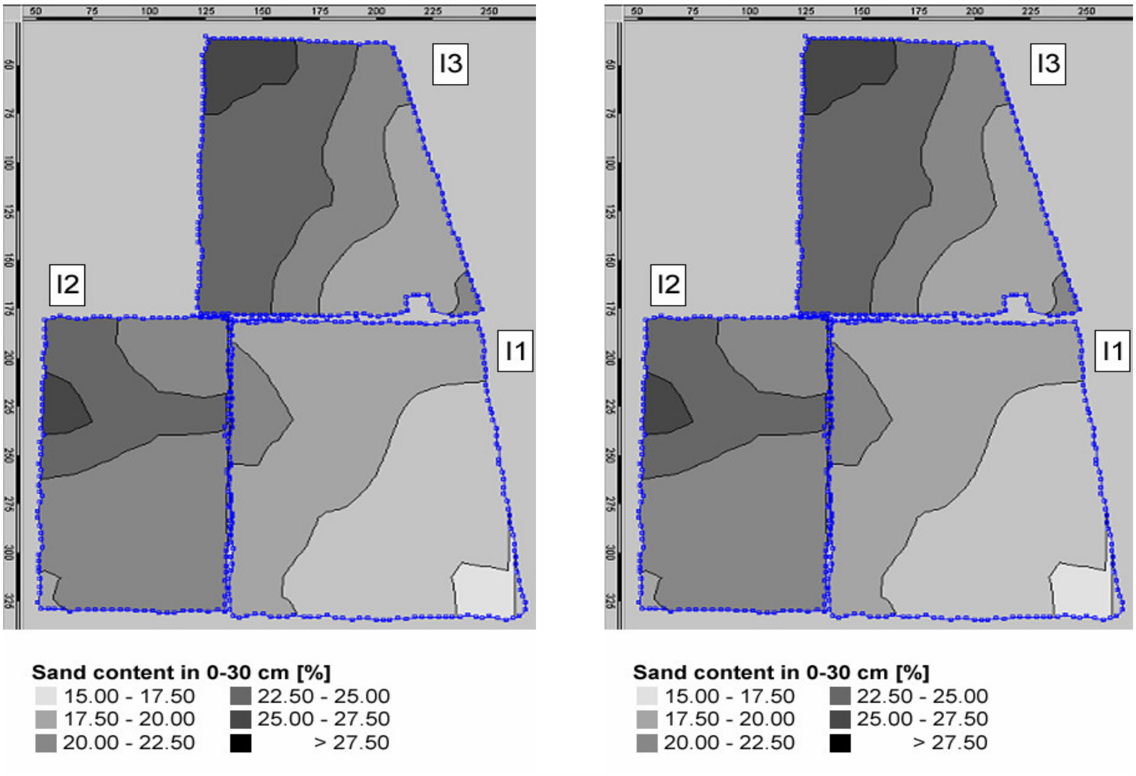

Figure 13. Spatial distribution of sand and clay content in the upper soil layer (0-30 cm) of the fields I1, I2, and I3 in the year 2000 (taken from Vetter et al., 2001).

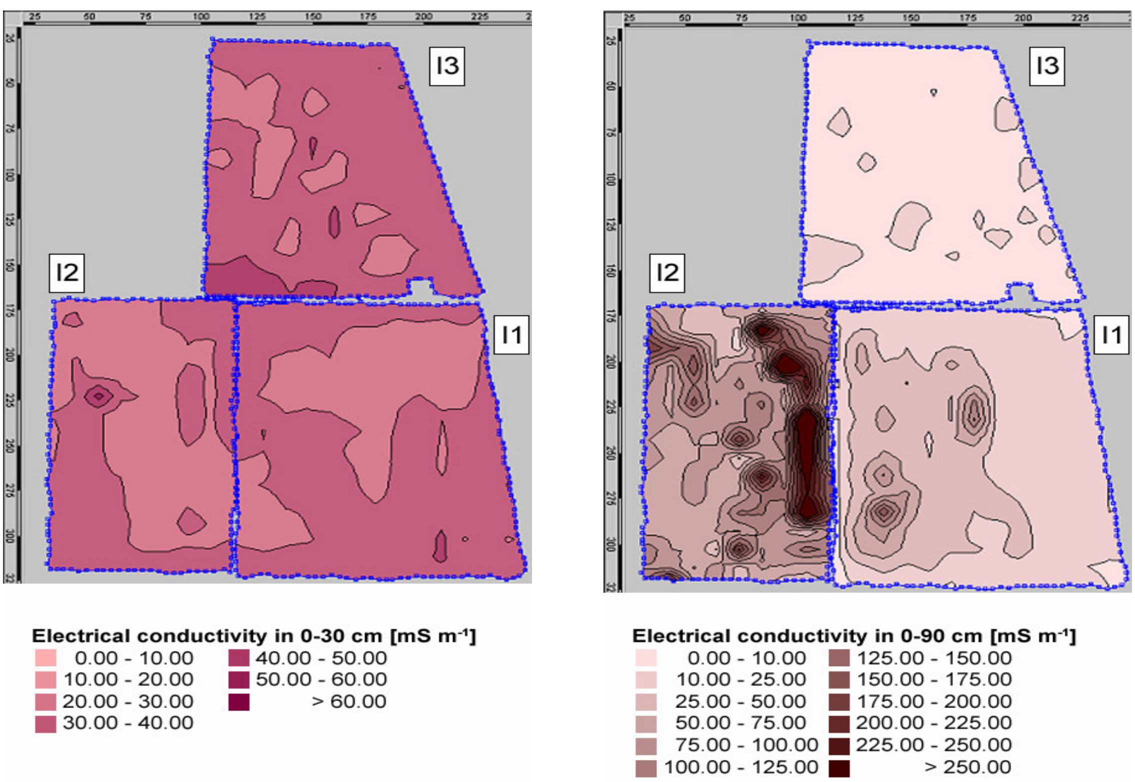

Figure 14. Spatial distribution of soil electrical conductivity (mS m^{-1}) of the fields I1, I2, and I3 in March 2001 (taken fromVetter et al., 2001).

In the project conducted by Vetter et al. (2001), measurements of the soil electrical conductivity (EC) were performed on the three fields (Figure 14). The measurement was done with a VERIS 3100 (Veris Technologies, Salina, KS, USA), which is a coulter-based sensor designed to determine soil EC at soil depths of 0-30 cm and 0-90 cm. The results indicated significant differences in soil EC (mS m^{-1}) between the fields at both soil depths. Measurements from the top layer indicated effects of management, whereas measurements from the deeper layer identified natural soil variability. High values of soil electrical conductivity led to the conclusion that raised clay, water and/or salt concentration in these fields, which may affect potential yield influenced measured corn yield. Differences in soil electrical conductivity indicated the effect of historic management within the fields.

Since 1998, the corn grain yield in the three fields was collected on a spatial scale using a yield monitor and differential Global Positioning System (dGPS) on a combine harvester. Table 4 shows the annual average corn grain yield within each field, corrected to 0 % moisture. The mean corn grain yields ranged from 6644 kg ha^{-1} in 1998 to 10494 kg ha^{-1} in 2000. The corn grain yield also varied within each field, which is indicated by the range of yield for each year and field (Table 4).

Table 4. Mean and range corn grain yield (kg ha^{-1}) of the fields I1, I2 and I3 over the 7-year period of investigation.

	1998	1999	2000	2001	2002	2003	2004
I1	5670 1048-7428	8240*	11200 1678-14939	7840 2253-14665	9090 1679-13160	7550 2124-10814	9140 3940-14824
I2	5930 675-11628	7580 1571-12294	11040 406-14315	9030 3299-11404	8090 2720-14288	7640 2132-13724	8450 3091-14770
I3	8320 831-13644	8560 729-13160	9250 3307-12919	6560 73-10238	9140 3328-14688	8220 61-12608	9410 2228-14101

* I1 in 1999 yield of wheat is shown

The different yield pattern in each field raised assumptions about varying growth conditions within and among the fields. Thus, on the one hand the corn yield seemed to be influenced by temporal variations in cultivar, climate and management and by spatial variation of possibly yield-limiting factors like nutrient availability or water supply on the other hand.

In order to optimize management strategies (i.e. nitrogen application) the underlying yield-limiting factors causing the spatial and temporal yield variability need to be determined in these three fields.

4 Precision Farming

This chapter provides an overview of precision farming. Besides the definition of precision farming, also a discussion about management zones, the process of gathering information about spatial variability, and the possibilities to implement precision farming for nitrogen fertilization strategies were displayed.

4.1 Definition of Precision Farming

The management of agricultural production is undergoing a change, both in philosophy and technology. Until recently, agricultural managers have generally made decisions regarding fields based on average conditions within those fields, with data that was often sparse and qualitative in nature. Soil fertility was determined by composition of soil cores in a single sample that was intended to best describe conditions across a field. Field scouting for crop condition or pest infestations was done at a few locations within the field, and observations often have been more qualitative than quantitative.

In the classical agricultural practice, fields are considered as basic management units and have been managed during the last decades for the mean condition or, in the case of fertilizer management, managed intensively to overcome variability within that field. In contrast to the classical agricultural practice of uniform treatment of a field, agriculture is now experiencing a vast increase in the amount of information available due to the incorporation of information technologies into agricultural production. The application of new information technologies in agriculture is known by several terms, including precision farming, precision agriculture and site-specific management. In the context of this work the term precision farming will be used.

Precision Farming (PF) is characterized as a systems approach to manage uncertainty in crop and soil properties “through better understanding and management of spatial and temporal variability” (Dobermann et al., 2004). This means PF is mainly a management decision, which deals with timing and type of tillage, seeding and planting, fertilization, pest control and timing of harvest (Bouma, 1997a). Two different approaches may be distinguished at this time: the reactive approach including the continual monitoring of soil and crop conditions, (as well as the guidance of the on-the-go management), and the proactive process, which is characterized as a process-oriented approach, where modeling is used to determine stress factors within fields (Bouma, 1997a). The information derived from the proactive approach could be used to avoid stress factors and the associated crop damage (Bouma, 1997a). In order to detect the practicallity of PF, a characterization and interpretation of the spatial and temporal variability needs to be performed first. In a next step, management needs to be adapted and the outcome should be monitored (Dobermann et al., 2004).

4.2 Management Zones

A key difference between conventional management and PF is the application of modern information technologies to provide, process, and analyze multisource data of high spatial and temporal resolution for decision-making and operations in the management of crop production. Under this approach a field is divided into sub areas, which are managed differentially according to their physical soil properties (Bouma, 1997b). The efficiency of PF mainly relies on the accurate locating of zone boundaries (Chang et al., 2003). In the literature, different approaches are shown, dividing fields into grids, transects or management zones (Chang et al., 2003; Ping and Dobermann, 2003).

Grids are characterized as rectangular or quadratic areas that are spread even over a field. The samples taken in each grid are assumed to represent the characteristics of a whole grid area (Wollenhaupt et al., 1994). The grid size normally matches with the working width of a producer to adapt application (of e.g. fertilizers) to the grid size. Ping and Dobermann (2003) pointed out that the chosen grid size might influence the spatial fragmentation in maps of yield classes. Thus, increasing the grid size may create more continuous yield classes, whereas smaller grids sizes would reflect the short distance yield variability (Ping and Dobermann, 2003). On the one hand, grid sampling provides excellent soil nutrient information if the points are close enough to assure spatial dependence, and on the other hand, important information may be missed when the grid distance is to large (Chang et al., 2003). Koch et al. (2004) characterized the grid-based application as most expensive, attributed by the additional cost for soil samplings within each grid. Due to high sampling cost associated with grid soil sampling, samples should be directed in coarser management units (Nemdahl and Greve, 2001).

A transect is mainly used to determine the variability over a field (Paz et al., 1999), but it has no meaning in the practice of PF. A transect consists of small stripes, which are laid over a whole field.

The most common approach to implement PF is the use of management zones, which are thought to be different in terms of soil characteristics and crop growth (Dobermann et al., 2004). The management zone approach is based on the hypothesis that a field is a mosaic of different conditions with each having unique characteristic that influence soil properties and management (Doerge, 1999; Fleming et al., 2000). The management zones are delineated on the basis of yield maps, soil survey maps (Franzen et al., 2002), soil electrical conductivity (Chang et al., 2004), soil nutrients (Fleming et al., 2000), soil moisture, topography or remote sensing data, and thus are adapted to specific characteristics of the field. The disadvantages of the management zone approach might be that it does not necessarily match the working width of the producer. If so, the application cannot be applied as precise as compared to a grid raster. The advantage when a management zone approach underlies the PF application is the reduction in preparation expenses and time for soil sampling. Dobermann et al. (2004) characterized the management zones as the only cost effective method for commercial use.

However, the potential for individually managing small areas, whose size is determined by local characteristics and crop value, is one of the most enticing aspects of PF. The ability to repeatedly locate a specific site and measure agronomic characteristics provides an opportunity to optimize management throughout the production area. Subdividing a field into small management units may improve both the economic and environmental sustainability of crop production systems.

Therefore, PF systems can be envisioned as systems that can respond to the yield potential of a crop as it varies within the growing season. The approach takes into account that yield patterns are not homogenous across and within fields. Several studies indicated that corn yields varied spatially and temporally within fields (Lamb et al., 1997; Machado et al., 2002; Eghball et al., 2003). Yield variation may be caused by many factors including spatial variability of soil type, landscape position, crop history, soil physical and chemical properties, and nutrient availability (Wibawa et al., 1993). Also, interactions among biotic factors like pests or diseases and abiotic factors, which include soil physical and chemical characteristics may lead to spatial variability of crop growth (Mulla and Schepers, 1997; Sadler et al., 2000). Swinton et al. (2002b) also showed that corn yield response to nitrogen varies spatially with quantifiable field characteristics, like soil moisture.

4.3 Technologies of Precision Farming

In order to manage a field on a sub-field level, different preconditions are required. The following discussion provides an overview of the PF technologies and practices that were used in this study. In order to determine the magnitude of spatial variability within a field, several methods could be implemented, including yield mapping, soil sampling, soil electrical conductivity mapping, remote sensing, crop scouting and weed detection systems (Pedersen, 2003). For more detailed information, the reader may want to access additional literature sources such as Pierce and Sadler (1997), Robert et al. (1995), and Robert et al. (1996).

4.3.1 Yield Mapping

Yield mapping is widely used to determine the spatial yield variability within a field (Jaynes, 1997; Lamb et al., 1997; Machado et al., 2002) and to delineate areas with different yield potentials over the time (Blackmoore, 2000). Yield mapping systems record the relative spatial distribution of yield while the crop is being harvested. These systems collect georeferenced data on crop yield and characteristics such as moisture content. The maps can illustrate areas of yield variability resulting from either natural processes or agricultural practices. However, a yield map does not provide information about the underlying factor leading to yield variability. Pedersen (2003) postulated that yield maps should primarily be used to monitor yield response and afterwards be used to calculate the amount of nitrogen that has been recovered by the crop. Because yield is a primary factor in most management decisions, precise yield maps are desired to confirm spatial treatment decisions.

4.3.2 Soil Sampling

Soils vary significantly as a result of regional geological origins and past and present cultural practices. At the highest level of resolution, soil physical, biological, and chemical properties vary vertically, horizontally, with treatment, and with time. Since soil physical, chemical, and biological properties have dramatic effects on crop production information about spatial variability in soil patterns is indispensable.

Soil sampling can provide information about soil nutrient content, current water status, soil texture, and bulk density. Soil samples are mainly used to determine the pH level within a field or the content of soil nutrients like phosphorous and potassium (Wollenhaupt et al., 1994; Franzen and Peck, 1995), where the content is stable over time. Soil sampling to determine soil available nitrogen content is less common, because of the cost required for more frequent sampling for nitrogen status (Ferguson et al., 2002). Nitrogen content in soil is known to vary across the field (Eghball et al., 2003). Information about the nitrogen content in the soil could be accounted for in nitrogen application rates, because remaining nitrogen in the soil is prone to leaching to the groundwater and the atmosphere. Spatial variability of physical, chemical and biological properties of the soil might result in different magnitudes of nutrient transformation and availability. While the spatial distribution of nutrients, like potassium and phosphorous, are stable over time, the nitrogen availability can vary a lot over time within a field. If the nitrogen supply does not match the nitrogen demand of the plant, this could either result in overfertilization or in underfertilization. Both scenarios are reprobate from an economic point of view. The risk of nitrogen losses by nitrate leaching is increased due to overfertilization, whereas the risk of yield reduction caused by nutrient deficiency is enhanced due to underfertilization. In order to reduce these risks, the nitrogen application should be applied in regard to the spatial nutrient variability within a field.

4.3.3 Soil Electrical Conductivity

In additional to soil sampling, soil electrical conductivity mapping provides an efficient and inexpensive method to determine soil variability within a field. Soil electrical conductivity is correlated with soil properties like soil texture (Doerge et al., 2002), drainage conditions, organic matter (Nehmdahl and Greve, 2001) and salinity. Water content, salinity and organic matter increase the electrical conductivity, whereas it is decreased with soil depth and low soil temperatures (Pedersen, 2003).

4.3.4 Crop Scouting

Crop scouting is an important technique to determine crop viability within a field during a growing season. Crop scouting provides useful information on weed population, soil characteristics and additional factors that can affect crop yield (Ess and Morgan, 1997), or detecting crop nitrogen status in critical growth stages (Schröder et al., 2000). Scouting for pests is very difficult because insects move within a field from year to year. Weed detection is difficult because of scouting requirements and automatic detection devices have a difficult time discriminating between weeds and the crops. Currently there are no commercial autonomous weed detection systems on the market (Pedersen, 2003).

4.3.5 Remote Sensing

Remote sensing includes methods like ground-based sensors, aerial photos and satellite images. Aerial photos and satellite images are not commonly used to determine the variability of crop characteristics within a field, however ground-based sensors are available on the market (Pedersen, 2003). The company Acri Con (Jahna, Germany) provides the N-sensor, which measures the reflection of light from the crop canopy. The reflection indicates the chlorophyll content of a leaf, which is related to the nitrogen content in a plant and thus gives information about the current nitrogen demand of the crop. Using this sensor, the nitrogen application rate can be adapted to the nitrogen demand of the plant and the yield expectations (Liebler, 2003). Small improvements in yield were shown when the N-sensor was used for the nitrogen application in winter wheat. When nitrogen application is performed on basis of the N-sensor, on high yielding areas more nitrogen is broadcast, and leading to an improved nitrogen uptake and development of biomass compared to low yielding areas (Liebler, 2003). This result indicated that adapted nitrogen fertilization strategies are able to match the demand and supply of nitrogen.

There exists the potential for a vast increase in the timeliness and amount of information if additional means of data collection and analysis become available. Sensors will play an important role in supporting technology for precise applications of nutrients, pesticides, and other inputs. Basic research in the sensors area is fundamental to an improved understanding of the variations in site-specific crop production in a wide variety of regional production systems.

The previous sections have described some of the factors that can limit crop growth, and the possible site-specific decisions that producers can make over the course of a cropping season. PF has the potential to affect crop management practices by reducing or removing the effects of yield-limiting factors. It seems clear from the evidence to date that PF technologies will be used in the management of some factors for some crops in some regions. Major limitations to adoption in a broader range of cropping systems include an incomplete understanding of agronomic parameters and their interactions, the cost of obtaining site-specific data, and a limited ability to integrate information from sources with varying resolutions and timing. There are many possibilities for incorporating detailed information into management decisions. The realization of those possibilities will depend on the invention and improvement of the tools of PF.

4.4 Nitrogen Fertilization

PF can be implemented in all aspects of the crop production process, including tillage, planting, spraying, harvesting and fertilizing (Ess and Morgan, 1997). In this study the main focus was on the variable-rate application of fertilizer, namely nitrogen. The application of fertilizer in terms of PF implies the estimation of the fertilizer demand, either by soil sampling or by plant analysis. Both methods are commonly used, depending on which nutrient to apply. The aim beyond variable-rate fertilization is the reduction of applied fertilizer in order to increase the economic income and to reduce the environmental pollution by agrochemicals.

The adaptation of nitrogen application rates to low and high yielding areas in the field could result in two different strategies. On the one hand the application rate could be increased for low yielding areas and decreased in high yielding areas. This strategy is based on the idea to level the yield potential of the entire field, which could be realized only when nitrogen was determined as the main yield-limiting factor. On the other hand, more nitrogen could be applied on high yielding areas and less on low yielding areas. This strategy is more common (Mulla et al., 1992; Verhagen et al., 1995) and based on the fact that high yielding areas have greater response to nitrogen (Jørgensen, 2002). In order to minimize nitrogen losses, the adaptation of the nitrogen application rate needs to follow the second strategy.

In general the producer has different complex possibilities for assessing the nitrogen level and deriving the nitrogen application map. In a first and simple attempt he can evaluate the soil nitrogen levels across a field by taking soil samples, analyzing them for nutrient content, and interpolating values between the sampling points (Wollenhaupt et al., 1994). A second, more complex approach would be the use of ground-based sensors to monitor the plant nitrogen status during a growing period using e.g. the N-sensor mounted on an nitrogen applicator to determine the optimum nitrogen needed to maximize yield. Currently, this approach is only available for cereals, but it is not possible to implement the N-sensor for corn production. In a third, highly complex, holistic approach the producer could establish a nitrogen fertilization map on a site-specific scale using a crop growth model as decision support system. Based on detailed information about soil, weather and management of the field, a crop growth model is able to simulate the interaction within a cropping system and thus could provide information about optimum nitrogen application rates.

The advantage of using a crop growth model is the flexibility of a crop growth model. It can be used to analyze different scenarios in order to develop an optimum nitrogen fertilization strategy. Thus, for a calibrated crop growth model, it is not absolutely necessary to perform cost and labor intensive nitrogen sampling in each growing season.

Beside the widely known and used technique of collecting soil samples in order to determine the soil nitrogen content, this study focused on the implementation of a progressive crop growth model to determine the optimum nitrogen fertilization strategy.

4.5 Impact on Economical and Environmental Issues

In order to increase economic and environmental benefits from PF, it is required that spatial variation exists within a field and thus it can be divided into management zones. Pedersen (2003) pointed out that the crop response to the input is significant and predictable, and that the input applications can be done accurately while keeping the additional cost low (Dobermann et al., 2004).

The cost of breaking up the field into smaller management units is justified for the field with more spatial variation (Thrikawala et al., 1999). Babcock and Pautsch (1998) found that less productive fields possessed more yield variability than productive fields and therefore they assumed that the value of variable-rate technology will be greater for less productive fields. Even though the fields have a high spatial variation in soil conditions and yield potentials, it might very well be the case that it is not economically viable to invest in site-specific equipment, simply because the arable farm area is too small (Pedersen, 2003). Results of Swinton et al. (2002b) showed that the added revenue from variable-rate nitrogen application was generally insufficient to cover the cost of site-specific data acquisition and variable-rate fertilization application. In this case no surplus was left that could pay for the development of variable-rate nitrogen fertilizer strategies. Ferguson et al. (2002) found that there also was no advantage that would justify the cost and effort of variable-rate application.

Fertilizers saving between 10 % and 20 % using PF were determined in the literature (Van Alphen and Stoorvogel, 2000; Forcella, 1993), but the measured yield increases of 3 % up to 5 % due to PF did not warrant the investment in PF technology (Pedersen, 2003). Koch et al. (2004) showed that on farms with a total size of approximately 500 ha, variable-rate technology was most profitable, when it was adapted to management zones and based on variable yield goals within the management zones. Studies of Mamo et al. (2003) showed that variable-rate nitrogen management increased profitability and decreased the required nitrogen application rate when both spatial and temporal variability are considered appropriately. As long as the additional costs are below the additional gain in yield or reduction in fertilizer application, variable-rate technology will be economically feasible (Ferguson and Hergert, 1999; Thrikawala et al. 1999). The analysis of Pedersen (2003) indicates that for farms in Denmark the costs of gathering information are relatively high, in particularly on small production units. The potential savings are small compared with the costs.

In addition to economic pressure, there are likely to be greater constraints on land use and farming practice in order to meet environmental criteria. These constraints are emerging in the form of policy initiatives such as the Nitrogen and Environmental Sensitive Area Schemes and the EU Nitrification Directive. EU policy makers are becoming increasingly keen that environmental considerations should play a role in agricultural policy and it is widely accepted that the future shape of the farming industry will depend substantially on the policy decisions made over the next few years. Producers in the future will have to operate under management systems that will maximize output and reduce target inputs, while causing little harm to the surrounding environment. The increasing awareness of environmental pollution has resulted in increasing legislation concerning fertilizer use. Conventional approaches to field operations treat a field as uniform with no alternations to drilling rates or greenhouse effects by reducing emissions of greenhouse gases and sequestering carbon (Lal et al., 1998). In such circumstances, conventional management practices no longer apply.

The objective of PF has reached a status where the achievement of sustainable profit and the reduction of environmental impact are most important (Dobermann et al., 2004). Thus, the overall goal of PF is to increase the profitability, the product quality, the risk reduction and the environmental protection (Bouma, 1997b). While there may be positive farm benefits from variable-rate technology for certain individual producers, a major off-farm advantage of PF technologies is the reduction in the level of polluting residuals (Thrikawala et al., 1999). In studies of Larson et al. (1997) it was shown that utilizing site-specific nitrogen management could reduce the amount of nitrogen leached, as well as potentially leachable nitrogen remaining in the soil after harvest. Eghball et al. (2003) assumed that by reducing variability and quantity of residual soil nitrate, the leaching and subsequent groundwater contamination potential should be reduced. Thus implementing PF technology could be an option to optimize nitrogen fertilization strategies.

The environmental constraints may be imposed in terms of the use of inputs and practices such as nitrogen use, or on limits on environmental impacts such as leachate to ground or surface water. In either case, producers will have to record and report that they are meeting the set criteria. PF has a role to play for monitoring and confirming compliance. Constraints on farming for environmental purposes initially are likely to come in technological packages, similar in concept to the blanket prescriptions of the conventional approach. Environmentally sensitive low input - low output systems are unlikely to sustain a viable farm sector without significant levels of income support.

However, PF could help to formulate and implement locally relevant farming strategies, which, through better-targeted input use, achieve financially viable farming systems, which simultaneously comply with environmental quality criteria. In its most sophisticated form, PF would involve instrumentation and control for spatially variable field operations. Thus, PF would reduce risk inherent in environmentally sensitive farming systems, and provide the means of protecting environmental quality without compromising.

5 Spatial Variability and Temporal Stability of Corn (*Zea mays* L.) Grain Yields in the Upper Rhine Valley (Germany) – Relevance of Grid Size[1]

5.1 Abstract

Corn yields are frequently heterogeneous across space and time. A 5-year field experiment was conducted in the Upper Rhine Valley to determine spatial yield variability and temporal stability of corn (Zea mays L.) within three farmer fields (I1, I2 and I3). The objectives of this study were to evaluate the spatial variability and temporal stability of yields and to identify the factors affecting the yield variability. Therefore yield data was analyzed at the field scale and for three different grid sizes (case A, B and C).

Spatial yield variability was analyzed by calculating the variance and the coefficient of variability (CV). The temporal yield stability was analyzed by Pearson's correlations (r) for year-to-year yields. The effect of plant yield parameters and soil characteristics on yield variability were tested by linear and multiple regressions and evaluated using the coefficient of determination (r^2).

Results indicated that the grid size required to capture the spatial yield variability and temporal yield stability was different over the three fields. In general, smaller grid sizes (15.0 m x 11.0 m) were able to describe yield variability more precisely, whereas larger grid sizes (15.0/22.5 m x 27.5 m) were able to more accurately describe yield stability. In field I3, yield variability and yield stability could be described by most of the grid sizes. In field I1 and I2 yield variability was best described by the smallest grid sizes, whereas yield stability was best described by the large grid size.

Plant yield parameters (plants ha^{-1}, cobs m^{-2}, kernels m^{-2}) and plant nutrients did not correlate well with yield. Therefore plant yield parameters and plant nutrients were not the driving factors affecting yield. There was also no relationship between yield and individual plant nutrient levels (N, P, K, Mg). However, significant relationships were found between combinations of soil nutrient levels, soil characteristics and yield. Based on these results, it appeared that soil characteristics were the primary factor affecting spatial yield variability in the three farmer fields in the Upper Rhine Valley.

To develop units for site-specific management, grid size should be determined in consideration of temporal yield stability and in consideration of the underlying factors leading to spatial yield variability. If the underlying factor is highly variable within the

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field smaller grid sizes are useful. If the underlying factor is less variable within the field larger grid sizes seem to be more suitable for site-specific management.

5.2 Introduction

Understanding and managing yield variability within fields is challenging to both producers and researchers. Site-specific field management promises to maximize field level net return and minimize environmental impact by managing fields using spatially variable management practices (Paz et al., 1998b). The success of site-specific farming depends upon the discovery of relationships describing yield response to biotic and abiotic factors and environment impact, and using these relationships to define optimum prescriptions on a site-specific scale.

Yield variation may be caused by many factors including spatial variability of soil type, landscape position, crop history, soil physical and chemical properties, and nutrient availability (Wibawa et al., 1993). Interactions among biotic factors like pests, diseases, nutrient availability and abiotic factors which include soil physical and chemical characteristics may also lead to spatial variability of crop growth (Mulla and Schepers, 1997; Sadler et al., 2000). However, yield variability can also occur because of variation in plant density, plant stresses and the effects of crop management. Furthermore, spatial and temporal variability of biotic and abiotic factors (e.g. weather) can create unpredictable spatial and temporal yield patterns in a field.

In order for producers to capitalize on spatial yield variability, it is necessary that they understand the underlying causes of yield variability and how these factors interact with weather to create both spatial and temporal yield variability. Classical statistics based on the methods of ordinary least squares are frequently used to explore functional relationships between crop productivity and controlling factors (Long, 1998). Moore et al. (1993) used correlation to examine the potential relationship between topographic attributes and soil properties that contribute to crop productivity. Tomer and Anderson (1995) used linear regression to predict spatial patterns in yield based on soil fertility.

Producers also need to understand the spatial structure of yield in order to define management zones that represent areas of similar yield response to stress. Recent research has focused on the use of management zones as a method to more efficiently apply variable crop inputs across fields (Ferguson et al., 2003). Different approaches have been proposed in the literature to delineate management zones for site-specific farming (Franzen et al., 2002; Kitchen et al., 2003; Varvel et al., 1999). Most studies have approached this problem by first identifying areas of similar soil properties and then testing for reduction in yield variability or yield response to inputs within these areas (Fraisse et al., 2001). These methods rely on using general knowledge of crop production to identify the important yield-limiting factors to include in the analysis. However, the results are often valid for only one year (Jaynes et al., 2003). Schepers et al. (2004) and Boydell and McBratney (2002) proposed yield mapping over multiple years as an improved approach to delineate management zones. However, practical application of yield mapping to identify management zones has been plagued by spatial and temporal variation in measured yield

(Sadler et al., 1995). In order to use yield maps to delineate management zones, high and low yielding areas in a field have to be consistent, or stable, from year to year.

Several studies have shown that producers collecting yield monitor data over a number of years observe patterns of yield variability in fields that are stable from year to year. Therefore yield maps can be classified to delineate areas with different relative yield and yield stability within a field (Blackmore, 2000). Areas of a field that vary temporally in yield should be managed differently, as crop removal (e.g. nutrients) should vary. However, other studies have found that yield patterns are not stable over multiple years. Lamb et al. (1997) found that corn yield patterns from one year accounted for only 4 to 42 % of the spatial pattern of corn yield in subsequent years. The lack of stability in yield patterns made it difficult to predict yield from previous yield maps (Eghball and Varvel, 1997) and to delineate management zones. Thus, the relationships between spatial yield patterns and the underlying factors causing yield variability may not be the same across years, because the underlying crop growth processes and their response to concomitant soil processes may be variable in space (Nielsen et al., 1999) and time (Stafford et al., 1998).

According to Moran et al. (1997), information on seasonally stable yield conditions and variability is required to successfully implement site-specific management practices. Therefore, yield mapping as one approach to delineate management zones requires yield stability, which means that areas with similar yield potential (low or high) can be found in the same geographic locations over a series of years. Thus, for farming by management zones to be effective, it is necessary to demonstrate a strong and consistent relationship between spatial yield patterns used to delineate management zones and spatial patterns in soil and crop properties over yearly variations in weather. Otherwise, the variable application of crop inputs like nitrogen, based on the yield-derived management zones will likely to be incorrect.

To evaluate spatial yield stability, yield data has to be aggregated into grids, but the choice of grid size may be essential for determining temporal and spatial stability (Long, 1998). To compare data from different sources like yield monitor data from different years, soil electrical conductivity, plant and soil parameters, data must be aggregated to a common grid size. In choosing the grid size, there is often a trade-off between maintaining spatial precision by selecting a small grid size and reducing noise by selecting a larger grid size (Long, 1998). Long (1998) examined the change in correlation coefficients between yield, elevation and the normalized differences vegetation index (NDVI). Long (1998) showed that the correlation coefficient increased as the grid size increased. Grid applications are often based on coarse grids with 100-m spacing or more and simple interpolation or geostatistical, interpolation procedures are used to evaluate yield stability (Burrouhgs and McDonnel, 1998). However, there is no consensus on which grid design and size are best suited for site-specific farming. Grids should represent larger, spatially contiguous areas of a field that reflect major and consistent differences in attainable yield, and exclude noise introduced by annual factors and measurement (Ping and Dobermann, 2003). Increasing the grid size may create larger and more contiguous yield classes but requires understanding of the relationships between grid size, yield variability accounted for and spatial stability of yield pattern. The grid size may depend on many factors but ultimately on the spatial structure of each field (Sadler et al., 1998), including the range of spatial correlation and variation (Mohamed et al., 1996).

The objective of this study was to investigate the spatial structure of yield variation within three fields in the Upper Rhine Valley by (i) evaluating the spatial variability and stability of corn grain yields over 5 years, (ii) identifying the processes affecting the underlying observed yield variability, and (iii) determining the grid resolution that captures enough information to represent yield spatial variability and stability at a scale appropriate to delineate management zones.

5.3 Materials and Methods

5.3.1 Site Description

The study was conducted as an on-farm study from 1998 through the 2002 growing season on three fields (I1, I2, I3) in the Upper Rhine Valley near Weisweil (48° 19' N, 7° 67' E), northwest of Freiburg, Germany. The research area consisted of three farmer fields totaling about 5.5 ha (I1 = 1.8 ha, I2 = 1.2 ha, I3 = 1.5 ha) and the major soil type as delineated by the State Soil Evaluation (1934) was a silty loam with 1.7 % organic matter. The upper soil layer (40-80 cm) consisted of loam and chalky silt. The soil layer underneath consisted of chalky sandy gravel. In general no differences in elevation and soil water availability existed within the experimental area. The ground water table was located at a depth of approximately 4 m.

The mean annual precipitation in this area is 910 mm, of which about 67 % occurs during the growing season (April-October). The mean temperature is about 9.5° C and varies from a mean of 2.2° C in January to 19.7° C in August. The average total annual solar radiation in the Upper Rhine Valley is approximately 11390 kJ m^{-2}.

During the 5-year period of investigation the annual mean precipitation ranged from 898 mm in 1998 to 1056 mm in 2001, which was near the 30-year mean of 910 mm. The mean maximum temperature ranged from 16.7° C in 2000 to 15.8° C in 2001. The mean minimum temperature ranged from 5.6° C in 1998 to 6.7° C in 2000. The mean temperature of each year was about 10-20 % higher than the 30-year mean of 9.5° C. Total annual solar radiation ranged from 11020 kJ m^{-2} in 2002 to 11527 kJ m^{-2} in 2000 during the period of investigation. Wind speed averaged about 9.0 m s^{-1} during each year. All weather data were obtained at the nearest station of the German Weather Service located at Emmendingen-Mundingen and Freiburg, which are about 16 and 25 km from the trial site, respectively.

5.3.2 Treatments

Corn was grown each year from mid of April or early May until October during the years 1998-2002 in all three fields, with the exception of field I1, where wheat was planted in 1999. Each field was managed uniformly using the producer's current management practices. The fields were ploughed in spring and harrowed shortly before planting. Corn was planted with a 4-row planter (0.75 m row spacing) at a rate of 85000-105000 kernel ha^{-1}. The corn cultivars varied for each field and year.

At sowing, a starter fertilizer of approximately 31 kg N ha^{-1} given as KAS (13 % NH_4-N, 13 % NO_3-N) was applied uniformly to all fields in all 5 years. Around the 4th leaf stage mixed soil samples at a depth of 0-90 cm were taken at data collection points all over the three fields and analyzed for N_{min} in the soil. Urea (46 % N) was applied uniformly to each field based on N_{min} around the 4^{th} leaf stage. Nitrogen rates varied for each field and year, and ranged from 44-120 kg N ha^{-1}. The amount of nitrogen in each field and year reached the specific value of 250 kg N ha^{-1}. In 2001 swine manure was applied in field I2, which provided an additional amount of 40 kg N ha^{-1} to this site. No other field received swine manure applications. Herbicides and pesticides were broadcast as needed to control pests. After harvest in October, the corn residue was left on the surface of each field.

5.3.3 Yield Monitoring

Geo-referenced corn grain yield data were collected over the 5-year period using a differentially corrected global positioning system (dGPS) on a combine harvester (Claas, Lexion). Corn grain yield and corn grain moisture content were measured every 5 seconds (over a 10-m distance), resulting in about 200 yield monitor data points per hectare. Corn grain sub samples were manually collected for each field from the grain storage bin and dried at 105° C in a forced-air oven and corn grain yield was adjusted to dry matter basis. In the following part of this paper, yield is defined as corn grain dry matter yield. Data with missing yield or grain moisture content values, as well as yield values greater than 15000 kg ha^{-1} were excluded from the yield monitoring dataset.

Yield monitor data were analyzed at several spatial scales. Yields were computed from yield monitor data for three different grid sizes (case A, B and C) and also analyzed at field scale. Grid sizes were constituted at 15.0 x 11.0 m (case A, Figure 15), 22.5 x 16.5 m (case B, Figure 16), and 15.5/22.5 x 27.5 m (case C, Figure 17) respectively. The three grid sizes (case A, B and C) were used to determine which size best represented the spatial structure of yield, and were practical to implement in the field.

5.3.4 Plant and Soil Sampling

In 2000, stationary plant and soil data collection points (DCP) were established in each field at a 40 x 40 m spacing, resulting in 7 DCPs per hectare. The location coordinates for each DCP were recorded with a handheld dGPS (Agrocom Computer Terminal, Agrocom). Soil and plant samples were taken at these 30 DCPs once or twice a year during the growing season.

In 2000 plant yield parameters such as number of plants ha^{-1}, cobs m^{-2}, kernels m^{-2}, thousand-kernel weight (TKW), corn grain moisture content were measured at each DCP by hand harvesting an area of 1 m^2. The plant samples were split, and one part of the plant samples was dried at 105° C in a forced-air oven to determine the dry matter yield and corn biomass for each DCP. The other part of each plant sample was dried at 40° C and analyzed for nutrient concentration of the whole plant (grain and stem).

In 2000, about 10 soil samples of the upper soil layer (0-30 cm) were taken at each DCP after the growing season to obtain information about the variability of soil characteristics.

The soil samples were analyzed for soil type, soil texture, total nitrogen content (N_t), phosphorous (P), potassium (K) and magnesium (Mg) content, pH and organic matter (OM) content.

In March 2001 soil electrical conductivity (EC) was measured with a Veris 3100 (Veris Technologies, Salina, KS, USA) from soil depths 0-30 cm and 0-90 cm. The Veris 3100 is a coulter-based sensor, which uses direct current flow in the soil to determine soil EC. Measurements from the top layer indicate effects of management, whereas measurements from the deeper layer identify natural soil variability. To collect soil EC data, the Veris 3100 was pulled by a vehicle at a speed of 10 km h^{-1}. This resulted in EC (mS m^{-1}) measurements every 2-3 m in the field, totaling approximately 860-960 measurements per hectare. By integrating the unit with a dGPS and data logger, field scale maps were created for EC in all three fields.

5.3.5 Data Analysis

Yield data were analyzed for spatial variability and temporal stability over years for each of the three different grid sizes (case A, B and C) around each DCP. Geo-referenced yield data corresponding to these grids were used for further calculations. Linear and multiple regression models (r^2) were used to assess the additive effects of plant yield parameters and soil characteristics on yield. Analogous to a study of Taylor et al. (1998), Pearson's correlation coefficients (r) were calculated between grid-level yields over years. The coefficients of variability (CV %) were calculated for in-field yield variability at field-level and grid-level. CV was defined as standard deviation/mean x 100. Analysis of variance was performed for yield at all grid sizes to examine differences in yield between and within the three fields. All statistical analysis was performed using the general procedures of Sigma Stat 2.0 (Jandel Scientific, San Rafael, CA, USA). Statistical differences are indicated at the $\alpha = 0.005$ and $\alpha = 0.001$ probability level (Tuckey, Dunn's).

5.4 Results

5.4.1 Corn Grain Yield

In order to obtain information about spatial variability and temporal stability of yields, different grid sizes were imposed on the field as described below. Mean yield is defined as mean yield over all fields. Grid-level yield is defined as mean yield of all grids within a field. Single grid-level yield is defined as yield of a single grid.

5.4.1.1 Field Scale

The mean yield in all three fields over the 5-year period was approximately 8500 kg ha^{-1}. Table 5 shows the annual yield at the field scale for each field and the annual mean yields over the three sites. Mean yield ranged from 6640 kg ha^{-1} in 1998 to 10490 kg ha^{-1} in 2000. Both, cultivar and weather had a strong influence on measured yield. The yields were higher in 1999, 2000 and 2002 compared to 1998 and 2001 due to more favorable temperature and precipitation. In 2000, the mean minimum and maximum temperatures were the highest, resulting in the highest yields at field scale. In 1998 and 2001, the measured yields were lower due to lower mean temperatures and precipitation (1998), and because short season cultivars were planted in 1998. The only exception was the high yield in field I2 in 2001, which could be attributed to the high yielding cultivar PESO, and an additional application of manure (40 kg N ha^{-1}) on this field. There were significant differences in the mean yield for the three fields over the 5-year period. In fields where the same corn cultivars were grown, significant differences in yield were attributed to differences in field and site characteristics. Whereas significant differences between yields with different cultivars likely resulted from genetic differences in the cultivars and therefore differences in the response to the environment.

5.4.1.2 Grid Scale of 15.0 x 11.0 m (Case A)

Yield monitor data were aggregated to grids that were 15.0 x 11.0 m in size to examine spatial behavior of yield at a smaller grid scale (case A). Note that when the grids were overlaid on the DCP locations in each the field, some areas of the field were not included in any grids (Figure 15). The differences between grid-level yield in case A and yield at field scale was less than 5 % over all years, indicating that grid-level yield in case A represented the yields measured at the field scale (Table 5). Statistical analysis showed significant differences between grid-level yield of each field in case A in years 1998 and 2001. In the three remaining years no significant differences between the grid-level yields of the three fields were observed (Table 5).

5.4.1.3 Grid Scale of 22.5 x 16.5 m (Case B)

Yield was also computed at the grid scale of 22.5 x 16.5 m to evaluate yield differences in smaller zones in the field (case B). Because the grids were square and the grids were centered on each DCP, the grid representation of the field did not match the field boundary. Thus, some parts of the field were not included in the grid network (Figure 16). The differences between yield at field scale and grid-level yield in case B for each site were less than 10 %, indicating that grid-level yield in case B represented the yields measured on field scale (Table 5).

Table 5. Yield (kg ha^{-1}) at field scale and grid-level yield of field I1, I2 and I3 over the 5-year period (1998-2002).

Field	Scale	1998	1999	2000	2001	2002
I1	**Field scale**	5670 b	8240* a	11200 a	7840 b	9090 b
	Grid (case A)	5413 b	8587* a	7919 a	7605 a	8998 a
	Grid (case B)	5595 b	9028* a	10528 a	7604 a	9155 a
	Grid (case C)	5566 b	8377* a	10560 a	7698 b	8953 a
I2	**Field scale**	5930 b	7580 b	11030 b	9030 a	8090 a
	Grid (case A)	5524 b	7133 a	10111 a	9141 a	8391 a
	Grid (case B)	5401 b	8016 a	10639 a	9154 a	8097 a
	Grid (case C)	5349 b	7503 a	10524 a	8983 a	7915 b
I3	**Field scale**	8320 a	8560 a	9250 c	6560 c	9140 b
	Grid (case A)	8483 a	8508 a	8307 a	6393 b	9252 a
	Grid (case B)	8031 a	9111 a	9028 b	6307 b	8860 a
	Grid (case C)	8296 a	8243 a	8986 b	6282 c	8972 a

* In 1999 wheat was grown in field I1

Letters behind mean yield indicate significant differences between the same yield-levels of the three fields within each year at the 0.001 probability level.

Statistical analysis showed significant differences between grid-level yield of each field in year 1998, 2000 and 2001, influenced by both cultivars and site. In 1999 and 2002, no significant differences for grid-level yield were observed between the fields I1, I2 and I3 (Table 5).

5.4.1.4 Grid Scale of 15.0/22.5 x 27.5 m (Case C)

Yield monitor data was aggregated to larger area grids of 22.5 x 27.5 m in size and 15.0 x 27.5 m in size (case C). These two grid sizes were selected to better match the field geometry, and to include yield monitor data in grids near the boundary and corner of each field. The smaller grids (15.0 x 27.0 m) were placed at the edges of the fields, while the larger grids (22.5 x 27.5 m) were placed in the middle of the field (Figure 16). Differences between yield at field scale and grid-level yield in case C were less than 5 % indicating that this grid layout included nearly all parts of the field (Table 5). Statistical analysis of grid-level yields showed significant differences between all three fields in year 2000 and 2001. In year 1998 and year 2002 differences between grid-level yield of field I1 or I2 and I3 and I1 or I3 and I2 were shown, respectively (Table 5).

5.4.2 Spatial Variability of Corn Grain Yield

During the period of investigation the variability of yield was examined for each field at four different yield scales (field scale and case A, B, C). The level of variability in yields within each field (in-field variability), measured as coefficient of variability (CV), is shown in Table 6.

5.4.2.1 Field Scale

In years where the monthly precipitation during single months of the vegetative period was less than 50 mm, the in-field yield variability increased (2000, 2001). In 2000 the highest in-field variability was found in field I2 with a CV of 28.1 %. In 2001, a year with a lower maximum temperature, high in-field variability was detected for yield in field I1 and field I3 with a CV of 27.7 % and 26.9 % respectively. The low in-field variability (CV = 17.5 %) on field I2 probably resulted from the additional manure application on field I2 in this year. For the sites in the remaining years the CV ranged from 18.2-25.4 %, indicating a moderate yield variability (Table 6).

Table 6. Coefficient of variability (CV) describing the in-field yield variability (kg ha^{-1}) at field scale and grid-level for field I1, I2 and I3 over the 5-year period (1998-2002).

Field	Scale	1998	1999	2000	2001	2002
I1	**Field scale**	19.3	18.1*	24.2	27.7	19.6
	Grid (case A)	17.4	33.4*	61.6	14.0	14.4
	Grid (case B)	11.2	8.6*	15.4	6.8	9.7
	Grid (case C)	8.2	7.0*	9.5	4.8	12.5
I2	**Field scale**	22.4	21.4	28.1	17.5	22.0
	Grid (case A)	12.2	44.2	15.7	10.6	15.8
	Grid (case B)	11.0	17.7	12.0	11.6	13.5
	Grid (case C)	13.7	13.9	8.0	9.9	9.0
I3	**Field scale**	23.8	25.4	20.8	26.9	18.5
	Grid (case A)	13.7	39.7	38.2	14.0	9.8
	Grid (case B)	16.2	21.1	9.5	15.7	14.5
	Grid (case C)	15.2	18.2	6.7	9.9	10.0

* In 1999 the variability of wheat grain yield is shown in field I1

5.4.2.2 Grid Scale of 15.0 x 11.0 m (Case A)

The small grids in case A consisted of 2-3 yield monitor data points each. This resulted in a large variation between single grid-level yields and grid-level yield in case A. The deviation between the yield of a single small grid and the yield at field scale in the same year ranged from 62-154 %. This variability was reflected in the CVs, which was, in some years, more than twice as high compared to the CVs at the field scale (Table 6). In field I1 the CV ranged from 14.0 % in 2001 to 61.6 % in 2000. In fields I2 and I3, the lowest yield variability was found in 2001 (CVs of 10.6 % and 9.8 %, respectively), the highest yield variability was found in 1999 (CVs of 44.2 % and 39.7 %, respectively). These results indicated that the small grid size did capture the existing in-field variability in all fields.

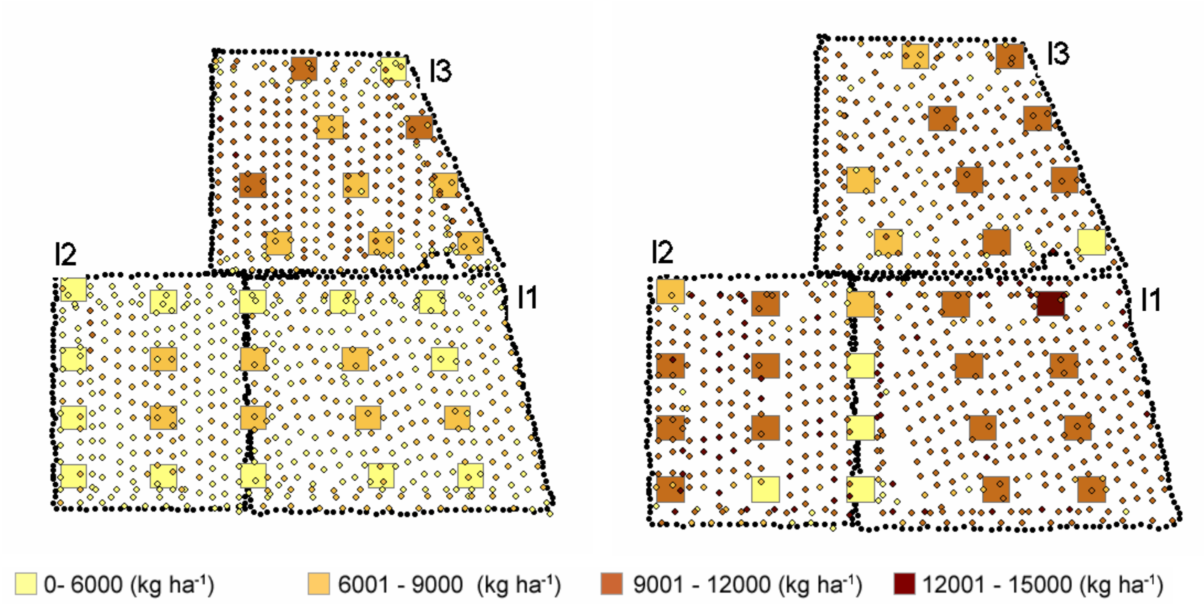

Figure 15. 30 Grids (15.0 x 11.0 m) around data collection points in field I1, I2 and I3 showing the distribution of high yielding and low yielding zones in 1998 and 2000 for case A.

Figure 15 shows the measured yield patterns for case A for the three fields in 1998 and 2000. In 2000, the single grid-level yields varied between 7094 and 12139 kg ha^{-1} (data not shown). In 1998 single grid-level yields were generally lower, but the range between the lowest (3364 kg ha^{-1}) and highest (10370 kg ha^{-1}) grid-level yields was extended (data not shown). In field I1, significant differences between single grid-level yields were found in three years (1999, 2001 and 2002), but not in the remaining two years. In field I2 significant differences between single grid-level yields were found only in year 1998 and in field I3 only in year 2001 (data not shown).

5.4.2.3. Grid Scale of 22.5 x 16.5 m (Case B)

The CV of grid-level yield for case B was less than the CV at field scale (Table 6). The variability of grid-level yield in field I1 decreased about 10 % compared to the field scale.

In field I2, the CV of grid-level yield in case B ranged from +4 % to -14 % compared to CV at field scale. The CV of grid-level yields in field I3 was only 5 % less than the CV at the field level.

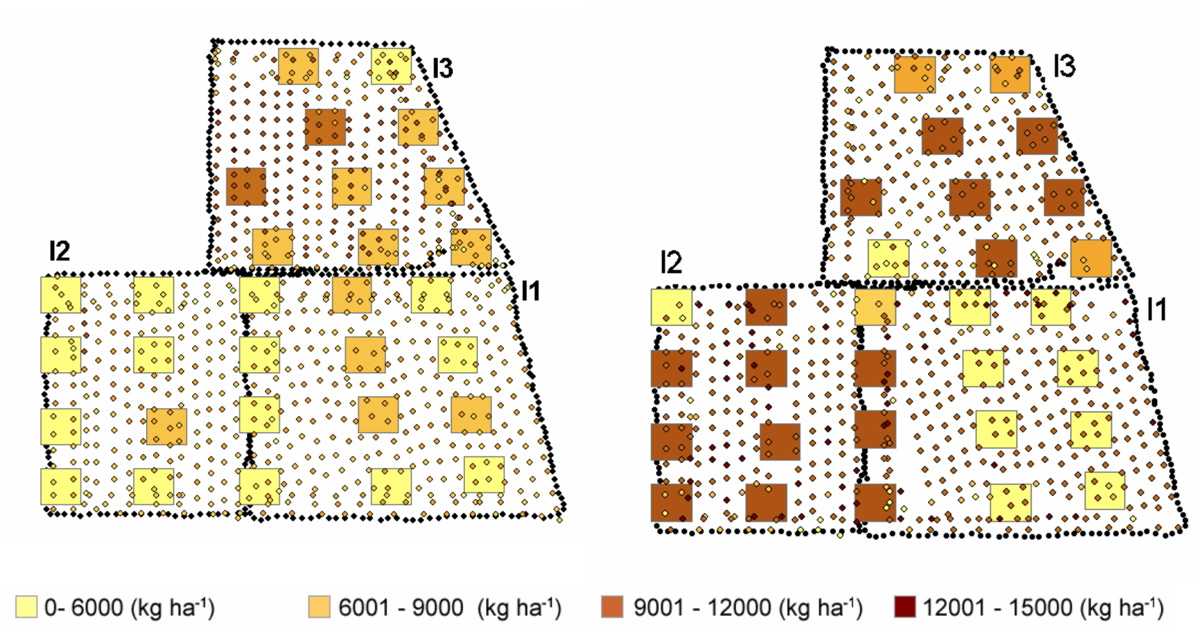

Figure 16. 30 Grids (22.5 x 16.5 m) around data collection points in field I1, I2 and I3 showing the distribution of high yielding and low yielding zones in 1998 and 2000 for case B.

Figure 16 shows the measured yield patterns for case B for the three fields in 1998 and 2000. In 2000, the single grid-level yields varied considerably and ranged between 5660 and 11845 kg ha^{-1} (data not shown). In 1998 single grid-level yields were generally lower, but differences between the lowest and highest grid-level yields were about the same with values ranging from 4244 to 10231 kg ha^{-1} (data not shown). During the 5-year period of investigation statistical analysis for field I3 indicated that there were significant differences in single grid-level yields for field I3 for each year, indicating high in-field yield variability. For field I1, significant differences in single grid-level yields were found in years 1999, 2000, and 2002. For field I2, significant differences in single grid-level yield were found in years 1999 and 2001. In the remaining years of investigation, no significant differences in single grid-level yields were found in fields I1 and I2 (data not shown). This result indicated that the grid size in case B did not match the existing in-field variability in field I1 and I2.

5.4.2.4 Grid Scale of 15.5/22.5 x 27.5 m (Case C)

In most cases the CVs for fields for case C were less than the CVs found for the other grid sizes. The CVs in case C was approximately 50 % less than the CVs at field scale for all fields. In field I1, the CV decreased more than 50 % compared to the CV at the field scale and ranged between 4.8 % in 2001 to 12.5 % in 2002. For field I2 and I3 the CV was lowest in 2000 (8.0 % and 6.7 % respectively) and highest in 1999, with values of 13.9 % and 18.2 %.

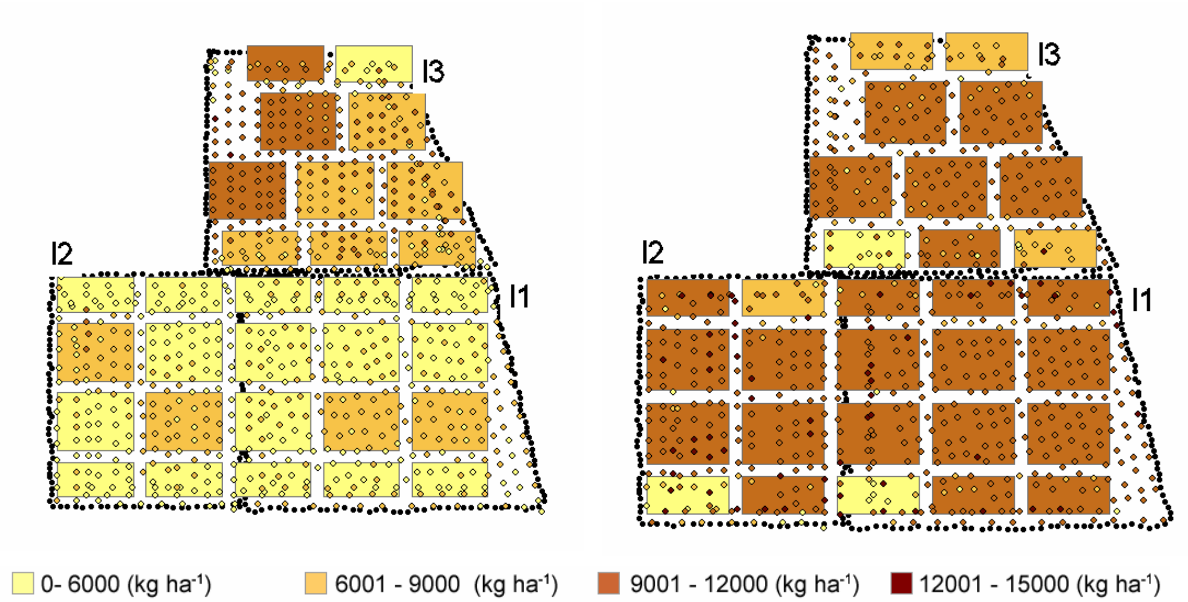

Figure 17. 30 Grids (15.0/22.5 x 27.5 m) around the data collection points in field I1, I2 and I3 showing the distribution of high yielding and low yielding zones in 1998 and 2000 for case C.

Figure 17 shows the measured yield for each grid in case C for the three fields in the years 1998 and 2000. In both years the single grid-level yield in case C varied considerably and ranged between 4288 and 10083 kg ha^{-1} in the year 1998 and between 7698 and 11631 kg ha^{-1} in year 2000. Significant differences between single grid-level yields were found in all fields and years, except for field I1 in year 2001 (data not shown), indicating that case C captured the existing in-field variability in all three fields.

5.4.3 Temporal Stability of Corn Grain Yield

In order to investigate the stability of yield on the three sites, the Pearson's correlation coefficient (r) was calculated for grid-level yields during the period of investigation. Temporal yield stability over years was defined as grids having a Pearson's correlation coefficient higher than $r = 0.5$.

5.4.3.1 Field Scale

At the field scale no calculations of temporal yield stability were performed.

5.4.3.2 Grid Scale of 15.0 x 11.0 m (Case A)

For grid-level yields in case A little correlation was found in most of the year-to-year yield patterns over the 5-year period (Table 7).

Table 7. Pearson's correlation coefficients (r) for yields in case A over different years for field I1, I2 and I3.

	Field	1999	2000	2001	2002
1998	**I1**		0.09 (0.78)	-0.15 (0.65)	**0.58 (0.05)**
	I2	0.32 (0.44)	-0.03 (0.94)	0.41 (0.32)	-0.11 (0.80)
	I3	0.08 (0.83)	0.07 (0.86)	0.18 (0.61)	**0.70 (0.03)**
1999	**I1**				
	I2		0.44 (0.28)	**0.51 (0.12)**	**0.76 (0.03)**
	I3		-0.55 (0.90)	-0.25 (0.50)	-0.15 (0.69)
2000	**I1**			-0.22 (0.49)	-0.08 (0.80)
	I2			-0.09 (0.83)	0.10 (0.82)
	I3			**0.80 (0.01)**	0.28 (0.43)
2001	**I1**				0.03 (0.93)
	I2				0.28 (0.45)
	I3				0.43 (0.22)

Level of probability in brackets

For field I1, high correlation was found between yields in 1998 and 2002 (r = 0.56). In field I2 good correlations were found between yields in 1999 and 2001 (r = 0.51) and yields in 1999 and 2002 (r = 0.76). In field I3 high correlation was found between yields in 1998 and 2002 (r = 0.70) as well as between years 2000 and 2001 (r = 0.80).

5.4.3.3 Grid Scale of 22.5 x 16.5 m (Case B)

Aggregating yields in grids of 22.5 x 16.5 m made it possible to delineate consistently high yielding and low yielding zones in each of the three fields in some years of investigation. Table 8 presents the results of the Pearson's correlation between the grid-level yields over the 5-year period for each field. In field I1 the strongest correlation was obtained between the yield pattern in year 1998 and 2002 (r = 0.71). In field I2 the strongest correlation was found between years 1999 and 2001 (r = 0.89). The strongest correlation of yield patterns in field I3 was found between years 2000 and 2002 (r = 0.76). The results presented in Table 8 indicated that the high and low yielding zones were stable across years, especially in field I3.

Table 8. Pearson's correlation coefficients (r) for yields in case B over different years for field I1, I2 and I3.

	Field	1999	2000	2001	2002
1998	**I1**		0.19 (0.55)	0.01 (0.99)	**0.71 (0.01)**
	I2	0.08 (0.86)	0.02 (0.65)	-0.07 (0.88)	0.18 (0.68)
	I3	0.02 (0.96)	0.35 (0.32)	**0.50 (0.10)**	**0.71 (0.02)**
1999	**I1**				
	I2		0.49 (0.22)	**0.89 (0.00)**	-0.32 (0.44)
	I3		**0.59 (0.07)**	-0.04 (0.92)	0.11 (0.76)
2000	**I1**			0.36 (0.25)	0.49 (0.11)
	I2			0.56 (0.15)	0.57 (0.14)
	I3			**0.65 (0.04)**	**0.76 (0.01)**
2001	**I1**				-0.06 (0.86)
	I2				-0.21 (0.61)
	I3				**0.74 (0.01)**

Level of probability in brackets

5.4.3.4 Grid Scale of 15.5/22.5 x 27.5 m (Case C)

Grid-level yields were also determined by aggregating the yield into 22.5 x 27.5 m and 15.0 x 27.5 m grids to better match the geometry of the field. Pearson's correlation coefficient for yields in field I3 were consistently higher than r = 0.50 (Table 9).

Table 9. Pearson's correlation coefficients (r) for yields in case C over different years for field I1, I2 and I3.

	Field	1999	2000	2001	2002
	I1		0.49 (0.11)	0.18 (0.57)	**0.70 (0.01)**
1998	**I2**	0.37 (0.36)	**0.94 (0.00)**	0.42 (0.30)	**0.81 (0.01)**
	I3	**0.65 (0.04)**	**0.51 (0.13)**	**0.85 (0.00)**	**0.92 (0.00)**
	I1				
1999	**I2**		**0.66 (0.07)**	**0.91 (0.00)**	0.33 (0.42)
	I3		**0.56 (0.09)**	**0.74 (0.01)**	**0.54 (0.11)**
	I1			**0.54 (0.07)**	0.44 (0.15)
2000	**I2**			**0.70 (0.05)**	**0.83 (0.01)**
	I3			**0.76 (0.01)**	**0.54 (0.11)**
	I1				-0.05 (0.87)
2001	**I2**				**0.52 (0.19)**
	I3				**0.79 (0.01)**

Level of probability in brackets

In field I2, a high correlation in year-to-year yield patterns was found for most of the years. However, in field I1, correlation coefficients above r = 0.50 were found between the years 1998 and 2000 (r = 0.70) and the years 2000 and 2001 (r = 0.54).

5.4.4 Plant Yield Parameters

In 2000, plant samples were taken at DCPs before harvest to estimate the impact of plants ha^{-1}, cobs m^{-2}, kernels m^{-2}, and TKW on spatial yield variability at the three sites.

Table 10. Plant yield parameters collected at data collecting points (DCP) in fields I1, I2 and I3 in 2000.

Field	Plants ha^{-1}	Cobs m^{-2}	Kernel m^{-2}	TKW (g)	DCP yield (kg ha^{-1})
I1	84167 a	10.83 a	5197.25 b	298.92 a	12098 a
I2	87500 a	10.25 a	6597.13 a	240.63 b	11760 a
I3	85000 a	9.00 a	5062.60 b	289.90 a	11780 a

Letters behind mean yield indicate significant differences between the three fields at the 0.001 probability level.

In contrast to the geo-referenced yield from the yield monitor, DCP yield calculated from the hand harvested plant samples (1 m²) showed no significant differences between field I1, I2 and I3 in 2000 (Table 10). The mean DCP yield calculated from the plant samples at each DCP was higher than the yield at field-level. The differences between yield at field scale and DCP yield were about -898 kg ha^{-1} in I1, in I2 about -730 kg ha^{-1} and in I3 -2530 kg ha^{-1}, which was less than 10 % in field I1 and I2.

Although the DCP yields in each field were nearly the same in 2000, differences in plant yield parameters were observed. In field I2 the number of kernel m^{-2} was significantly higher than in field I1 and I3. However, the TKW of 240.63 g was significantly less than in I1 and I3 with a kernel weight of about 289.82 g and 289.90 g respectively. The higher yield in I1 was caused by a high number of kernels m^{-2} and a high TKW. In field I2, TKW was about 10 % lower than the mean and in field I3 kernel m^{-2} was about 20 % lower than the mean, leading to the lower yield levels in these fields. As the results of the linear correlation analysis pointed out, the influence of kernel number on yield was stronger ($r^2 = 0.40$) than the influence of TKW on yield with $r^2 = 0.10$. Within each field, a very good agreement between kernel m^{-2} and DCP yields were obtained, resulting in $r^2 = 0.95$ in I1, $r^2 = 0.79$ in I2 and $r^2 = 0.89$ in I3. These results could not be shown for grid-level yields in case A, B and C, respectively (Table 11).

The number of plants ha^{-1} and the number of cobs m^{-2} were not significantly different between the three fields (Table 10). The number of plants ha^{-1} varied between 70000-90000 (mean 84167) in field I1, and varied in field I2 and field I3 between 80000-100000 (mean I2 was 87500, mean I3 was 85000). There was not a good agreement between plants ha^{-1} and DCP yield or grid-level yield, respectively.

Table 11. Results of linear and multiple regressions (r²) between selected plant yield parameters and grid-level yields of field I1, I2 and I3 in 2000.

	Scale	Plants ha^{-1}	Cobs m^{-2}	Kernel m^{-2}	TKW (g)	Kernel $cobs^{-1}$	Cobs $plant^{-1}$	Plants ha^{-1} + TKW (g)	Cobs m^{-2} + TKW (g)	Kernel m^{-2} + TKW (g)
I1	**Grid (case A)**	0.109	0.025	0.016	0.043	0.116	0.0000.	0.154	0.051	0.080
	Grid (case B)	0.106	0.108	0.224	0.015	0.007	033	0.121	0.108	0.244
	Grid (case C)	0.187	0.139	0.461	0.025	0.000	0.029	0.213	0.139	0.463
I2	**Grid (case A)**	0.320	0.020	0.043	**0.557**	0.006	0.176	**0.559**	**0.558**	**0.562**
	Grid (case B)	0.427	0.160	0.373	**0.572**	0.045	0.482	**0.581**	**0.630**	**0.799**
	Grid (case C)	0.217	0.057	0.038	0.083	0.456	0.006	0.234	0.117	0.103
I3	**Grid (case A)**	0.039	0.025	0.026	0.199	0.148	0.136	0.228	0.382	0.199
	Grid (case B)	0.002	0.134	0.000	0.003	0.203	0.118	0.004	0.148	0.299
	Grid (case C)	0.026	0.228	0.008	0.005	0.192	0.098	0.029	0.228	0.009
All	**Grid (case A)**	0.014	0.000	0.068	0.020	0.082	0.003	0.050	0.020	0.068
	Grid (case B)	0.067	0.017	0.240	0.003	0.000	0.063	0.087	0.022	0.025
	Grid (case C)	0.034	0.013	0.009	0.016	0.000	0.040	0.072	0.032	0.017

Unlike the number of plants ha^{-1}, the number of cobs m^{-2} were highest in field I1 with about 10.83 cobs m^{-2} compared to field I2 and field I3, which had a mean number of 10.25 cobs m^{-2} and 9.0 cobs m^{-2} respectively. For all sites, a high variability of cobs m^{-2} was found, which ranged from 7-15 cobs m^{-2} in field I1, from 9-14 cobs m^{-2} in field I2 and from 8-10 cobs m^{-2} in field I3. Despite the high variability of cobs m^{-2}, there were no significant differences in the number of cobs m^{-2} among the fields in 2000. Regression analysis showed good agreements between cobs m^{-2} and DCP yield, resulting in coefficients of determination of $r^2 = 0.56$ (field I2) and $r^2 = 0.48$ (field I3). While good agreement between DCP yield and single plant yield parameters were found for cobs m^{-2} and kernel m^{-2}, no correlation was found between grid-level yields and most of the measured plant yield parameters (Table 11). However in field I2, there was a small correlation between grid-level yield in case A and B and TKW ($r^2 = 0.56$ and $r^2 = 0.57$, respectively) and cobs $plant^{-1}$ ($r^2 = 0.48$) respectively. For field I1 and I3, no agreement between single plant yield parameters and grid-level yield at any scale was found. These results indicated that single plant yield parameters collected from specific DCP in the field could partially explain yield variability on a very small scale of 1 m². However, hand sampled plant yield parameters did not correlate very well to yields at any grid scale. Similar results were found for multiple regressions between plant yield parameters and yields.

A good correlation was found between kernel m^{-2} and TKW with DCP yield ($r^2 = 0.96$), indicating a strong influence of this combination of parameters on yield variability. With the exception of grid-level yield in field I2, combinations of yield parameters did not show good agreements with grid-level yield (Table 11). These results suggested that plant yield parameters were not the driving factor for measured in-field variability.

Nutrient availability over all fields was evaluated using the plant samples collected at DCPs. At harvest nutrient content of plants and kernel did not vary much across the sites. Almost no differences were visible in the mean nutrient content among and within the fields. At harvest N content of corn plants averaged 0.6 % (0.5-0.8 %), P content averaged 0.1 % (0.1-0.2 %), K content averaged 1.5 % (1.2-1.8 %) and Mg content averaged 0.1 % of the plant dry matter. The results indicated an adequate nutrient supply over each of the three fields, therefore no significant effect of nutrient supply on total yield was found.

Table 12. Results of linear and multiple regressions (r^2) between kernel or plant nutrient concentration (% of dry matter) and grid-level yield of field I1, I2 and I3 in 2000.

Field	Scale	Kernel N	Plant N	Kernel P	Plant P	Kernel K	Plant K	Kernel N + P + K + Mg	Plant N + P + K + Mg
I1	**Grid (case A)**	0.005	0.075	0.007	0.005	0.053	0.064	0.295	0.158
	Grid (case B)	0.162	0.009	0.290	0.074	0.279	0.125	**0.554**	0.495
	Grid (case C)	0.075	0.007	0.146	0.001	0.184	0.213	0.429	0.422
I2	**Grid (case A)**	0.441	0.171	**0.547**	0.193	0.362	0.155	**0.633**	**0.615**
	Grid (case B)	**0.715**	0.401	0.477	0.125	**0.575**	0.346	**0.931**	**0.874**
	Grid (case C)	0.062	0.000	0.003	0.012	0.018	0.035	0.399	0.099
I3	**Grid (case A)**	0.198	0.023	0.000	0.004	0.018	0.219	0.276	0.462
	Grid (case B)	0.094	0.007	0.070	0.159	0.193	0.004	0.302	0.242
	Grid (case C)	0.177	0.000	0.004	0.161	0.152	0.056	0.409	0.463
All	**Grid (case A)**	0.067	0.034	0.011	0.001	0.034	0.013	0.160	0.122
	Grid (case B)	0.224	0.026	0.278	0.234	0.021	0.000	0.475	0.257
	Grid (case C)	0.097	0.005	0.130	0.289	0.000	0.000	0.256	0.360

Nutrient content of plants did not correlate very well with DCP yields and grid-level yields, with the exception of field I2, where a weak correlation was found between plant N content and grid-level yield in case B ($r^2 = 0.41$). Linear regressions between nutrient content and grid-level yields were moderate (Table 12). With exception of field I2, no impact of single nutrient contents on grid-level yield could be found for the different grid sizes. The results for field I2 suggest that nutrients influenced grid-level yield in case B and in case A in this field.

5.4.5 Soil Parameters

Soil characteristics collected at the DCPs were analyzed to determine their influence on grid-level yield variability in the year 2000. Soil characteristics may be spatially variable due to natural soil variability, management practices and interaction between both.

There was nearly no variability in OM and pH within the fields. Silty loam was the dominant soil type across all fields, with an OM content of 1.7-1.8 %. The pH value ranged between 7.20 and 7.50 all over the fields, with a mean of 7.4. However, soil nutrients P, K and Mg varied across the fields, but in general levels were sufficient at each DCP. The regression analysis indicated that, with the exception of silt content and DCP yield in field I2 ($r^2 = 0.33$, data not shown), the OM content, pH, P, K, Mg and nitrogen content did not correlate well with DCP yields or grid-level yields (Table 13). Based on these results, spatial yield differences could not be explained by single soil characteristics. There were no relationships between DCP yield or grid-level yields and any soil nutrients. A small correlation was found between P and the grid-level yields in case A for field I1 ($r^2 = 0.53$). In general, spatial yield variability could not be explained with soil nutrient content in the three fields (Table 13).

Soil electrical conductivity (EC) was measured at a depth of 0-30 cm and 0-90 cm. Significant differences were found in soil EC (mS m^{-1}) between the sites at both soil depths. Although there were differences in EC within each site, the results of measuring EC in the top layer indicated homogenous management strategies. In 0-30 cm the EC averaged out about 31.2 mS m^{-1} over all sites, whereas in I3 the highest soil EC was measured (33.7 mS m^{-1}). In field I2, the lowest EC was 28.1 mS m^{-1}, and in I1, the lowest EC was 32.0 mS m^{-1}. There were differences among EC values at the 0-90 cm depth. In field I3, very low mean EC was measured (8.4 mS m^{-1}), with a range from 4.0-24.1 mS m^{-1}. Field I1 had a mean EC of 28.1 mS m^{-1}, with a range of 2.3-247.2 mS m^{-1}, and field I2 had a mean EC of 104.5 mS m^{-1}, with a range from 1.8-452.0 mS m^{-1}. This indicates high variability of natural soil properties. The high values of deep soil EC may indicate higher clay content, water and salt concentration in these fields, which may affect potential yield through deep soil water availability.

There was a correlation between grid-level yield in case B and EC in 2001 over all sites and both soil depths (Table 13). The analysis gave $r^2 = 0.49$ for the top layer (0-30 cm) and $r^2 = 0.63$ for the deeper soil layer (0-90 cm).

Studies of Sudduth et al. (1996) and Kravchenko and Bullock (2000) have shown that linear analysis alone often fails to produce functional models that explain yield variability. In order to possibly explain spatial yield variability, multiple regression analysis was performed between measured soil parameters and yields. Using multiple regressions, a relationship between grid-level yields at any scale and soil characteristics was found in 2000 (Table 14).

Table 13. Results of linear regression (r^2) between selected soil characteristics or soil nutrient content, respectively and grid-level yield of field I1, I2 and I3 in 2000.

Field	Scale	Clay (%)	Silt (%)	Sand (%)	OM (%)	pH	Nt (%)	P_2O_5 (g kg^{-1})	K_2O (g kg^{-1})	Mg (g kg^{-1})	EC (mS m^{-1}) 0-30 cm *	EC (mS m^{-1}) 0-90 cm *
I1	**Grid (case A)**	0.178	0.333	0.185	0.322	0.002	0.308	**0.529**	0.104	0.038	0.043	0.061
	Grid (case B)	0.000	0.017	0.029	0.005	0.012	0.002	0.199	0.080	0.015	0.068	0.228
	Grid (case C)	0.013	0.061	0.054	0.000	0.006	0.002	0.103	0.071	0.023	0.046	0.000
I2	**Grid (case A)**	0.095	0.126	0.000	0.109	0.001	0.272	0.054	0.028	0.011	0.028	0.011
	Grid (case B)	0.010	0.213	0.121	0.087	0.138	0.002	0.021	0.009	0.001	**0.659**	0.275
	Grid (case C)	0.141	0.030	0.048	0.047	0.008	0.016	0.033	0.001	0.134	0.268	0.025
I3	**Grid (case A)**	0.020	0.001	0.015	0.217	0.036	0.075	0.005	0.030	0.009	0.000	0.416
	Grid (case B)	0.113	0.247	0.167	0.070	0.103	0.023	0.007	0.022	0.135	0.188	0.335
	Grid (case C)	0.050	0.129	0.095	0.002	0.105	0.013	0.001	0.001	0.078	0.226	0.085
All	**Grid (case A)**	0.045	0.035	0.002	0.014	0.035	0.034	0.043	0.000	0.004	0.000	0.039
	Grid (case B)	0.001	0.018	0.039	0.119	0.000	0.046	0.054	0.020	0.013	0.488	**0.627**
	Grid (case C)	0.028	0.003	0.023	0.049	0.012	0.056	0.073	0.023	0.009	0.174	0.156

* Correlation between EC and grid-level yield was calculated for year 2001

The regression analysis for a combination of P, K, Mg and N content resulted in r^2 = 0.61 for I1, r^2 = 0.44 in I2 and r^2 = 0.52 for grid-level yield in case B. There was also a relationship between soil nutrient content (N, P, K, Mg), soil characteristics (OM, pH, clay or silt or sand respectively), electrical conductivity (0-30 cm and 0-90 cm respectively) and grid-level yields of all grid sizes. The coefficient of determination ranged from r^2 = 0.47 to r^2 = 1.00 (Table 14).

Table 14. Results of multiple regressions (r^2) between soil nutrient content N_t (%), P_2O_5 (g kg^{-1}), K_2O (g kg^{-1}), Mg (g kg^{-1}), soil characteristics EC (mS m^{-1}), clay (%), OM (%), pH and grid-level yield of field I1, I2 and I3 in 2000.

Field	Scale	N_t + P_2O_5 + K_2O + Mg	N_t + P_2O_5 + K_2O + Mg + Clay + EC 0-30 cm	N_t + P_2O_5 + K_2O + Mg + Clay + EC 0-90 cm	N_t + P_2O_5 + K_2O + Mg + Clay + EC 0-30 cm + OM + pH	N_t + P_2O_5 + K_2O + Mg + Clay + EC 0-90 cm + OM + pH
I1	**Grid (case A)**	0.136	**0.678**	**0.611**	**0.830**	**0.785**
	Grid (case B)	**0.605**	**0.930**	**0.885**	**0.679**	**0.780**
	Grid (case C)	0.267	**0.525**	**0.522**	**0.931**	**0.856**
I2	**Grid (case A)**	**0.613**	**0.974**	**0.970**		
	Grid (case B)	0.443	**0.998**	**0.988**		
	Grid (case C)	**0.510**	**0.899**	**0.859**		
I3	**Grid (case A)**	0.234	**0.569**	**0.649**	**0.998**	**0.776**
	Grid (case B)	**0.516**	**0.775**	**0.660**	**0.957**	**0.733**
	Grid (case C)	0.485	**0.543**	0.473	**0.977**	**0.541**
All	**Grid (case A)**	0.079	0.219	0.244	0.249	0.270
	Grid (case B)	0.076	0.284	0.166	0.297	0.247
	Grid (case C)	0.094	0.362	0.313	0.413	0.328

* Correlation between EC and grid-level yield was calculated for year 2001

For all three fields, better relationships were found using a combination of soil nutrient contents and EC from the soil layer 0-30 cm (instead of EC from the deeper soil layer 0-90 cm), and clay (instead of silt or sand) (data not shown). These results indicated a strong impact of the upper soil layer characteristics on the grid-level yield at all spatial scales in year 2000.

5.5 Discussion

Over a 5-year period spatial variability and temporal stability of corn grain yield were investigated in the Upper Rhine Valley. Temporal stability of corn yield was also investigated in studies of Taylor et al. (1998), whereas studies of Jaynes and Colvin (1997) and Lamb et al. (1997) focused on spatial variability of corn yields. Several studies showed that yield variability can be caused by biotic and abiotic factors (Mulla and Schepers, 1997; Braum et al., 1998).

Analogous to Long (1998), linear and multiple regressions were conducted between plant yield parameters, soil characteristics and grid-level yield at different spatial scales to quantify the relationship between yield and underlying factors. Although selected plant yield parameters such as number of plants ha^{-1}, cobs m^{-2} and kernels m^{-2} were variable across the fields (Table 10), results of regression analysis did not show strong correlations with grid-level yields and selected parameters at any scale (Table 11). Results of this study indicated that measured plant parameters did not explain spatial variability. Similar results were shown by Katsvairo et al. (2003), who observed that plant yield parameters such as plants ha^{-1} did not contribute to the spatial variability of corn yield.

High yield variability at field scale was due to low yields measured in the turn rows near the end of each field. Low yields in this area may be due to soil compaction and sometimes due to errors associated with yield monitor operations, caused by combine movement at the turn row and errors in grain flow as well (Blackmore and Moore, 1999; Arslan and Colvin, 2002). Spatial yield variability can also be caused by chemical and physical properties inherent to soil, which can affect nutrient availability (Penney et al., 1996). In some seasons, as much as 60 % or more of the yield variability can be explained by a combination of soil properties (Kravchenko and Bullock, 2000). Kravchenko and Bullock (2000) described soil properties as a permanent spatial factor that affects yield either directly or indirectly. There was a good correlation between soil properties and grid-level yields at all spatial scales in this study. Strong relationships were found between combinations of soil nutrient levels, soil characteristics and yield. Depending on grid size and parameter combinations, coefficients of determination of $r^2 = 0.93$, $r^2 = 1.00$ and $r^2 = 1.00$ were found for field I1, field I2 and field I3, respectively (Table 14). Thus, it appears that in this study soil nutrient level and soil characteristics were the primary factors that explained spatial yield variability in the fields in the Upper Rhine Valley. Spatial variability of nutrients resulted from spatial variations in underlying soil chemical and physical properties, OM, pH and, in some cases may be induced by management practices (Batchelor et al., 2002).

In spite of the large number of measured variables and the multiple years of yield data, some of spatial variability in yield remained unexplained in this study. This suggests, that there are more factors that influenced yield. In order to identify more of the underlying processes affecting the observed yield variability complex methods like crop growth models shall be used to analyze possible interactions of all relevant factors.

For precision farming to be a viable management option, it is necessary to identify zones in a field that give stable yield over multiple seasons. However, this is difficult because of the complex interactions that create variable stress or limitation of nutrients that reduce yield in different ways during different seasons. In order to develop management plans to capitalize on yield variability, it is important to understand the factors that limit yields spatially and temporally in a field.

The investigation of spatial variability and temporal stability of yield in this study gave different results depending on the grid sizes imposed on each field. In general, larger grids were able to adequately describe temporal yield stability (Table 9), but not spatial yield variability across seasons. Smaller grids were able to describe spatial yield variability, but not temporal yield stability across seasons (Table 7). Larger grids averaged out spatial yield variability by aggregating and averaging yield monitor measurements over a large land area, while small grids represented fewer yield monitor data points and thus, retained the spatial structure of yield. These results are consistent with studies of Ping and Dobermann (2003), which showed that increasing the grid size before or after classification into yield classes may create larger and more continuous yield classes. Also Long (1998) found that the range between minimum and maximum yield of a single grid decreased with increasing grid scale.

The smallest grid size (case A) represented the spatial yield variability as well as case B or the field scale. Grid-level yield ranged widely within fields and over years, but did not always show significant differences between the single grid-level yields. Results of Ping and Dobermann (2003) showed that grid size had little effect on mean relative yield of the resulting yield classes, but increased the CV within the yield classes. The small grids in case A did not represent temporal yield stability very well. This was expected since there were only 2-3 yield monitor data points within each small grid. Dobermann et al. (2003b) showed that yield classification based on small grid sizes resulted in spatially fragmented yield classes, where random yield variability was due to uncertainties associated with the yield mapping process as well as those due to true yield variability.

The investigation of different grid sizes in this study illustrated that the yields in case B gave a good representation of both the spatial and temporal yield stability and variability, especially in field I3. The grid-level yield in field I3 represented both the spatial and temporal yield patterns well for most seasons (Table 8).

The combination of different grid sizes in case C described spatial and temporal yield variability well over the 5-year period and seemed practical to implement. Although the large grid sizes averaged yield variability within the sites, which was similar to results of Ping and Dobermann (2003), there were significant differences between grid-level yields in the case C. In the Upper Rhine Valley using different grid sizes made it possible to better group areas of the field into high yielding and low yielding grids (Table 9). These results were opposite to the results of Taylor et al. (1998), who could not illustrate spatial stability for corn yield in a squared 55 m grid raster.

Data analysis indicated that the scale of yield variability was different in the three fields. Due to this fact the grid resolution required to describe yield variability and stability was different for different fields. These results were similar to Roel and Plant (2004), who showed that the grid density needed to capture spatial yield variability depended on site and year. There appeared to be a direct trade-off between maintaining spatial structure using a small grid network and maintaining temporal stability by selecting a coarser grid network (Wong, 1995; Long, 1998). Combining areal units into successively larger units, an agronomist will need to consider the scale at which the spatial variability of site-specific yield data has to be analyzed (Long, 1998).

Based on the results of this study the grid size should be selected in regard of the existing variability within the field and the underlying yield-limiting factors, which create the yield variability. Some of the underlying factors may have a high range of variability or continuity, whereas other factors might have a low range of variability or continuity. Due to the scale of variability of the underlying factor, different grid sizes should be selected to capture the spatial variability and stability within different sites and to delineate management zones.

5.6 Conclusion

During the 5-year field experiment in the Upper Rhine Valley spatial variability and stability of yield could be indicated. Whereas plant yield parameters did not explain the existing yield variability very well, soil characteristics were identified as the major factors affecting the observed yield variability in all three fields. Soil characteristics were described as characteristics with a high temporal stability and therefore could be used to demarcate management zones. The ideal grid size for the fields in this study was determined in consideration of the underlying factor affecting spatial yield variability. Due to different scales of yield variability, both, spatial variability and temporal stability of yield were displayed by different grid sizes. In general, larger grids were able to adequately describe temporal yield variability, but not spatial yield variability across growing seasons. Smaller grids were able to describe spatial yield variability, but not temporal yield variability across seasons. Therefore different grid sizes should be examined to determine the grid resolution that captures enough information to represent yield spatial variability and temporal stability at a scale appropriate to delineate management zones. If the underlying factor is highly variable within the field smaller grid sizes are useful to capture the measured yield pattern. If the underlying factor is less variable within the field larger grid sizes are more suitable for site-specific management.

Within the 5-year field experiment in the Upper Rhine Valley spatial variability and stability of corn grain yield could be determined, resulting in stable yield pattern for some years. The magnitude of the temporal stability of corn yield depended on the selected grid size. Smaller grids were able to describe spatial yield variability, but not temporal yield variability across seasons, whereas larger grids were able to adequately describe temporal yield variability, but disregarded some of the spatial yield variability across growing seasons. The spatial yield variability was mainly caused by varying soil characteristics (nitrogen, phosphorous, potassium, magnesium and organic matter content of the soil, pH, soil texture, electrical conductivity). However, some of the yield variability could not be explained. Thus, for further investigations of the spatial yield variability a crop growth model was implemented.

6 Crop Modeling

Precision farming (PF) strategies attempt to adjust field practices to accommodate a known variability of important factors. As practiced today, PF is primarily based on a few parameters, such as soil nutrients or weed maps. Understanding the impact of multivariate interactions is a challenge to producers, consultants, and scientists. As more and more sensors and new technologies are developed for PF, the amount and complexity of available information has increased at a phenomenal rate. But up to now, producers may find themselves uncertain about what information to use and how it can add value to their production systems. The ability to extract useful information out of large databases to conduct the right management decision still has to be developed. As precision management systems can be envisioned as reactive approach to spatially and temporally variable conditions within a growing season an integrative approach is needed to assess the need for and delivery of production inputs. Thus, the complete realization of PFs potential may depend on the development of predictive crop growth models that can vary the manageable factors on a specific scale.

Hanks and Ritchie (1991) paraphrase a model as an imitation of the reality. Thus, a model is “a representation of reality used to simulate a process, understand a situation, predict an outcome, or analyze a problem. A model is structured as a set of rules and procedures, including spatial modeling tools that relate to locations on the Earth’s surface“ (www.epa.gov/maia/html/glossary.html, 2004). Models are useful not because they reproduce reality, but because they simplify reality and enable the most important processes to be identified, studied, and simulated and enable outcomes to be predicted in advance (Addiscott, 1993). Thus, models can be used to organize and bring together knowledge of a specific topic, in order to display interactions among many factors (Hanks and Ritchie, 1991).

6.1 Categories of Models

Models might be categorized into empirical, mechanistic, functional or process-oriented model types.

Empirical models describe what happens, without telling how it happens, resulting in a black box approach. The mathematical relationships of the model do not necessarily correspond to a biological, chemical or physical process (Thornley and Johnson, 1990; Motulsky and Christopoulos, 2004) and therefore do not explain the mechanism in the relationship. Such models could be used to summarize the data or to preclude generalization beyond the data sets and the specific conditions for which the model is parameterized (Benbi and Nieder, 2003b). The empirical models examine or represent data and thus no new information is acquired (Thornley and Johnson, 1990). Many of the growth and yield relations with the input of nutrients or water belong to this category (Benbi and Nieder, 2003b).

A mechanistic model is more complex than an empirical model and attempts to describe the possible mechanisms of the underlying process and their interaction in the most fundamental way, the cause-effect relationship (Thornley and Johnson, 1990; Benbi and Nieder, 2003a). Thus, the mechanistic models provide insight into a process that is thought to govern the phenomenon under study (Motulsky and Christopoulos, 2004). The mechanistic models have been classified as deterministic and stochastic models, whereas deterministic models present a single outcome or unique solution and stochastic models give the probability of an outcome (Benbi and Nieder, 2003b). The major advantage of mechanistic models is that they can be transferred to another set of conditions, and thus offers more possibilities for manipulating and improving the system, which makes them ideal for scenario building (Thornley and Johnson, 1990; Benbi and Nieder, 2003b). Thus, mechanistic models need to maintain the balance between complexity and simplicity.

Functional models are defined as models that incorporate simplified approaches to describe more complex processes (Hoogenboom, 2003), whereas the simplest model is a linear regression equation (Hodges, 1991). Functional models do not rely on many parameters, and thus it is more likely to simplify the process than a mechanistic model (Benbi and Nieder, 2003b). Despite the simplification, functional models may provide as good a simulation as mechanistic models (Benbi and Nieder, 2003b). Thus, functional models are normally used as management tools, whereas mechanistic models are used in the research.

The two major purposes of crop growth modeling are to enhance the scientific understanding of processes and to predict the consequences of cropping system manipulation (Hammer et al., 2001). Based on the second purpose, crop growth models can help in saving resources and costs. The goal to evaluate agriculture and the associated impact on economic, environmental and human health related aspects has lead to the development of models that simulate the behavior of complex cropping systems (Van Ittersum and Donatelli, 2003). In order to simulate complex systems, process-oriented models were implemented, which contain a combination of different model types.

6.2 Yield Response and Growth Models

One of the first scientists, who developed a yield responses model for agricultural crops, was E. A. Mitcherlich (Overman and Schultz III, 2002a). In order to describe the crop response to a given management factor e.g. phosphorous fertilization, Mitcherlich used the following equation:

$$Y = Y0 + (Ym- Y0)\ [1 - \exp(-cN)] \qquad [5]$$

with Y = dry matter yield, Y0 = dry matter yield at N = 0, Ym = maximum dry matter yield at high N, c = nutrient response coefficient, N = applied nutrient. The yield response curve of oats to applied phosphorous based on equation [5] was first published by Russel (1912). This empirical model, which determines the seasonal dry matter to applied nutrients without any physical basis, stimulated a lot of interest and generated considerable controversy (Russel, 1912; Van der Paauw, 1952).

Yield response models are based on the cause-effect relationship only, whereas the mechanism underlying this relationship is not visible. In order to discover the impact of underlying processes on final yield, the crop growth, devolvement and environment need to be included into the model approach. However, whereas yield response models focus on the response of seasonal dry matter to applied nutrients, crop growth models account for the accumulation of dry matter and plant nutrients within time (Overman and Schultz III, 2002a) taking the environment and genetics in consideration (Hoogenboom, 2003). Normally, the growth rate of a crop is slow in the beginning, followed by a rapid phase, and ends with a decreasing growing rate (Overman and Schultz III, 2002b), which is best described with a sigmoidal curve. There clearly is an environmental impact on crop growth as well, which should not be disregarded. Hoogenboom (2003) defines yield as a function of biomass and harvest index. In order to consider the biomass, growth and development of a plant need to be known, and in order to consider the harvest index, the genetics and yield-limiting stress factors need also to be known. In the remarks of Hoogenboom (2003) growth and development of a plant depend on the impact of the environment, stress and genetics. The environment again is a function of temperature, solar radiation, carbon dioxide and the photoperiod. Stress is defined by abiotic and biotic factors and genetics, whereas the genetics are a function of cultivar and species. Thus, to simulate the complex system of crop growth all available data should be coupled into a single model.

For the agricultural purpose models were used since the 1970s (Hoogenboom, 2003), whereas the first crop growth models were based on approaches of simulating industrial processes (Forrester, 1961). At the University of Wageningen, Netherlands, Brouwer and de Witt (1968) and de Witt et al. (1970) developed some of the early crop growth models. The main aim of these modeling activities was to obtain an understanding at the crop scale based on the underlying processes (Van Ittersum et al., 2003). Thus, the underlying approach of this modeling group was based on systems ecology in which the state of the system can be expressed at any point in time and changes of the system can be expressed through mathematical terms (Hoogenboom, 2003).

In the past decade the dynamics of crop growth models has made substantial progress (Gerdes, 1993). Models have been developed in recent years that solve complex problems by taking into account many factors and interactions (Hanks and Hill, 1980).

A number of simulation models of agricultural and environmental purpose exist that describe some crop growth processes in dependency of the environmental conditions (management, soil, climate) or focus especially on the nitrogen cycle processes occurring in soil-plant-system (ammonia volatilization, leaching, denitrification), respectively. Agronomic models condense assumptions about biological processes interacting with the physical and chemical environment through mathematical equations (Van Ittersum and Donatelli, 2003). On the server for ecological modeling http://eco.wiz.uni-kassel.de/ecobas.html (2004) currently 111 different models are listed dealing with agricultural topics. The models deal with the examination of the overall effects of management practices on carbon and nitrogen flow through the systems, long term changes in soil nitrogen dynamics or are designed to provide fertilizer strategies (Benbi and Richter, 2003b). In the following section five major and most widely used generic process-oriented crop growth models will be described more precisely. These generic models provide a detailed simulation of plant growth and development, as well as a soil and plant water and nitrogen balance (Hoogenboom, 2003). While all models have achieved various degrees of success in application, they all have their weakness and fail under certain circumstances, wherefore authors of models should clarify the limitations of their models and ranges of applications (Ma and Schaffer, 2001).

6.2.1 APSIM

The APSIM model has been developed by the Agricultural Production Systems Research Unit in Australia. APSIM stands for Agricultural Production Systems SIMulator. The model was developed to simulate biophysical processes in farming systems, in particular where there is interest in the economic and ecological outcomes of management practices in the face of climatic risk (Keating, et al., 2003). APSIM has been developed in a way that allows the user to configure a model by choosing a set of sub-models from a suite of crop, soil and utility modules (Figure 18). Any logical combination of modules can be simply specified by the user "plugging-in" required modules and "pulling out" any modules no longer required (APSRU, 2004).

The APSIM model is able to simulate yield of crop as corn, wheat, barley, pastures and forest, but not for rice (Keating et al., 2003). All plant species use the same physiological principles to capture resources and use these resources to grow, whereas the main differences are the thresholds and shapes of their response function (Keating et al., 2003).

The soil water balance of the model was taken from the CERES model (Ritchie, 1972; Jones and Kiniry, 1986) and PERFECT (Littleboy et al., 1989; Littleboy et al., 1992). Also the mineralization of nitrogen is the same algorithm as in the CERES (Jones and Kiniry, 1986) or PAPRAN model (Seligman and van Keulen, 1981), but instead of two pools for organic matter, the APSIM models use three pools (Keating et al., 2003).

The required minimum data for the model input are cultivar, management and site characteristics, including soil characteristics, weather, soil surface characteristics and surface residue definition (Keating et al., 2003).

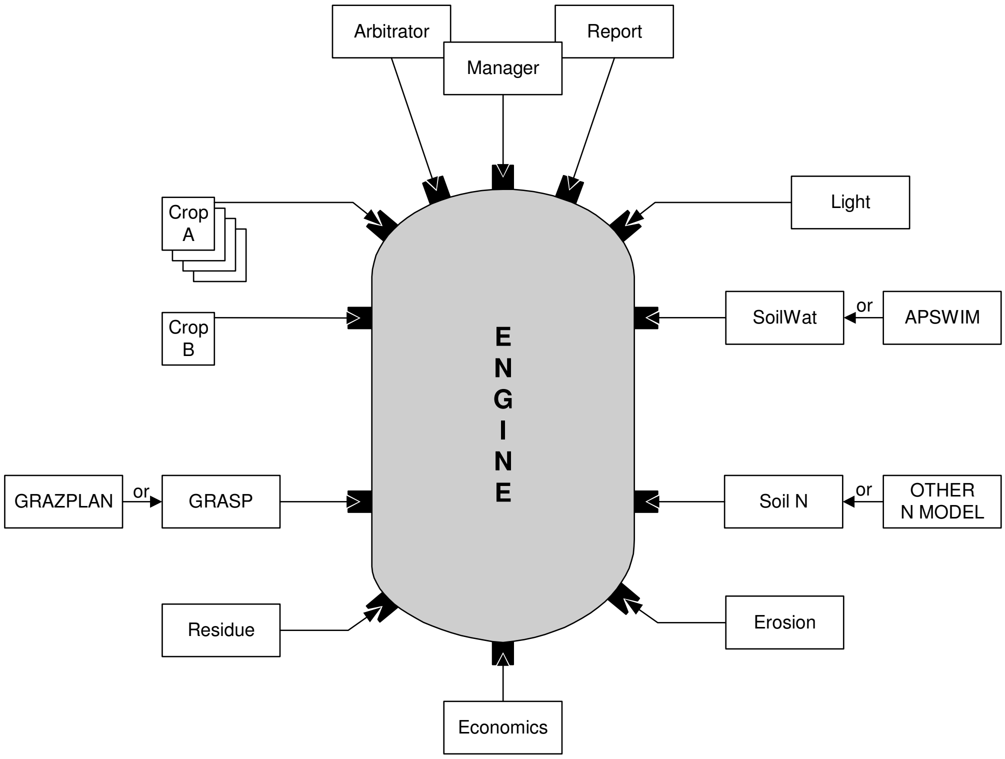

Figure 18. Diagrammatic representation of the APSIM simulation framework with individual crop and soil modules, module interfaces and simulation engine (modified from Keating et al., 2003).

APSIM has been used in a broad range of applications, including support for on-farm decision-making, farming design for production or resource management objectives, assessment of the value of seasonal climate forecasting, risk for government policy-making and as a guide to research and education activity (Keating et al., 2003).

6.2.2 CropSyst

The CropSyst model was developed to "serve as an analytic tool to study the effect of cropping systems management on productivity and the environment" (http://eco.wiz.uni-kassel.de/model_db/mdb/cropsyst.html, 2004). The model simulates the soil water and nitrogen budgets, crop growth and development, crop yield, residue production and decomposition, soil erosion by water, and salinity (Stöckle et al., 2003). The implementation of a generic crop simulation enables the simulation of both, yearly and multiple-year crops and crops rotations via a single set of parameters (Stöckle et al., 2003).

The main components of the CropSyst shell are the CropSyst parameter editor, the cropping systems simulator, a weather generator, a GIS-CropSyst simulation co-operator, a watershed analysis tool, and several utility programs (Figure 19, Stöckle et al., 2003).

The water redistribution in the soil is simulated by the Richards's soil flow equation (Campell, 1985; Ross and Bristow, 1990). In order to calculate evapotranspiration either the Pennman-Monteith model (Monteith, 1965) or the Priestley-Taylor model (Priestley and Taylor, 1972) can be chosen. The nitrogen uptake is modeled by adapting the approach presented by Godwin and Jones (1991). The mineral budget includes separate budgets for nitrate and ammonium. Nitrogen transformation and ammonium sorption follow the approach of Stöckle and Campbell (1989), while symbiotic nitrogen fixation is based on Bouniols et al. (1991). The simulation of crop phenology is mainly based on the thermal time, taking water stress and crop temperature into consideration (Stöckle et al., 2003). The biomass accumulation is based on a daily rate, by determining the potential biomass growth of the crop and then corrected by water and nitrogen limitations. The simulation process is described by Tanner and Sinclair (1983).

Figure 19. Flowchart of biomass growth calculations in CropSyst (modified from Stöckle et al., 2003).

To run the model five input files are required (Stöckle et al., 2003), including simulation control (starting point and ending of simulation, crop rotation, value initialization), location (latitude, weather), soil (cation exchange capacity, pH, SCS curve number, soil layer thickness and texture), crop (phenology, morphology, growth, residue, harvest index) and management (scheduled and automatic management like irrigation, nitrogen fertilization, tillage, residue management).

The model has been widely used to simulate cropping systems including corn, wheat, sorghum, soybean, rice and potato (Stöckle et al., 2003). Therefore, the model has been applied to perform risk and economic analyses of scenarios involving different cropping systems, management options and different soil and climate conditions (Stöckle et al., 2003).

6.2.3 DSSAT

One of the most widely used modeling systems across the world is the Decision Support System for Agrotechnology Transfer model (DDSAT), which was initially developed under the auspices of the International Benchmark Sites Network for Agrotechnology Transfer (Hoogenboom, 2003). The DSSAT model includes 16 generic simulation models, like the cereal model CERES for wheat, corn, barley, sorghum, millet and rice (Ritchie et al., 1998), the grain legume model CROPGRO for soybean, peanut, dry bean, and chickpea (Boote et al., 1998), the SUBSTOR model for potato, the CROPSIM model for cassava, OILCROP for sunflower and CANERO for sugarcane (Hoogenboom, 2003). These models are process-oriented, designed to have global applications, and work independent of location, season, crop cultivar, and management system. The models simulate the effects of weather, soil water, genotype, and soil and crop nitrogen dynamics on crop growth and yield (Jones et al., 2003). DSSAT is also used to evaluate nitrogen fertilization strategies on nitrogen uptake and nitrogen leaching from soil and in global change research to evaluate the potential effects of climate warming and changes in precipitation and water use efficiency due to increased carbon dioxide (Jones et al., 2003).

In comparison with the original crop growth models of the CERES and CROPGRO family the DSSAT crop growth models have been re-designed and programmed to facilitate more efficient incorporation of new scientific advances, applications, documentations and maintenance (Jones et al., 2003). The new DSSAT cropping system models are organized in modules including separated soil, weather, soil-plant-atmosphere, crop template, crop and management modules. Figure 20 presents a diagram of database, application and support software components and their use for crop growth model application.

In the CERES family of crop growth models the same simulation subroutines form the basis for carbon, nitrogen and water simulations. The carbon subroutine is based on Godwin and Singh (1998), the nitrogen subroutine is calculated according to Godwin and Jones (1991), whereas the water movement is based on Ritchie (1998).

Biomass and yield production is calculated as a function of radiation, leaf area index and reduction factors for temperature and moisture stress. Crop development is primarily based on degree-days, whereas leaf and stem growth rates are calculated depending on phenological stages.

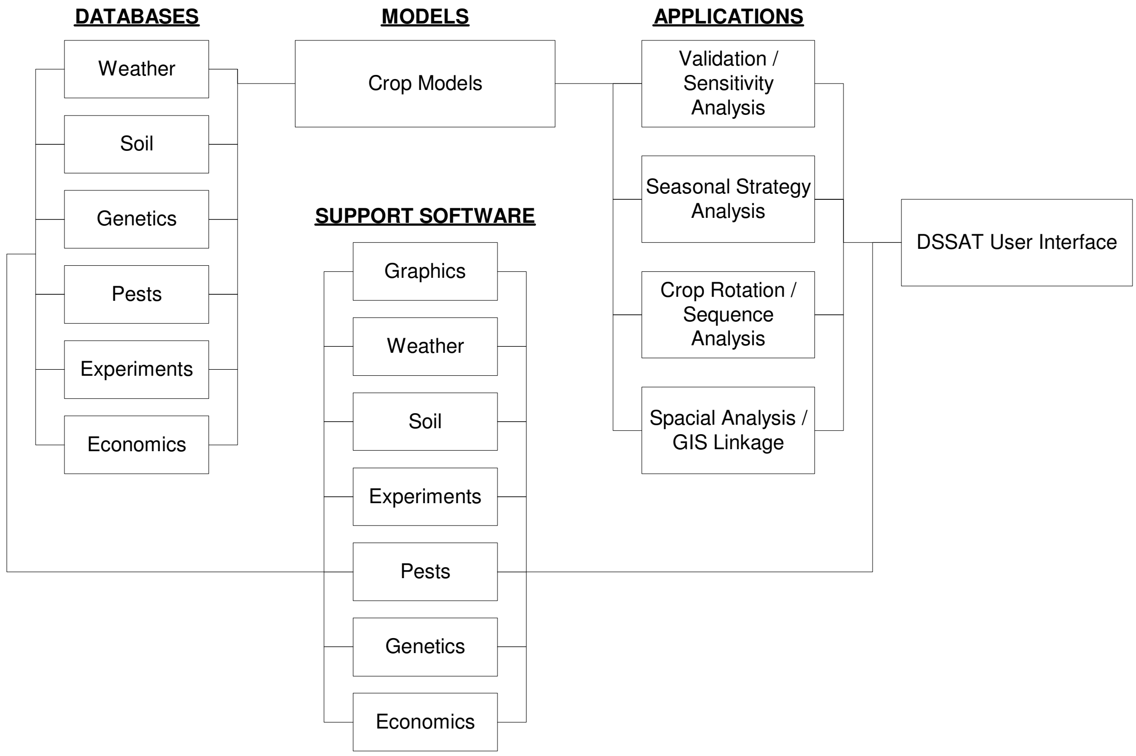

Figure 20. Diagram of database, application and support software components and their use for crop growth model application in DSSAT v3.5 (modified from Jones et al., 2003).

In order to run the model climate variables (latitude, radiation, minimum and maximum temperature and rainfall), management variables (sowing date, plant density, irrigation schedules, fertilization), crop genetic constants, and soil parameters (soil albedo, soil layer thickness, organic matter and nutrient content) are required as minimum dataset (Jones et al., 2003).

The model provides information on above-ground dry matter, nitrogen content, grain dry matter and nitrogen content, summaries of water balance and soil mineral nitrogen (Jones et al., 2003). The Strategy Evaluation Program in DSSAT allows users to evaluate the merits of simulated strategies and identify the best one. The program uses cumulative probability functions to develop and select the strategy with the preferred mean and variability characteristics. “With this program users can determine the effectiveness of crop management strategies, the economic return of a new cultivar, or the suitability of a site for a specific crop“ (http://eco.wiz.uni-kassel.de/model_db/mdb/dssat.html, 2004).

6.2.4 EPIC

The Erosion-Productivity Impact Calculator model (EPIC) is a mechanistic simulation model used to examine long-term effects of various components of soil erosion on crop production (Williams et al., 1983). The model was developed by USDA-ARS in the 1980's (Williams et al., 1985). “The model includes several components, like soil erosion, economic, hydrologic, weather, nutrient, plant growth dynamics and crop management" (http://eco.wiz.uni-kassel.de/model_db/mdb/epic.html, 2004) and has been used for a wide range of applications, including erosion, pollution, sustainability, climate change and others (Edwards et al., 1994; Easterling et al., 1996; Brown and Rosenberg, 1997; Bernados et al., 2001; Mearns et al., 2001).

The model inputs are relatively simple. EPIC requires information about soil series (bulk density, field capacity, wilting point, texture), weather data and management (irrigation, fertilizer, liming, crop rotation, variety of tillage operations) in order to simulate yield for most of the important agronomic crops.

The simulation of hydrology is based on the Penman, the Penman-Montieth, the Hargreaves or the Priestly-Taylor model, respectively (http://www.soilerosion.net/sen/doc/report_6/EPICmod.htm, 2004). The nitrogen and carbon processes (Seligman and van Keulen, 1981) and the nitrogen mineralization (Williams, 1995) in EPIC are modifications of the PAPRAN model. The nitrogen uptake is calculated from the difference between current plant nitrogen content and the optimal nitrogen content (Williams, 1995). The plant growth is not a mechanistic model, because it uses a series of conversion or scaling factors to estimate biomass, leaf area index, plant height, root growth and yield (Ma and Schaffer, 2001).

Currently, there are a lot of management files that exist for EPIC and an effort is underway to catalogue these files and provide them to users. The model provides outputs on crop yields, economics of fertilizer use and crop values (http://eco.wiz.uni-kassel.de/model_db/mdb/epic.html, 2004).

6.2.5 STICS

The generic model Simulateur multidisciplinaire pour les Cultures Standard (STICS) was developed at the INRA (France) by Brisson et al. (1998) based on many components of other existing models. The model simulates crop growth as well as soil water and nitrogen balances driven by daily climatic data over one or several crop cycles (Brisson et al., 2003). However, STICS is not a fixed model, but rather an interactive modeling platform (Brisson et al., 2003). Thus, the model is organized in modules as shown in Figure 21, dealing with different specific mechanisms of crop growth.

One of the key elements of STICS is its adaptability to various crops (Brisson et al., 2003). STICS is able to simulate productivity of different cropping systems, including crops, such as wheat and corn (Hoogenboom, 2003).

The data required to run the model is related to climate (solar radiation, minimum and maximum temperatures, rainfall, evapotranspiration, and possibly wind and humidity), soil (water content, mineral nitrogen content and organic nitrogen content of different horizontal layers) and crop management. Crops are generally perceived in terms of their aboveground biomass and nitrogen content, leaf area index and the number and biomass of harvested organs (Brisson et al., 2003).

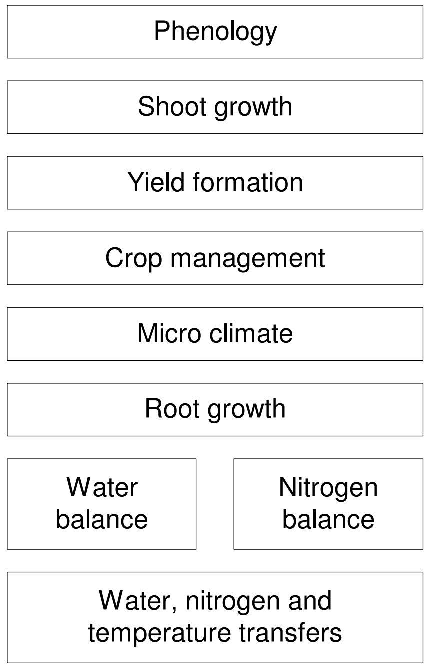

Figure 21. The various modules of the STICS model (modified from Brisson et al., 2003).

In the model crop growth is driven by the plant carbon accumulation described by de Wit et al. (1978), whereas the crop development is driven either by a thermal index (degree-days) or a photothermal index (Brisson et al., 2003). The crop nitrogen content depends on the carbon accumulation and the nitrogen availability in the soil (Brisson et al., 2003). Water stress and nitrogen stress reduce leaf growth and biomass accumulation, based on stress indices that are calculated in water and nitrogen balance modules (Brisson et al., 2003).

In the past, crop growth models were generally used to simulate plant growth and yield in the whole field (Irmak et al., 2001). Meanwhile crop growth models are increasingly used in PF research (Dobermann et al., 2004), but their complexity has often hampered the use of modeling in making practical decisions on input use (Angus et al., 1993). However, recent crop growth models are used to determine and understand spatial variability within a field. The additional information provided by the model is then used to simulate scenarios for PF (Paz et al., 1999; Booltink et al., 2001; Paz et al., 2003). In conclusion, many models for predicting how crops respond to climate, nutrients, water, light, and other conditions already exist, yet most of these do not include a spatial component appropriate to PF applications (Sadler and Russell, 1997). In a first attempt Batchelor et al. (2004) have developed the model Application of Precision Agriculture for Field Management

Optimization (APOLLO), which is designed to determine spatial yield variability and which assists researchers and producers in site specific management decisions.

6.2.6 APOLLO

The APOLLO model is still a prototype decision support system, which “was developed to assist researchers in using the CROPGRO-Soybean and CERES-Maize models to analyze precision farming datasets for soybean and corn” (Batchelor et al., 2004). The underlying algorithm is based on the CROPGRO-Soybean and CERES-Maize, respectively. Therefore the input files require the same minimum data set as the CROPGRO or CERES model.

“APOLLO has modules that allow the user to: 1) calibrate the models to simulate historic spatial yield variability, 2) validate the models for seasons not used for calibration, and 3) estimate the yield response and environmental impacts of nitrogen and plant population prescriptions. The calibration module allows users to use an optimizer to adjust up to 10 soil properties in zones defined in the field to minimize the root mean square error between simulated and observed yield. Once a field is calibrated, the validation module allows the user to test the performance of the calibration for seasons not used in the calibration. Finally, the user can run the crop growth models for numerous combinations of plant population and nitrogen rates to generate yield and nitrogen loss information that can be used to compute the economic and environmental effects of different prescriptions” (Batchelor et al., 2004).

6.3 Case Study

Sufficient and accurate information is needed for profitable crop management decision-making. Some fields require little information to determine the exact cause of within-field variability. Others require multiple sets of information and data before good decisions can be made. Crop growth models can be used to determine variability within a field and to develop the optimum management strategies. The amount of information needed to make profitable and environmental decisions is based on the variability of a certain field. Fields with little variation may not warrant the necessity of complex crop growth modeling techniques. Some of the easiest changes in management strategies to benefit crop production have been through simple visual interpretations of the field. For example, wet areas or improper planting depths can be dealt with fairly easily for the next management season. However, if a high spatial and temporal variability exists within a field, the underlying factors may be complex and several factors may interact, hampering the development of the right management decision. In the following section a case study is done, to describe different levels of complexity models can achieve. Depending on the variability of a given field, the level of accuracy of the results and thus the management prescriptions can differ widely.

A case study was carried out to explain the measured yield variability of the three fields in Weisweil (I1, I2, I3), by evaluating various models, which differs in their level of complexity. First the relationship between available phosphorous and yield were tested in a linear regression. Then the relationship between soil nutrients like nitrogen, phosphorous, potassium and magnesium and yield were simulated in a multiple regression. Next, the CERES-Maize model, which is part of the DSSAT and the APOLLO model – the extension of the DSSAT model to a site-specific scale – were used for this case study. For both crop growth models a short description was given in the previous section. All approaches were tested for their ability to simulate the measured yield on the experimental sites in Weisweil, by comparing measured with simulated yields.

The linear regression was used to determine the relationship between phosphorous in the soil and the grid level yield in the year 2000 (case study 1). For this case study, the area of the three sites was divided into grid cells, resulting in 30 grids over the three sites. Each grid contained a mean yield over the grid area. The mean yield within each grid was determined with the software ArcView (ESRI, USA). Afterwards a multiple linear regression was calculated to determine the relationship between nutrient content in the soil and grid level yield in the year 2000 (case study 2). The yields, which were used in the study, were the same as in case study 1. Next, the DSSAT model was used to simulate the yield of the three sites in Weisweil at the field level (case study 3). The DSSAT model belongs to the crop growth models and thus the underlying factors, which cause spatial yield variability, were considered. Beside nutrient availability, especially nitrogen and water availability were taken into account. The field level yield was calculated by averaging the yield over each field. In the forth approach the DSSAT model was used to simulate the yield of the three sites in Weisweil on a grid level (case study 4), whereas the yields were calculated as in case study 1 and 2. In a fifth approach the APOLLO model was used to simulate the yield on the three sites in Weisweil at the grid level (case study 5). In the crop growth model APOLLO, additional to the previous factors, also soil properties, like rooting depth or soil fertility were incorporated into the simulation of crop yield. The yields, which formed the basis for this calculation, were the same as in the previous study. Compared to case study 4, the simulation was performed on a site-specific scale.

6.3.1 Simple Linear Regression Model

The results of the linear regression in case study 1 are shown in Figure 22. The correlation between phosphorous in the soil and the grid level yields in the year 2000 was weak, indicating that the yield variability was not mainly caused by phosphorous availability in the soil. Based on the linear regression model only 7 % of the spatial yield variability in year 2000 could be explained by the phosphorus supply.

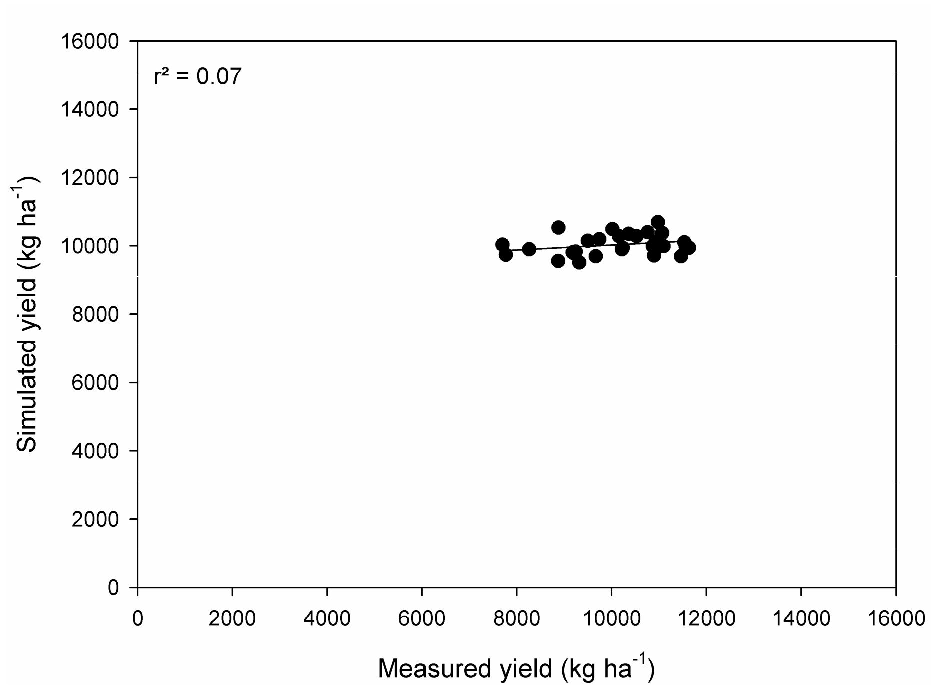

Figure 22. Measured versus simulated grid level yield (kg ha^{-1}) of the year 2000 in field I1, I2 and I3. The simulated yields were determined via linear regression based on phosphorous content (mg P_2O_5 100 g soil^{-1}) in the soil.

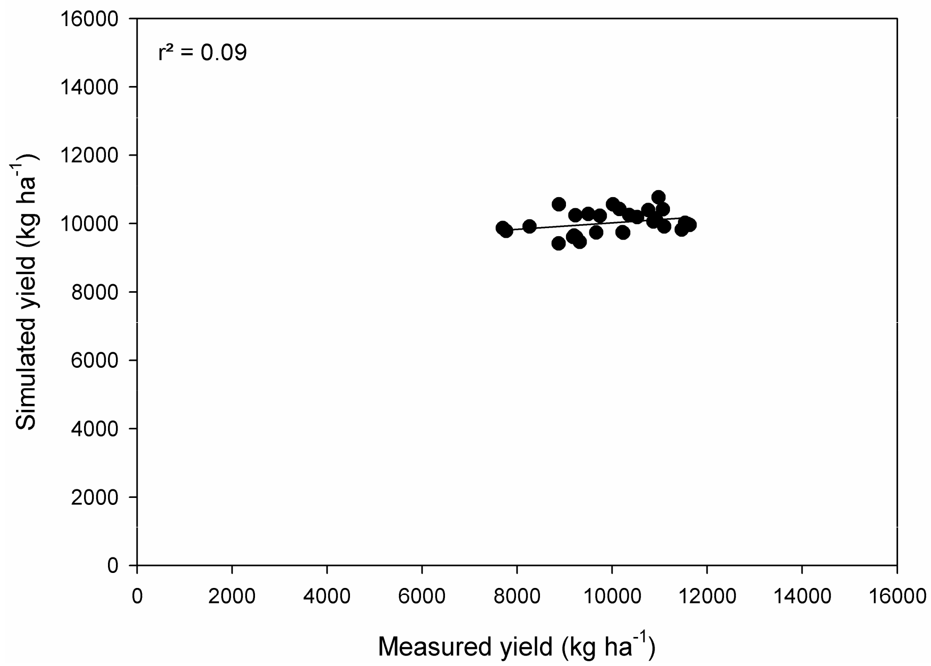

Figure 23. Measured versus simulated grid level yield (kg ha^{-1}) of the year 2000 in field I1, I2 and I3. The simulated yields were determined via multiple linear regression based on nitrogen content (N_t %), phosphorous content (mg P_2O_5 100 g soil^{-1}), potassium content (mg K_2O 100 g soil^{-1}) and magnesium content (mg MgO 100 g soil^{-1}) in the soil.

6.3.2 Multiple Linear Regression Model

The results of case study 2 are shown in Figure 23. The multiple correlation between nitrogen, phosphorous, potassium and magnesium content in the soil and grid level yield resulted in $r^2 = 0.09$. It is obvious, that the combination of multiple soil parameters increased the significance of the model only slightly. Thus, the combination of the soil nutrients could explain up to 9 % of the spatial yield variability within the field in the year 2000. However, most of the yield variability remained unexplained, when multiple regression was implemented for the analysis.

6.3.3 Crop Growth Model DSSAT

For case study 3 the yield data were entered into the DSSAT model, combined with the available information about soil, weather and management data. The simulation of yield was done in consideration of the environmental conditions.

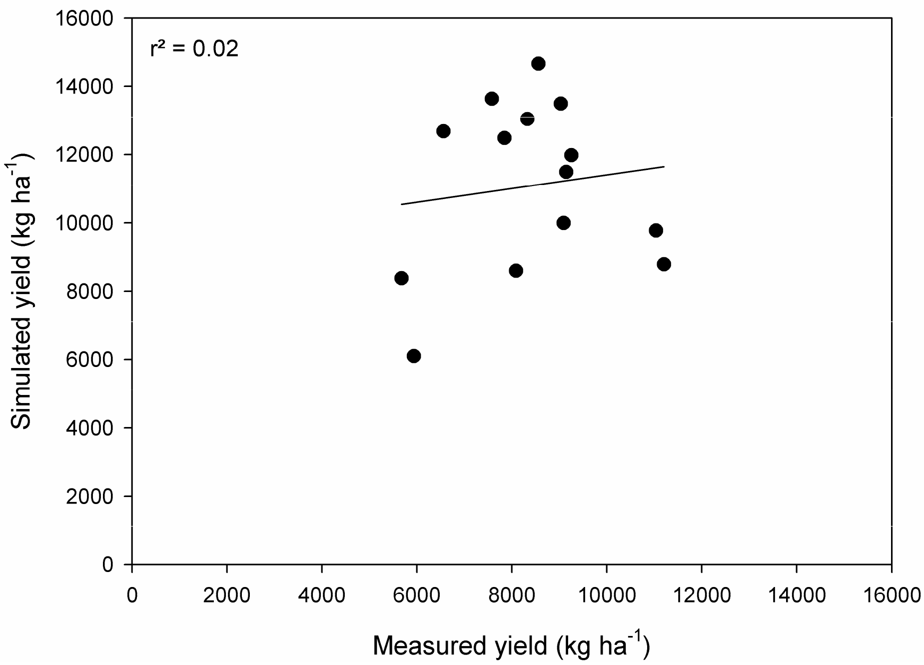

Figure 24. Measured versus simulated field level yield (kg ha^{-1}) of the years 1998-2002 in field I1, I2 and I3. The simulated yields were determined with the DSSAT 4.0 model taking water stress and nitrogen stress into consideration.

The results of case study 3 are shown in Figure 24. The simulation of the field level yield resulted in a weak correlation ($r^2 = 0.02$) between the simulated and the measured yields. In the DSSAT model the yield calculations were performed in consideration of water and nitrogen stress especially. It was shown, that the DSSAT model overestimated the yield in most cases. In the high yielding year of 2000 the DSSAT model underestimated the field level yields. The underestimation of yields was due to nitrogen stress in the model. The results indicated that the DSSAT model was not able to simulate the mean field level yields over the 5-year period accurately.

The results of case study 4 are shown in Figure 25. The DSSAT model simulated the grid level yields in all three fields with an accuracy of 0.05 % ($r^2 = 0.05$). The slight improvement of the results was caused by the site-specific consideration of the data, including more detailed information about the site and spatial referenced yield data. However, as in the previous case study the model overestimated the yield for most of the grids. But in year 1998, when the fields were managed due to the regulations in a water protection area, the model underestimated the yields. This resulted in the underestimation of grid level yields, which was mainly caused by severe nitrogen stress in the nitrogen subroutine of the model during the growing season in all three fields. The fact that the DSSAT model overestimated the grid level yields in other years might be due to the disregard of diseases and other nutrient deficiencies.

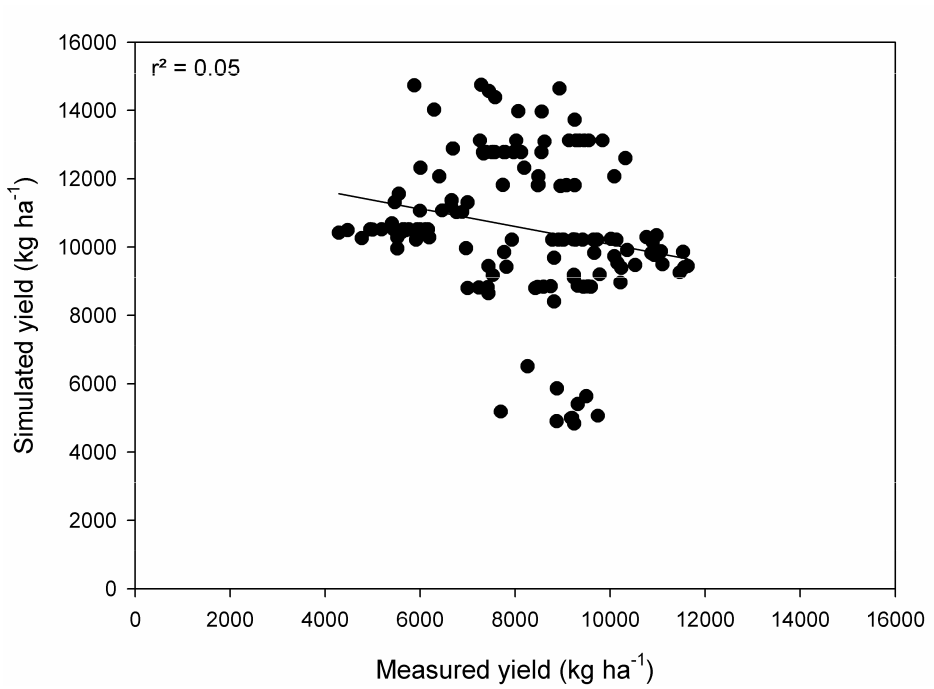

Figure 25. Measured versus simulated grid level yield (kg ha^{-1}) of the years 1998-2002 in field I1, I2 and I3. The simulated yields were determined with the DSSAT 4.0 model taking water stress and nitrogen stress into consideration.

Again, the simulation of yield in the DSSAT model was based on the influence of water and nitrogen flows in the systems. The results of case study 3 and 4 implied that this factor might not be the most important factor for spatial yield variability in the three fields in Weisweil.

6.3.4 Crop Growth Model APOLLO

The results of the yield simulation using the APOLLO model (case study 5) are shown in Figure 26. The agreements between simulated and measured yields were good and reached a value of $r^2 = 0.60$. The assumption of varying rooting depth and varying soil available water within the field formed the basis of this simulation and explained about 60 % of the measured spatial yield variability within the three fields. The results indicated that not only water and nitrogen stress were responsible for the spatial yield variability, but also varying rooting depth and varying soil available water seemed to influence the yield pattern within the fields.

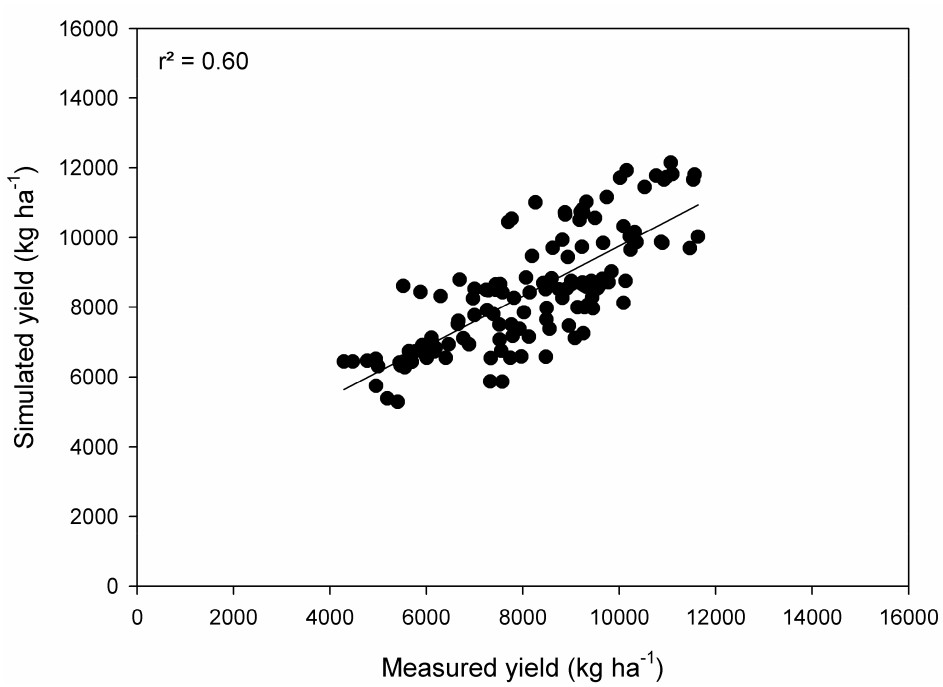

Figure 26. Measured versus simulated grid level yield (kg ha^{-1}) of the years 1998-2002 in field I1, I2 and I3. The simulated yields were determined with the APOLLO model, taking the effects of a restrictive layer and rooting depth into consideration.

The agreement between simulated and measured yield were increased, when in addition to varying rooting depth and varying soil available water, a varying restrictive layer was taken into consideration. The restrictive layer described as a factor that is mainly induced by management practices, especially the effect of soil compaction after tillage (Lindstrom and Voorhees, 1994; Lipiec and Simonta, 1994). Due to continuous cultivation of corn, like in this study, it is highly possible that a restrictive layer exists in the field. As a result of a restrictive layer, root distribution could be affected and led to spatial yield variability (Arvidsson and Håkansson, 1996). The results of case study 5, including a restrictive, layer rooting depth and soil available water for the simulation scenario are shown in Figure 27.

The combination of these yield-limiting factors explained up to 75 % of the measured spatial yield variability within the three fields.

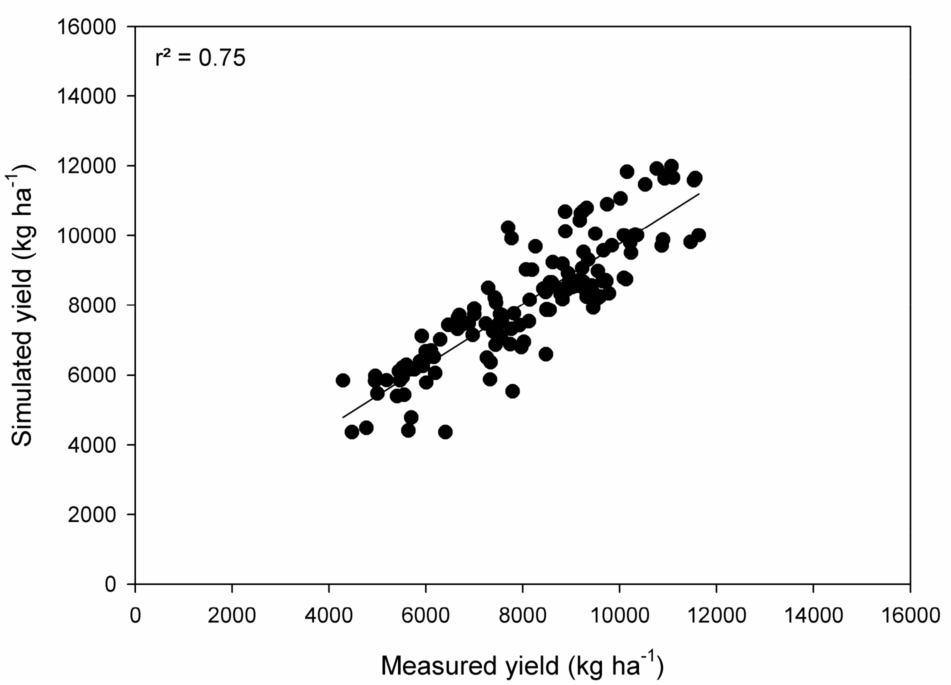

Figure 27. Measured versus simulated grid level yield (kg ha^{-1}) over the years 1998-2002 in field I1, I2 and I3. The simulated yields were determined with the APOLLO model, taking the effects of a restrictive layer, rooting depth and soil available water into consideration.

Overall, the results indicated that the accuracy of the model results increased when the spatial resolution was regarded in the calculations and when yield-limiting factors, like a restrictive soil layer, the rooting depth or soil available water were taken into consideration for the simulation of corn yields. In the linear and multiple regression models less information was included for the simulation, compared to the crop growth models DSSAT and APOLLO. Nevertheless, the results were as uncertain as for the DSSAT model. However, the accuracy of the model was improved as soon as different soil parameters were used for the model calibration and the spatial yield variability was taken into account.

In conclusion, crop growth models have the potential to provide considerable amounts of useful information for decision-making in PF. A suite of tools could be used in the future to assess and manage agronomic factors important to crop production. For these new tools to function properly, however, they will need to be user-friendly for producers and consultants. Information technologies will produce enormous data sets on crops and their interactions with their environment. The challenge remains how to convert these data into useful suggestions to aid in the decision-making process for the producer. Crop growth models might be one step into this direction.

7 Procedure to Evaluate Spatial Corn (*Zea mays* L.) Yields in the Upper Rhine Valley (Germany) Using a Crop Growth Model[2]

7.1 Abstract

Spatial yield variability is a result of complex interactions of many factors, including soil properties, weather, pests, fertility and management. Past efforts to correlate yield on a site-specific scale to soil type, fertility, and other biotic and abiotic factors to characterize yield variability have had limited success. Crop models have proven to be useful tools to evaluate these complex interactions and to provide insight into causes of yield variability. The goal of this study was to use the APOLLO model to determine possible factors causing spatial yield variability in small fields in the Upper Rhine Valley (Weisweil, Germany), and to develop and test different calibration strategies to characterize spatial yield variability.

The model was calibrated to five years of spatial corn yield data in three farmer fields (I1, I2, I3), where corn was grown continuously. Each field was divided into a specified number of grids. Mean measured yield was computed from yield monitor data in each grid. Two calibration strategies were applied to the data set: (i) soil parameters were calibrated one at a time to determine which parameter appeared to have the greatest power to explain spatial yield variability, and (ii) combinations of soil parameters identified in (i) were calibrated to determine if combinations of soil parameters improved the simulation of spatial yield variability. Additionally, an in-season correction considering soil available nitrogen was imposed in the model to determine if this additional information improved the accuracy of the model (case D). All calibration strategies were carried out at different spatial scales to evaluate the effect of grid size (case A, B and C) on the ability of the model to explain spatial yield variability.

The adjustment of single soil parameters provided a good fit between simulated and measured yield. However, the correlation coefficients between simulated and measured yield increased and the root mean square error decreased for most of the calibration strategies when multiple soil parameters were used in the calibration process. Furthermore, the results of the model calibration were affected by the grid size used for calibration. The model gave more accurate simulated yields for larger grids, suggesting that the applied calibration process may be more effective under large grid sizes. A slight improvement of the model accuracy was found when additional information about soil available nitrogen around the 4th leaf stage was imposed on the calibration process.

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Co-authors for this paper were S. Graeff [a], W. D. Batchelor [b], J. O. Paz [b], K. R. Thorp [b] and W. Claupein [a]
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Overall the APOLLO model performed well in simulating spatial yields and explaining the causes of spatial yield variability over the 5-year period on the three fields in the Upper Rhine Valley. Therefore, the APOLLO model appears to be a useful tool for the investigation of spatial yield variability on small fields in Germany.

7.2 Introduction

Spatial yield variability is a result of complex interactions among different yield-limiting factors, such as soil properties, nutrient and water availability, rooting depth, pests and management. In order to manage spatial yield variability within a field, yield-limiting factors must be identified and understood. Initial efforts to study yield variability have focused on taking static measurements of soil, management, or plant properties and regressing these values against grid level yields (Cambardella et al., 1996; Sudduth et al., 1996). Classical statistics based on ordinary least squares have frequently been used to explore functional relationships between crop productivity and controlling factors (Long, 1998). Tomer and Anderson (1995) used linear regression to predict spatial patterns in yield based on soil fertility. However, it is difficult to represent the temporal effects of time dependent interactive stresses (i.e. water stress) on crop growth and yield using classical statistical techniques.

Process-based crop growth models are a promising tool to help identify relationships between yield-limiting factors, management and environment. Crop growth models such as the DSSAT or the APOLLO model can be used to identify spatial yield-limiting factors (Jones et al., 2003; Batchelor et al., 2004b). Both models are based on the CROPGRO (Boote et al., 1998) and CERES (Ritchie et al., 1998) family of process-oriented crop growth models. Based on information about management (i.e. cultivar, planting, fertilization, plant protection, harvest) and environmental conditions (soil, weather), the models compute the daily rate of plant growth, resulting in an estimation of final yield and plant biomass. Therefore the models simulate the daily interaction of plant growth, water, nitrogen, and pest stress on plant growth processes.

Characterization of yield variability requires the analysis of both spatial and temporal behavior of soil, weather, management and environmental factors. Thus, extending the use of crop growth models to examine within-field spatial yield variability is an intriguing challenge. Many studies have shown that the DSSAT models can accurately simulate corn and soybean spatial yield variability, taking into account yield-limiting factors such as water stress in soybeans (Paz et al., 1998a), soybean cyst nematodes (Paz et al., 2001), water stress in corn (Fraisse et al., 1998) and interaction of corn population and water stress (Paz et al., 1999). In few current studies, the APOLLO model was used to analyze causes of spatial yield variability in soybean (Batchelor et al., 2004b).

The APOLLO model is a precision agriculture decision support system designed to use the CROPGRO-Soybean and CERES-Maize models to analyse causes of yield variability and to estimate the economic and environmental consequences of prescriptions (Batchelor et al., 2004a). Techniques in APOLLO have never been tested outside of the United States. To date, the APOLLO model has only been used in large fields with grid sizes of about 0.15 ha.

The overall goal of this work was to use the APOLLO model to study the spatial yield variability of three fields in the upper Rhine Valley (Germany) and to determine if crop growth model calibration techniques developed in the United States could be transferred to small fields in Germany. The specific objectives of this study were (i) to develop and test different calibration strategies to minimize the error between simulated and measured spatial corn yield, (ii) to evaluate the impact of grid size on the error in simulated spatial yield variability, and (iii) to interpret the results of the model calibration.

7.3 Materials and Methods

7.3.1 Site, Treatments and Yield Monitoring

The study was conducted as an on-farm study over five growing season on three fields (I1, I2, I3) in the Upper Rhine Valley near Weisweil (48° 19' N, 7° 67' E), northwest of Freiburg, Germany. The mean annual precipitation in this area is 910 mm, the mean temperature is about 9.5° C and the sum of the yearly solar radiation averages about 11390 kJ m^{-2}. The major soil type is a silty loam.

The aggregated size of the three fields was approximately 5.5 ha in total. Corn was grown each year from April-October during the years 1998-2002 in all three fields, with the exception of field I1, where wheat was grown in 1999. The corn cultivars varied for each field and year (Table 15).

Table 15. Corn cultivars planted on field I1, I2 and I3 during the 5-year period (1998-2002).

Field		1998	1999	2000	2001	2002
I1	**Cultivar**	Helix	Soissons*	Marista	Benicia	Marista
	Maturity	K220		K400	K250	K400
		PC0002		PC0005	PC004	PC0005
I2	**Cultivar**	Marista	Helix	Marista	Peso	Marista
	Maturity	K400	K220	K400	K290	K400
		PC0005	PC0002	PC0005	PC006	PC0005
I3	**Cultivar**	Helix	Helix	Benicia	Benicia	DK514
	Maturity	K220	K220	K250	K250	K400
		PC0002	PC0002	PC004	PC004	PC004

* In year 1999 on field I1 wheat was grown.
K indicates the maturity classification based on BSA (1998).
The identification PC0002 (short season cultivar) – PC0006 (long season cultivar) refers to the genetic properties of the cultivar in the DSSAT v3.5 model.

Each field was managed uniformly using the producer's current management practices. At sowing, a starter fertilizer of Ø 31 kg N ha^{-1} was applied uniformly as KAS (13 % NH_4-N, 13 % NO_3-N) to all fields in all five years. In the years 2001 and 2002 around the 4th leaf stage, soil samples at a depth of 0-30, 30-60 and 60-90 cm were taken at 30 data collection points, which were set up at a distance of 40 x 40 m, and analyzed for soil available nitrogen. Table 16 shows the mean values of soil available nitrogen (kg N ha^{-1}) in the upper 90 cm of the soil layer around the 4th leaf stage. Around the 4th leaf stage Urea (46 % N) was applied uniformly to each field based on the results of soil available nitrogen. Rates varied for each field and year, and ranged from 44-120 kg N ha^{-1}, to give an average of 250 kg N ha^{-1} in each field. In 2001 swine manure was applied in field I2, which provided an additional 40 kg N ha^{-1} in this field. No other field received swine manure.

Herbicides and pesticides were applied as needed to control pests. After harvest in September or October, the corn residue was left on the surface of each field.

Table 16. Mean and range of cumulative soil available nitrogen (kg N ha^{-1}) in the upper soil layer (0-90 cm) around 4th leaf stage; average for all data collection points (DCP) in field I1, I2 and I3.

Field	Soil available nitrogen (kg N ha^{-1})		
	2000	2001	2002
I1	106	59	118
		24-139	92-185
I2	45	98	176
		25-359	119-230
I3	53	49	87
		18-63	73-107

Geo-referenced corn grain yield data were collected over the 5-year period using a differentially corrected global positioning system and a yield monitor mounted on a combine harvester (Claas, Lexion). Corn grain yield and corn grain moisture content were measured every five seconds (10-m distance), resulting in about 200 yield monitor data points per hectare. Yield monitor points with missing values for yield or grain moisture content, or yield values greater than 15000 kg ha^{-1} were excluded from the yield monitoring dataset. In this paper, yield was calculated as corn grain yield at 0 % moisture content.

Yield monitor data were studied in four different scenarios (case A – D). Therefore a grid network was established using grid sizes defined for case A (grids of 15.0 x 11.0 m), case B (grids of 22.5 x 16.5 m) and case C (grids of 22.5 or 15.0 x 27.5 m). In case C two grid sizes were used to better match the field boundaries. The smaller grids (15.0 x 27.5 m) were placed in the turning rows, and the larger grids (22.5 x 27.5 m) were placed in the middle of the field. The arrangement of the grids in cases A, B, and C is shown in detail by Link et al. (2004a). The grids were overlaid onto yield maps and the average yield for each grid was computed using software that was developed and described by Thorp et al. (2004). Each grid contained at least three yield monitor points. Case D used the same grid configuration as in case C, but measured soil available nitrogen in the upper soil layers (0-30, 30-60 and 60-90 cm) around the 4th leaf stage in the years 2001 and 2002 (Table 2) was used to adjust model state variables on the measurement date during the simulation.

7.3.2 APOLLO

7.3.2.1 Description of APOLLO

APOLLO (Application of Precision Agriculture for Field Management Optimization) is a precision farming decision support system, which is based on the CERES (Ritchie et al., 1998) and CROPGRO (Boote et al., 1998) family of crop growth models. APOLLO was developed to assist users in evaluating causes of spatial yield variability and to develop optimum prescriptions (Batchelor et al., 2004a). It has modules to assist the user in 1) calibrating spatial soil inputs to minimize error between simulated and measured yield, 2) validating the calibrated model for independent seasons, and 3) developing prescriptions.

7.3.2.2 Model Input Files

Management, soil, weather and cultivar information are required as input files to run the model. The management file (*.mzx) contains model inputs including weather file name, soil composition, initial soil water, nitrate, and ammonia, planting date, row spacing, and residue amount. The soil profile characteristics for each grid are stored in the soil input file (*.sol). This file contains information such as bulk density, saturated hydraulic conductivity, upper and lower drained limit and root growth factors. Daily weather data, including daily maximum and minimum temperature, rainfall and solar radiation were stored in the weather file (*.wth). All weather data were obtained at the nearest German Weather Service station located at Emmendingen-Mundingen and Freiburg, which are about 16 and 25 km from the trial site, respectively. The cultivar file (*.cul) contains information about the rate of development and the required growing degree days (GDDs) for each genotype. Yield data for each grid in the field were stored in a separate yield file (*.mza).

7.3.2.3 Model Calibration

Soil properties entered into the crop growth model are often mean values. However, when trying to simulate spatial yield variability at small spatial scales, it is necessary to adjust soil properties over their expected range in order to more accurately reflect spatial soil properties within the field. APOLLO allows the user to adjust up to ten soil parameters (Table 17) for each grid. The user can test if one or a combination of these soil parameters may help explain the spatial yield variability. When a user selects the parameters to adjust, APOLLO uses the simulated annealing optimization algorithm to estimate the parameter values that minimize the root mean square error (RMSE) between simulated and measured yield over selected years in each grid selected by the user. The RMSE indicates the degree of variation in simulated yields with respect to the measured yield and low RMSE values are desirable. Calibration of each grid results in a unique set of soil properties for each grid.

Table 17: Soil parameters available for the calibration in the APOLLO model.

	Parameters		Unit	Minimum	Maximum	Initial
1	**CN**	SCS Curve Number		40	90	70
2	**DR**	Drainage Rate	fraction day^{-1}	0.1	0.5	0.4
3	**ETDR**	Effective Tile Drainage Rate	1 day^{-1}	0.01	0.25	0.05
4	**SHC**	Saturated Hydraulic Conductivity of Deep Impermeable Layer	cm day^{-1}	0.001	2	0.01
5	**HPF**	Hardpan Factor/Restrictive Layer	0.0 - 1.0	0.01	1.0	0.5
6	**DHP**	Depth to the Hardpan	cm	5	150	30
7	**RDRF**	Root Distribution Reduction Factor		-0.1	-0.001	-0.05
8	**NMF**	Nitrogen Mineralization Factor	0.0 - 1.0	0.1	1.0	0.8
9	**SFF**	Soil Fertility Factor	0.0 - 1.0	0.7	1.0	0.99
10	**ASW**	Available Soil Water	%	-20	20	0

In this study APOLLO was used to calibrate soil inputs, and several genetic coefficients were adjusted to set the maximum yield of different cultivars. APOLLO was used to compute soil inputs to minimize error between simulated and measured yield for each grid size scenario (case A, B and C) and for the scenario, where measured soil available nitrogen (kg N ha^{-1}) at 4th leaf stage was used to adjust simulated soil available nitrogen in the model database (case D).

Two calibration strategies were applied to the data set:

- Soil parameters were calibrated one at a time to determine which parameter appeared to have the greatest power to explain spatial yield variability.
- Combinations of soil parameters identified in (i) were calibrated to determine if combinations of soil parameters improved the simulation of spatial yield variability.

These calibration strategies were applied to different scenarios, and the effects of grid resolution on model accuracy were examined. The accuracy of the model was evaluated by the correlation coefficient R between simulated and measured yields and RMSE.

7.4 Results

In general the two calibration strategies described above were applied to different scenarios (case A, B, C and D) and the relevance of grid size for the accuracy of the model predictions was investigated.

7.4.1 Calibration Using Single Soil Parameters

In the first step of the model calibration, single soil parameters were adjusted to minimize RMSE between simulated and measured yield over five years of corn growing seasons in three fields in the Upper Rhine Valley, Germany. The results of model calibration showed that the adjustment of some soil parameters resulted in a good fit between simulated and measured yield. The calibration of the five soil properties (HPF + DHP, RDRF, NMF, SFF and ASW) reduced RMSE between simulated and measured yield compared to the default values, and thus, partially explained spatial yield variability (Table 18). However, the adjustment of soil parameters SCS CN, DR, ETDR + SHC (described in Table 17) did not significantly reduce error between simulated and measured yield and thus, did not explain spatial yield variability (data not shown). Thus, not all soil parameters available for calibration by APOLLO contributed to explain spatial yield variability. Table 18 shows the correlation coefficient R and RMSE for simulated and measured yields after model calibration using single soil parameters HPF + DHP, RDRF, NMF, SFF and ASW for the four scenarios (cases A – D).

7.4.1.1 Case A (15.0 x 11.0 m Grid Size)

The parameters that generally explained most of the yield variability in all three fields were HPF + DHP, RDRF, NMF, SFF and ASW. These single parameters were not able to explain much of the spatial yield variability by themselves, and thus, low R values were found between simulated and measured yields at this spatial scale (grid size 15.0 x 11.0 m). Additionally, the model did not reproduce the measured yields in case A very well, based on R and RMSE values (Table 18).

The agreement between simulated and measured yields was the lowest for field I3. The correlation coefficient between simulated and measured yield varied between R = –0.22 (ASW) and R = 0.27 (HPF + DHP). In field I2, the agreement between simulated and measured yields varied between R = 0.05 for NMF and R = 0.55 for HPF + DHP. However, in field I1 the correlation coefficient between simulated and measured yield ranged between R = 0.40 (RDRF) and R = 0.47 (HPF + DHP). In field I1 the RMSE varied between 1441 and 1852 kg ha^{-1} that was about 19.3 % and 24.7 % of the mean yield. In field I2 the RMSE varied between 1109 and 1514 kg ha^{-1} that was about 13.8 % and

18.8 % of the mean yield. In field I3 the RMSE varied between 459 and 1073 kg ha^{-1}. This was about 5.6 % and 13.1 % of the mean yield.

In all three fields the soil parameter HPF + DHP explained more spatial yield variability than other parameters. These results indicated a possible yield-limiting effect caused by a restrictive layer in a soil depth of 11-103 cm (I1), 28-88 cm (I2) and 37-56 cm (I3), respectively.

7.4.1.2 Case B (22.5 x 16.5 m Grid Size)

Using this larger grid size increased the agreement between simulated and measured yields compared to the smaller grid size used in case A (Table 18). For almost all model calibrations, the agreement between simulated and measured yield was twice as good as in the model calibration for case A.

An increase in accuracy of the model was especially noticeable for field I1. Depending on the soil parameter used for calibration, the model explained between 56 % and 81 % of the spatial yield variability. The best agreement between simulated and measured yield was obtained by using the SFF parameter for model calibration (R = 0.90). Calibration using parameters HPF + DHP, SFF and ASW, respectively, resulted in RMSE values lower than 1000 kg ha^{-1}, which corresponded to approximately 12 % of the mean yield in field I1.

In field I2, the model calibration for case B produced varying results depending upon the parameters that were calibrated. Some parameters such as NMF did not explain much of the spatial yield variability within the field. However, other parameters such as HPF + DHP, explained about 59 % of the spatial yield variability (R = 0.77). For all calibrations, the RMSE ranged between 1062 and 1476 kg ha^{-1}, which was 12.9 % and 17.9 % of the mean yield in field I2, respectively.

A different result was found for field I3, where the calibration of single soil parameters gave mixed results. Calibration of parameters NMF, SSF and ASW resulted in low correlations between simulated and measured yields. However, calibration of HPF + DHP and RDRF gave correlation coefficients of R = 0.70 and R = 0.54, respectively.

HPF + DHP was the soil parameter that explained most of the spatial yield variability (56 % and 49 %, respectively) in field I2 and I3, whereas in field I1, the parameter SFF explained most of the spatial yield variability (81 %) for grid yields in case B (Table 18).

7.4.1.3 Case C (15.0/22.5 x 27.5 m Grid Size)

As in the previous model calibration, a good agreement between simulated and measured yields was found for most of the soil parameters that were used for calibration (Table 18). The correlation coefficient for simulated and measured yields in field I1 ranged between R = 0.76 for the parameter RDRF and R = 0.92 for the parameter SFF. The RMSE ranged between 8.0 % and 15.9 % of the mean yield of field I1.

Table 18. Correlation coefficient (R) and root mean square error (RMSE) for simulated and measured yield after model calibration (2000 iterations) of field I1, I2 and I3 using multiple years of corn yield data and single soil parameters (5-10).

		Parameters									
		HPF + DHP		RDRF		NMF		SFF		ASW	
	Scale	R	RMSE ($kg\ ha^{-1}$)	R	RMSE ($kg\ ha^{-1}$)	R	RMSE ($kg\ ha^{-1}$)	R	RMSE ($kg\ ha^{-1}$)	R	RMSE ($kg\ ha^{-1}$)
Field I1	**Case A**	0.47	1441	0.40	1852	0.42	1821	0.46	1483	0.43	1484
	Case B	**0.83**	848	**0.75**	1328	**0.81**	1183	**0.90**	742	**0.81**	949
	Case C	**0.88**	738	**0.76**	1304	**0.81**	1189	**0.92**	656	**0.82**	919
	Case D	**0.96**	514	**0.96**	539	**0.96**	531	**0.95**	569	**0.96**	541
Field I2	**Case A**	**0.55**	1308	0.30	1312	0.05	1514	0.21	1109	0.09	1275
	Case B	**0.77**	1062	**0.52**	1177	0.14	1476	0.36	1062	0.21	1251
	Case C	**0.80**	1020	**0.50**	1182	0.08	1516	0.34	1055	0.18	1258
	Case D	**0.74**	993	**0.54**	930	-0.04	1009	0.33	1005	0.17	923
Field I3	**Case A**	0.27	1058	0.18	963	-0.14	459	-0.05	1073	-0.22	781
	Case B	**0.70**	884	**0.54**	823	-0.02	434	0.18	1070	-0.06	802
	Case C	**0.81**	372	0.43	892	-0.33	421	-0.03	1056	-0.31	764
	Case D	**0.83**	922	**0.66**	1198	**0.51**	841	0.31	1115	0.25	1033

R >0.50 is written in bold letters. Yield was calculated in dependency of the grids in case A (15.0 x11.0 m grid size), case B (22.5 x 16.5 m grid size), case C (15.0/22.5 x 27.5 m grid size) and case D (15.0/22.5 x 27.5 m grid size).

In field I2 the agreement between simulated and measured yields varied between R = 0.08 for NMF and R = 0.80 for parameters HPF + DHP. In field I2 the RMSE was in the range of 12.7 % to 18.8 % of the mean yield. For field I3, correlation coefficients up to R = 0.81 (HPF + DHP) were obtained using single soil parameters for the model calibration. For field I3 the RMSE was generally very low and ranged between 5.2 % and 12.9 % of the mean yield. The parameters HPF + DHP and RDRF explained most of the spatial yield variability in field I2 (64 % and 25 %, respectively) and I3 (66 % and 18 %, respectively). However, SSF and HPF + DHP explained 85 % and 77 % of the spatial yield variability within field I1.

7.4.1.4 Case D (15.0/22.5 x 27.5 m Grid Size)

Including measured soil available nitrogen values at the 4th leaf stage as a real time adjustment to the model improved the model accuracy in field I1. The correlation coefficient R between simulated and measured yields was increased by about 0.1, for all parameters, except for the SFF in field I1 and I2. The RMSE decreased for all parameter calibrations and was < 600 kg ha^{-1} for all soil parameters used for calibration (Table 18).

However, for field I2 the agreement between simulated and measured yields decreased slightly compared to case C. Similar to case C, the correlation coefficient R was really low for NMF (and ASW), which indicated that these parameters did not have a major impact on simulated spatial yield variability for field I2. However, good results were found for parameters HPF + DHP (R = 0.74) and RDRF (R = 0.54), indicating that these parameters had some power in explaining spatial yield variability. The RMSE of calibration results was approximately 1000 kg ha^{-1}, which was about 12.4 % of mean yield for field I2 (Table 18).

In contrast to the results of field I1 and I2, the addition of the real time adjustment for soil nitrogen led to increase in R for field I3. There was a good agreement between simulated and measured yields, with correlation coefficients ranging from R = 0.25 to R = 0.83. Again, the parameters leading to the most accurate simulated yield were RDRF and HPF + DHP. Thus, adjusting these parameters allowed the model to explain 44 % to 69 % of the spatial yield variability. The RMSE ranged between 841 and 1198 kg ha^{-1}, which was equivalent to approximately 10.3 % and 14.7 % of the mean yield in field I3.

7.4.2 Calibration Using Multiple Soil Parameters

The second calibration strategy was to calibrate combinations of parameters found in the previous calibration strategy that appeared to partially explain spatial yield variability. Based on the previous results of calibrating single soil parameters, the parameters HPF + DHP, RDRF, NMF, SFF and ASW were selected for further model calibration and applied

Table 19. Correlation coefficient (R) and root mean square error (RMSE) for simulated and measured yield after model calibration (2000 iterations) of field I1, I2 and I3 using multiple years of corn yield data and multiple soil parameters (5-10).

		Parameters											
		HPF + DHP + ASW		HPF + DHP + RDRF + SFF		HPF + DHP + RDRF + NMF + SFF		HPF + DHP + RDRF + SFF + ASW		HPF + DHP + NMF + SFF + ASW		HPF + DHP + RDRF + NMF + SFF + ASW	
	Scale	R	RMSE (kg ha^{-1})	R	RMSE (kg ha^{-1})	R	RMSE (kg ha^{-1})	R	RMSE (kg ha^{-1})	R	RMSE (kg ha^{-1})	R	RMSE (kg ha^{-1})
Field I1	**Case A**	0.49	1318	0.52	1368	0.59	1219	0.52	1330	0.58	1261	0.62	1215
	Case B	**0.86**	728	**0.92**	569	**0.94**	484	**0.93**	547	**0.94**	480	**0.95**	463
	Case C	**0.88**	622	**0.95**	438	**0.96**	407	**0.95**	440	**0.96**	408	**0.96**	430
	Case D	**0.97**	479	**0.97**	471	**0.97**	427	**0.97**	445	**0.97**	439	**0.97**	432
Field I2	**Case A**	0.66	1154	0.62	1218	0.60	1254	0.64	1142	0.65	1181	0.66	1191
	Case B	**0.80**	958	**0.77**	969	**0.84**	958	**0.84**	966	**0.86**	814	**0.86**	875
	Case C	**0.81**	938	**0.83**	953	**0.83**	943	**0.87**	763	**0.87**	752	**0.88**	719
	Case D	**0.80**	949	**0.82**	781	**0.82**	854	**0.84**	819	**0.85**	735	**0.86**	756
Field I3	**Case A**	0.29	1035	0.30	989	0.32	978	0.34	951	0.32	997	0.35	957
	Case B	**0.82**	672	0.72	787	**0.80**	704	**0.82**	674	**0.82**	669	**0.75**	718
	Case C	**0.82**	667	**0.82**	672	**0.83**	667	**0.85**	590	**0.83**	614	**0.82**	657
	Case D	**0.86**	859	**0.85**	878	**0.86**	757	**0.86**	809	**0.88**	676	**0.88**	696

R >0.75 is written in bold letters. Yield was calculated in dependency of the grids in case A (15.0 x 11.0 m grid size), case B (22.5 x 16.5 m grid size), case C (15.0/22.5 x 27.5 m grid size) and case D (15.0/22.5 x 27.5 m grid size).

to the different scenarios (case A – D). Table 19 shows the correlation coefficient R and RMSE for simulated and measured yield after model calibration of field I1, I2 and I3 using multiple soil parameters.

7.4.2.1 Case A (15.0 x 11.0 m Grid Size)

In case A the accuracy of the model was increased for all three fields, when multiple soil parameters were used for model calibration (Table 19). In field I1 the correlation coefficient between simulated and measured yields ranged between R = 0.49 and R = 0.62 for combinations of soil parameters HPF + DHP + ASW and HPF + DHP + RDRF + NMF + SFF + ASW, respectively.

In field I1 similar results were achieved for single soil parameter and multiple soil parameter model calibrations in case A. As in field I1, the lowest agreement between simulated and measured yields was found for HPF + DHP + ASW (R = 0.29). In field I3, the highest agreement was found using the parameters HPF + DHP + RDRF + NMF + SFF + ASW (R = 0.35). Thus, the correlation between simulated and measured yield for field I3 was very low with values clearly below R = 0.50. In field I2 the correlation coefficient ranged between R = 0.60 and R = 0.66 for a combination of soil parameters HPF + DHP + RDRF + NMF + SFF + ASW and HPF + DHP + ASW, respectively. The RMSE ranged between 1215 and 1368 kg ha^{-1} in field I1, between 1181 and 1254 kg ha^{-1} for field I2, and between 951 and 1035 kg ha^{-1} in field I3, respectively. These RMSE values were approximately 15 % of the mean yield in each field.

7.4.2.2 Case B (22.5 x 16.5 m Grid Size)

In field I1 and I2, the combination of soil parameters that gave the best fit between simulated and measured yields was HPF + DHP + RDRF + NMF + SFF + ASW. The correlation coefficient for this parameter combination was R = 0.95 and R = 0.86 in fields I1 and I2, respectively (Table 19). In field I1 the RMSE was 463 kg ha^{-1}, which was about 5.6 % of the mean yield, while in field I2 the RMSE was about twice as high (874 kg ha^{-1}), which was about 10.6 % of the mean yield. The highest correlation coefficient in field I3 was found by calibrating the soil parameter combination of HPF + DHP + NMF + SFF+ ASW, which gave R = 0.82, and a RMSE of 669 kg ha^{-1} (8.1 % of the mean yield). The lowest correlation between simulated and measured yields were found when the soil parameters combination HPF + DHP + ASW were calibrated in field I1 (R = 0.86) and HPF + DHP + RDRF + SFF in field I2 (R = 0.77) and I3 (R = 0.72). At the same time the RMSE reached values of 728 kg ha^{-1} in field I1 (8.9 % of the mean yield), 969 kg ha^{-1} in field I2 (11.7 % of the mean yield) and 787 kg ha^{-1} in field I3 (9.5 % of the mean yield).

7.4.2.3 Case C (15.0/22.5 x 27.5 m Grid Size)

By increasing the grid size in case C, a good agreement was found between simulated and measured yield for all combinations of soil parameters. Many parameter combinations gave good results; however, the best correlation between simulated and measured yields in field I1 resulted by calibrating the parameters HPF + DHP + RDRF + SFF + ASW. The combination of these soil parameters explained about 92 % of the spatial yield variability in field I1 (R = 0.96). The RMSE was 407 kg ha^{-1}, which was about 5.0 % of the mean yield, indicating that these parameters were highly correlated to spatial yield variability. In field I2 the best simulation of spatial yield variability occurred when the soil parameter combination of HPF + DHP + RDRF + NMF + SFF+ ASW was used for calibration (Figure 28).

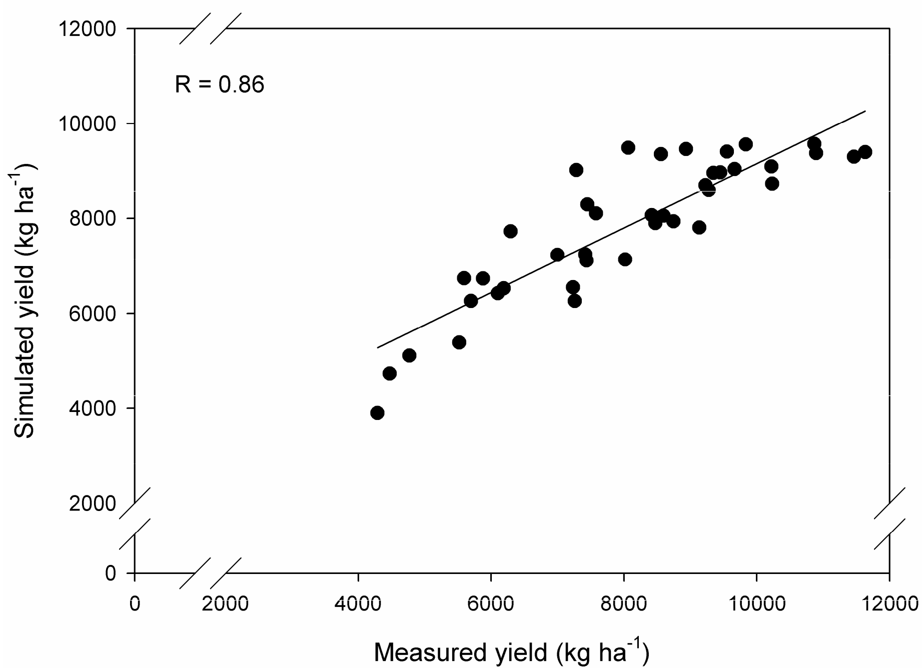

Figure 28. Simulated vs. measured corn grain yields (kg ha^{-1}) in field I2 in the years 1998-2002. Grid yields of case C and soil parameters HPF + DHP + RDRF + NMF + SFF + ASW were used for model calibration.

This parameter combination explained about 77 % of the spatial yield variability in field I2 (R = 0.88, RMSE of 719 kg ha^{-1}, 8.9 % of the mean yield). In field I3 the combination of soil parameters HPF + DHP + RDRF + SFF+ ASW resulted in the best fit between simulated and measured yield (R = 0.85). The RMSE was 590 kg ha^{-1}, which was about 7.2 % of the mean yield.

7.4.2.4 Case D (15.0/22.5 x 27.5 m Grid Size)

The additional information about soil available nitrogen at the 4th leaf stage improved the relationship between simulated and measured yields. In field I1 all combinations of calibrated soil parameters resulted in a very good correlation between simulated and measured yields. The correlation coefficient was R = 0.97 for all combinations of soil parameters, whereas the lowest RMSE was found for the parameter combination HPF + DHP + RDRF + NMF + SFF with 427 kg ha^{-1} (Table 19, Figure 29). The results showed a slight improvement compared to the calibration results for case C, where soil nitrate levels were not included in the calibration.

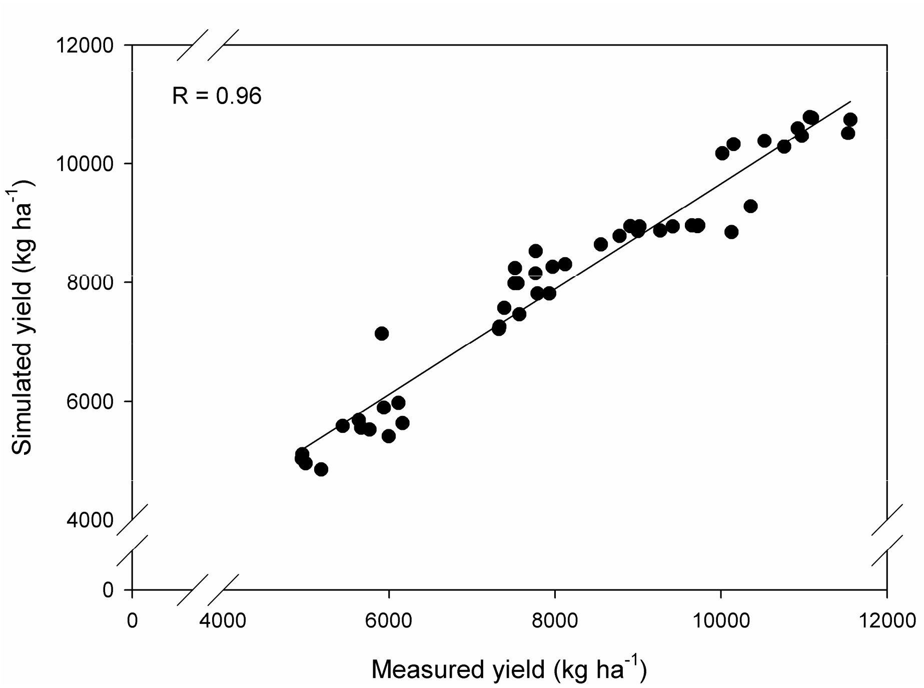

Figure 29. Simulated vs. measured corn grain yields (kg ha^{-1}) in field I1 over the years 1998-2002 (yield in 1999 is missing, because in this year wheat was planted). Grid yields of case D and soil parameters HPF + DHP + RDRF + NMF + SFF were used for model calibration.

For field I2, the simulated yield was good, with correlation coefficients ranging between R = 0.80 and R = 0.86 (Table 19). However, the results were not as good as for case C. The different combinations of soil parameters explained between 64 % and 74 % of the spatial yield variability. The RMSE ranged from 735 to 949 kg ha^{-1}, which was around 10 % of the mean yield in field I2.

However, for case D, all combinations of soil parameters described the spatial yield variability better than case C for field I3. The correlation coefficient ranged from R = 0.85 for HPF + DHP + RDRF + SFF up to R = 0.88 for HPF + DHP + NMF + SFF+ ASW. The RMSE reached values of 676 kg ha^{-1} (8.3 % of the mean yield) and 878 kg ha^{-1} (10.8 % of the mean yield), which was less 1000 kg ha^{-1}. A graph of the best-fit calibration for field I3 is shown in Figure 30.

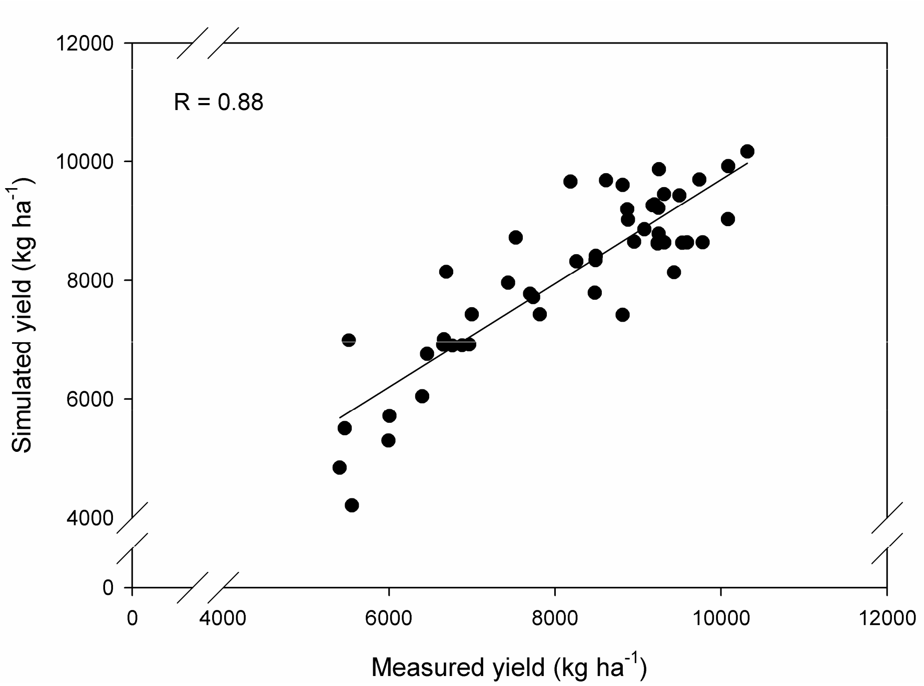

Figure 30. Simulated vs. measured corn grain yields (kg ha^{-1}) in field I3 in the years 1998-2002. Grid yields of case D and soil parameters HPF + DHP + NMF + SFF + ASW were used for model calibration.

In general, based on the previous results (calibration in case C), the improvements of the model calibration in case D was not as high as expected. Thus compared to the operating expenses the additional information soil available nitrogen in the soil was low. Due to the trade-off between cost and benefit, for further investigations this information might not be absolutely necessary for the model calibration and accuracy improvement.

Overall, the model explained the spatial yield variability in all grids over five years very well. Whereat in all three fields, slightly different combinations of soil parameters led to the best calibration of the model. The highest accuracy of the model was achieved in field I1 using yield values of case D and a combination of the soil parameters HPF + HPD + RDRF + NMF + SFF. These soil parameters explained about 94 % of the spatial yield variability in field I1 (Figure 29).

In field I2 a combination of the soil parameters HPF + HPD + RDRF + NMF + SFF + ASW explained about 77 % of the spatial yield variability (Figure 28), when yield values of case C were used for the calibration process. However, in field I3 a combination of the soil parameters HPF + HPD + NMF + SFF + ASW explained about 77 % of the spatial yield variability, calculated by yield values of case D (Figure 30). These results implied that the spatial yield variability was mostly influenced by six soil parameters. The soil parameter parameters HPF + HPD + RDRF + NMF + SFF + ASW counted for at least 75 % of the spatial yield variability.

In general, the model gave more accurate simulated yields for larger grids, suggesting that the applied calibration process may be more effective under large grid sizes. A slight improvement of the model accuracy was found when additional information about soil available nitrogen around the 4^{th} leaf stage was imposed on the calibration process. These results indicated that the adjustments of soil parameters accounted for a high amount of spatial and temporal yield variability within the three fields.

7.5 Discussion

The goal of this 5-year field study was to use the APOLLO model to analyze the spatial yield variability of three fields in the Upper Rhine Valley and to determine if crop growth model calibration techniques developed in the United States could be transferred to small fields in Germany. Management input files for three fields in Germany were developed and different calibration strategies for the analysis of spatial yield variability were tested. In four different case studies the impact of grid size on simulated spatial yield variability was assessed. The results of the model calibration were interpreted in terms of reasonable effects of yield-limiting soil parameters.

The results of the model calibration implied that the CERES-Maize crop growth model APOLLO, which has been successfully used to evaluate causes of spatial yield variability in the United States (Batchelor et al., 2002; Batchelor et al., 2004b) also performed very well under German conditions (Table 19). Although the three fields in the Upper Rhine Valley were very small compared to conditions in the United States, the model gave good simulations of spatial yield after calibration. Therefore the APOLLO system, coupled with the CERES-Maize crop growth model, appears to be a good tool to investigate spatial yield variability on small-scaled fields in Germany.

The accuracy of the calibration results depended on the soil parameter used for calibration and on the grid size used for calibration of the APOLLO model. The calibration of single soil properties indicated that the parameters HPF + DHP accounted for most of the yield variability. In all three fields, good correlations between simulated and measured yields were found when these parameters were used for model calibration (Table 18). In field I1, the parameter SFF also affected simulated spatial yield variability. However, in field I2 and I3 RDRF was the second strongest parameter in explaining spatial yield variability. The soil parameters SCS CN, DR, ETHDR + SHC failed to explain a large part of the spatial yield variability (data not shown), which was expected due to the situation in the fields. The fields were almost flat, so runoff potential (SCS CN) did not have much influence on spatial yield variability. Additionally, as the fields were not drained, the soil parameters DR, ETHDR + SHC, which are related to subsurface tile drainage, could not explain a significant amount of spatial yield variability. However, although NMF normally did not vary across the field, it did improve simulated yields in all three fields.

Grid size had a strong influence on the results of the model calibration. In general, using the smaller grids (case A) for model calibration resulted in weak correlations between simulated and measured yields (Table 19). However, when larger grids (case B or case C) were used for calibration, the accuracy of the model improved. The larger grid size contained more yield monitor data points and thus, averaged over some of the spatial yield variation that occurs between two sequential yield monitor data points. Thus, the larger grid sizes averaged yield variability within the grid, which was similar to results of Ping and Dobermann (2003). To work with spatial data sets in crop growth models, there appears to be a trade-off between maintaining spatial precision by selecting a small grid size and reducing noise in yield monitor data by selecting a larger grid size (Wong, 1995; Long, 1998). Combining area units into successively larger units, an agronomist will need to consider the scale at which the spatial variability of site-specific yield data has to be analyzed (Long, 1998). Considering the underlying soil factors that had either a high range of variability or continuity, the model accuracy was improved by choosing larger grid sizes that captured the spatial variability and stability within different sites (Link et al., 2004a).

Although a strong influence of many available soil parameters could be determined, the best simulation of yield was achieved for the soil parameters HPF + DHP. In all three fields good correlations between simulated and measured yields were determined, when these parameters were used for model calibration. These results implied that HPF + DHP were the parameters with the biggest impact in explaining spatial yield variability. Hardpan is described as a factor that is mainly induced by management practices. The effect of soil compaction after tillage is described in the literature (Lindstrom and Voorhees, 1994; Lipiec and Simonta, 1994). Due to continuous cultivation of corn at all three fields over the 5-year period, it is highly possible that the hardpan or restrictive layer was strongly manifested in all fields. As a result of a restrictive layer in the field, root distribution could be affected and led to spatial yield variability, as also assumed in studies of Arvidsson and Håkansson (1996). RDRF explained much of the spatial yield variability especially in field I2 and I3. In model simulations where RDRF was considered, high correlation coefficients were achieved in all three fields, indicating a strong influence of RDRF factor on yield. In addition, soil fertility seemed to have an influence on the spatial yield variability, especially in field I1. ASW might be spatially different due to a probably inhomogeneous flint layers in the deeper soil, which affects the water supply in the field.

In general the APOLLO model preformed well in simulating yield of the three fields in the Upper Rhine Valley over the 5-year period. Among the yield-limiting factors that were examined in this study, restrictive layer seemed to have a big impact on yield variability. However, one cannot discount the effect of other factors or interactions such as rooting depth, water availability etc. Nevertheless, the technique presented in this study demonstrates the value of using a crop growth models in quantifying individual as well as combined effects of factors leading to spatial yield variability. However, there is a need to further test and validate the model outputs by verifying the yield-limiting factors through direct field measurements.

7.6 Conclusion

The characterization of spatial yield variability within a field is necessary for the implementation of site-specific management strategies. This study demonstrates the use of the crop growth model APOLLO to evaluate the causes of spatial yield variability of corn in small fields in Germany. In general the APOLLO model performed well in simulating spatial yield variability in field I1, I2 and I3. The spatial yield variability seemed to be mostly affected by the two soil parameters HPF + DHP within the three fields. The correlation between simulated and measured yields provided information about the strength of the soil parameter affecting the yield within these fields.

The calibration results were influenced by the grid size. Whereas smaller grids provided more random monitor yield data, larger grids provided a more representative set of yield monitor data, due to the coverage of a larger area. Consequently, the APOLLO model performed better when yields belonging to larger grids were used for model calibration. The applicability of the model can be extended by developing prescriptions for different management strategies (e.g. plant population, nitrogen fertilizer), thus enhancing the possibilities of successfully implementing site-specific management strategies.

In the previous paper a crop growth model was used to further investigate the spatial yield variability, which was not fully explained by linear regression models in Chapter 5. This study demonstrated the use of the crop growth model APOLLO to evaluate the causes of spatial yield variability of corn in small fields in Germany. Overall APOLLO was able to simulate spatial yield variability in field I1, I2 and I3, indicating that most of the spatial yield variability was caused by a restrictive layer within the three fields.

In the following chapter the calibrated APOLLO model will be used to develop optimum nitrogen prescriptions for different management strategies, taking the yield-limiting soil parameters into consideration.

8 Using a Crop Model to Evaluating the Economic and Environmental Impact of a German Compensation Payment Policy under Uniform and Variable-Rate Nitrogen Management Strategies [3]

8.1 Abstract

Site-specific nitrogen (N) management has been suggested as management tool to increase nitrogen fertilizer efficiency and reduce environmental impacts. Environmental laws are being implemented throughout Europe to limit nitrogen fertilization on arable land, especially to protect drinking water areas. In response to the European Union (EU) legislation, the State of Baden-Württemberg (Southwest Germany) passed a law to further reduce the loss of nitrogen to groundwater from agricultural sources. Producers in governmental designated water saving regions will be paid a compensation for following specific nitrogen management plans that reduce nitrogen levels below a target threshold value in the soil after harvest. An efficient use of nitrogen inputs is therefore crucial. Precision agriculture aims at increasing this efficiency by incorporating spatial and temporal variation into fertilizer management. Crop growth models can help to determine the optimum nitrogen rate in grids across a field.

The purpose of this paper was to use the CERES-Maize crop growth model and the APOLLO precision farming decision support system to asses the importance of accounting for spatial variation in the design of policies to control groundwater nitrate concentration under the EU legislation. The policy was evaluated for uniform and variable-rate nitrogen management on a small-scale field, which was divided into 30 grids. The model was calibrated using 5-years of data from 30 grids in a 5.5 ha field in the Upper Rhine Valley, near Weisweil, Germany. The model simulated yield variability in the different grids quite well and explained approximately 60 % of the yield variability. Once the model was calibrated for each grid, optimum nitrogen rate to maximize the marginal net return considering the given target threshold value of soil nitrate after harvest was computed for each grid using 28-years of historical weather data.

Results indicated a spatial distribution of optimum nitrogen rates for grids across the field. Variable-rate nitrogen management (VRM) required lower amounts of nitrogen fertilizer (20-25 %), achieved similar yield levels and resulted in higher marginal net returns over the 28-years of weather data when compared to current uniform-rate nitrogen management (CUM). Higher marginal net return in VRM was achieved because the target

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groundwater nitrate level was satisfied in most grids under VRM resulting in a compensation payment for the producer. This did not occur as often under current uniform management practices, especially under extreme weather conditions. These results support the relevance of managing temporal and spatial variation on fields for groundwater protection applying dynamic nitrogen management strategies.

8.2 Introduction

The intensification of agricultural production over the last few decades has greatly increased food production, but at a high environmental cost (Smil, 1999; Tilman et al., 2001). Environmental effects of the intensification of agriculture has led to eutrophication and decreased biodiversity of natural areas, groundwater and atmosphere at local, regional and global scales. During the next 50 years, agricultural intensification will likely contribute further to an increase in nitrogen- and phosphorus-driven eutrophication of water bodies in the environment (Tilman et al., 2001). The intensification of agriculture has lead to imbalances in nutrient budgets (Smaling et al., 1999) especially for nitrogen. The degradation of environmental quality from poor management of nitrate continues to be at the forefront of public concern. Nitrate contributes to surface water degradation when it flows into subsurface drainage lines that discharge into streams and lakes or when it leaches below the active plant-root zone and into shallow ground water sources (Dinnes et al., 2002). The intensification of crop production and the increased use of nitrogen fertilizers have been identified as the primary source for nitrate (NO_3) contamination of groundwater.

To combat this problem, the European Union (EU) has launched several directives to reduce water pollution caused by nitrates from agricultural sources (EC-Council Directive, 1991). This law is designed to improve groundwater quality by providing incentives for producers to reduce nitrogen applications in order to meet the 1980 EC-Drinking Water Directive in shallow groundwater with a maximum concentration of 50 mg NO_3 L^{-1}. Stimulated by these directives, the State of Baden-Württemberg (Southwest Germany) implemented a policy (SchALVO) to further reduce the loss of nitrogen to groundwater from agricultural sources (Schulze, 2001). As a result of this policy, producers in governmental designated water saving regions will be paid a compensation of 165 € ha^{-1} for following specific nitrogen management plans that reduce nitrogen levels below a target threshold value of 45 kg N ha^{-1} in the soil after harvest (October 1st – November 31st). For corn, the management plan requires that producers split the application of total nitrogen between planting and the 4th leaf stage. At or prior to planting, the producer may apply a maximum of 40 kg N ha^{-1} for corn. Around the 4th leaf stage the producer can apply the second split application where the amount is calculated based on residual soil nitrogen and expected yield potential. The law further regulates the given possibilities for crop rotation, tillage and residue management, which will not be considered in this paper. After harvest the amount of nitrogen left in the soil is spot-checked by the government and compared to reference fields. If the producer has met the management plan and the nitrogen target threshold value is below 45 kg N ha^{-1} the producer will receive the compensation payment.

In the past, producers defined optimum nitrogen as the rate that maximizes profit. Producers would typically apply a starter nitrogen application, and then apply an additional nitrogen amount at the 4th leaf stage, which is normally the balance between the total nitrogen amount to achieve the yield potential of the field minus the amount of soil available nitrogen at this growing stage, determined by soil measurements or by results of a reference field. This new program changes the definition of profit, in that a generous compensation payment is now available to offset yield losses that may result from lower applications of nitrogen. The biggest problem for producers is to estimate the yield potential for the season, which is needed to compute nitrogen to be applied at the 4th leaf stage. The amount of nitrogen needed at the 4th leaf stage to maximize profit is highly dependent upon the weather conditions, which occur during the season, which is never known on the nitrogen application date. In addition to this, there is tremendous variation of yield within a field, which has a large impact on optimum nitrogen levels within a field. Thus, uniform application of nitrogen over a field may not be the most efficient approach to taking advantage of the compensation payments.

However, it remains questionable whether a simple accounting system will suffice to control nitrogen losses because it does not account for the effects of variability in soil properties that affect plant growth and nitrogen uptake. Several studies showed that corn yields are spatial variable within fields (Lamb et al., 1997; Machado et al., 2002; Eghball et al., 2003). Yield variation may be caused by many factors including spatial variability of soil type, landscape position, crop history, soil physical and chemical properties, and nutrient availability (Wibawa et al., 1993). Interactions among biotic factors like pests or diseases and abiotic factors, which include soil physical and chemical characteristics also lead to spatial variability of crop growth (Mulla and Schepers, 1997; Sadler et al., 2000). Swinton et al. (2002b) showed that corn yield response to nitrogen varies spatially with quantifiable field characteristics. Due to spatial variability within the field uniform nitrogen application resulted in over- and underfertilization in parts of the fields in studies of Frasier et al. (1999) and Thrikawala et al. (1999). Whereas overfertilization increases the probability of nitrate leaching (Meisinger and Randall, 1991) and higher emissions of nitrous oxide (Kauppi and Sedjo, 2001), underfertilization may limit yield as reported in the studies of Paz et al. (1997).

A more flexible and mechanistic approach to fertilizer management, applying knowledge on fundamental processes and dealing with different sources of variability could increase control over nitrogen losses. The consideration of spatial and temporal variability using Precision Farming (PF) may increase fertilizer use efficiency and enable producers to stay within nitrogen loss limits imposed by current and future policies. Rather than treating a whole field as a uniform unit by fertilizing one rate, site-specific management allows the fertilizer to be applied variably. Dampney et al. (1999) found a reduction in nitrate leaching in winter wheat when comparing uniform rate with variable-rate nitrogen management. Kitchen et al. (1995) found that variable-rate nitrogen management on corn decreased the amount of nitrogen in the soil at the end of the season compared with uniform nitrogen management. The assessment of spatial variability within a given field is necessary prior to the implementation of variable-rate fertilization (Paz et al., 1999). Process-oriented crop growth models are a promising tool to help researchers search for relationships between environment, management, and yield variability.

The CERES-Maize (Crop Environment Resource Synthesis) model is a predictive, deterministic model designed to simulate corn growth, soil, water and temperature and soil nitrogen dynamics at a field scale for one growing season. In the CERES nitrogen subroutine the turnover of soil organic matter and the decay of crop residue, including the associated mineralization and immobilization of nitrogen and nitrogen losses are simulated (Godwin and Singh, 1998). Many studies have been conducted to evaluate the capability of the model to simulate plant and soil nitrogen balance. In early studies by Godwin and Vlek (1985) it was demonstrated that the model performed well in simulating grain yield and plant nitrogen uptake for wheat. Studies of Jones and Kiniry (1986) showed that the model was able to simulate grain yield response to increasing nitrogen application rates. Keating et al. (1991) found the model did not perform well under semiarid and drought conditions in Kenya, pointing out the weakness of the model for such situations. Interactions of management, corn yield and weather were investigated by Thornton et al. (1995), indicating the capability of the model to simulate the variability of corn yields and nitrate leaching potential. Difficulties in simulating nitrate leaching were shown by Bowen et al. (1993) for Oxisols. However, Garrison et al. (1999) found good agreement between simulated and observed soil nitrate concentrations in a 3-year study in Iowa (USA). Bowen and Baethgen (1998) concluded that with appropriate input data, both economic return and the potential for excessive leaching of nitrate can be determined using the model.

Paz et al. (1999) used the CERES-Maize crop growth model to compute the optimum nitrogen rate for corn that maximized the marginal net return (MNR) for grids within a field. From an economic perspective, the optimum amount of nitrogen is the amount that maximizes MNR over a long period. Because future weather is unknown at the application date, they determined that the nitrogen rate that maximized the MNR over a long period is the only way to compute optimum nitrogen rate. The results described by Paz et al. (1999) showed that grid-level nitrogen management used lower amounts of fertilizer and produced higher yields than uniform fertilizer application. The approach by Paz et al. (1999) was recently incorporated into the APOLLO (Application of Precision Agriculture for Field Management Optimization) PF decision support system to allow others to implement this approach (Batchelor et al., 2004a).

Similar to the approach of Paz et al. (1999) the goal of the study was to use the CERES-Maize model and the APOLLO model (Batchelor et al, 2004a) to asses i) the importance of spatial variability in soil properties in the design of policies to control groundwater nitrate concentration and, ii) to compare uniform nitrogen management with variable-rate nitrogen management practices under the EU legislation. The model was calibrated using 5-years of data from 30 grids in a 5.5 ha field in the Upper Rhine Valley, near Weisweil, Germany. The Upper Rhine Valley is located in one of the most important drinking water areas in

Germany, characterized by a high natural variability. Due to intense corn production in this region, the quality of drinking water is deteriorating. In 2001, an investigation of the groundwater quality in the Upper Rhine Valley was conducted by the Interreg II project, which indicated that the threshold of 50 mg NO_3 L^{-1} was exceeded in 15 % of the measurements made at governmental fountains (Maier, 2003).

Following Braden et al. (1989), Mapp et al. (1994), and LaFrance and Watts (1995) our motivation was to determine if the environmental losses of nitrogen are reduced under variable-rate management and if there might be an economic advantage of spatially targeted policies over uniform policies leading to a higher marginal net return for the producer under variable-rate management.

8.3 Procedures

8.3.1 Site Description and Data Collection

Spatial distribution of corn yield was investigated in a small farm field (5.5 ha) in the Upper Rhine Valley near Weisweil (48° 19' N, 7° 67' E), northwest of Freiburg, Germany over the years 1998-2002. The mean annual precipitation in this area is 910 mm, the mean temperature is about 9.5° C and the sum of the yearly solar radiation averages about 11390 kJ m^{-2}. The major soil type is a silty loam. In a previous study the field was divided into 30 grids, of 0.055-0.2 ha in size. A detailed site description and the arrangement of the grids can be found in Link et al. (2004a).

Corn (*Zea mays* L.) was grown in the field each year from April – October, with exception of one part of the field, where wheat was grown in 1999. The field was managed uniformly using the producer's current management practices. The nitrogen application was split into two applications. Usually the first rate was applied on planting, and the second rate around the 4^{th} leaf stage. At sowing, a starter fertilizer of Ø 31 kg N ha^{-1} was applied uniformly as KAS (13 % NH_4-N, 13 % NO_3-N) to the field in all five years. Around the 4^{th} leaf stage urea (46 % N) was applied uniformly to the field. The rates were adapted in each year to measured soil available nitrogen and ranged from 70-120 kg N ha^{-1}, resulting in an average of 250 kg N ha^{-1}. Herbicides and pesticides were applied as needed to control pests. After harvest in September or October, the corn residue was left on the surface of the field and incorporated each year to a depth of 15 cm before winter.

Geo-referenced corn grain yield data were collected over a 5-year period (1998-2002) using a differentially corrected global positioning system and a yield monitor mounted on a combine harvester (Claas, Lexion). Corn grain yield and corn grain moisture content were measured every 5 seconds (10-m distance), resulting in about 200 yield monitor data points per hectare. Yield monitor points with missing values for yield or grain moisture content, or yield values greater than 15000 kg ha^{-1} were excluded from the yield monitoring dataset. In this paper, corn grain yield was adjusted to 0 % moisture content, to fit the yield data format of the CERES-Maize model.

Yield monitor data were aggregated to a grid network of 15.0/22.5 x 27.5 m in size. These two grid sizes were used to better match the field boundaries. The smaller grids (15.0 x 27.5 m) were placed in the turning rows, and the larger grids (22.5 x 27.5 m) were placed in the middle of the field. The arrangement of the grids can be found in Link et al. (2004a). The grids were overlaid onto yield maps and the average yield for each grid was computed using software, which was developed and described by Thorp et al. (2004). Each grid contained at least six yield monitor points.

8.3.2 APOLLO Decision Support System

APOLLO (Application of Precision Agriculture for Field Management Optimization) is a PF decision support system, which is based on the CERES (Ritchie et al., 1998) and CROPGRO (Boote et al., 1998) family of crop growth models. APOLLO was developed to assist users in evaluating causes of spatial yield variability and to develop optimum nitrogen prescriptions (Batchelor et al., 2004a). It has modules to assist the user in 1) calibrating spatial soil inputs to minimize error between simulated and measured yield, 2) validating the calibrated model for independent seasons, and 3) developing nitrogen prescriptions. In this study, the PF decision support system, APOLLO, was used to develop optimum nitrogen prescriptions for different scenarios.

8.3.3 Development of the Nitrogen Prescriptions

After calibrating the APOLLO model using the five years of corn yield data, optimum nitrogen prescriptions were developed for three different nitrogen applications strategies based on 28 years of historical weather data (1976-2003). In order to develop the optimum nitrogen prescription only the nitrogen application at 4th leaf stage was adjusted, while the nitrogen application rate at planting was set to 35 kg N ha^{-1}. Thus, the following strategies were considered:

Strategy 1: Current uniform management (CUM). This strategy was based on the current producer's practice on the field in Weisweil, which is to make a uniform nitrogen application of 105 kg N ha^{-1} at the 4th leaf stage in addition to a starter nitrogen application of about 35 kg N ha^{-1} at planting.

Strategy 2: Optimum uniform management (OUM). This strategy was developed based on the results of the APOLLO model and is the strategy which was found to maximize the 28-year mean MNR under a uniform nitrogen application at the 4th leaf stage, in addition to a starter nitrogen application of 35 kg N ha^{-1} nitrogen at planting

Strategy 3: Variable-rate management (VRM). This strategy was based on the results of the APOLLO model and is the strategy that maximizes the 28-year mean MNR for each grid, in addition to a starter nitrogen application of 35 kg N ha^{-1} at planting in each grid.

Each prescription was evaluated for the marginal net return (MNR) and the corresponding amount of nitrogen left in soil after harvest (November 15th) for each of the 28 years of historical weather. The optimum nitrogen prescription was defined as the combination of planting (35 kg N ha^{-1}) and 4th leaf stage nitrogen rates that maximized the 28-year average MNR in each grid. Note that the optimum MNR over the 28-year period is not necessarily optimum for any specific year. In low yielding years the 28-year optimum nitrogen application rate would provide more nitrogen than the plant can take up, whereas in high yielding years, nitrogen deficiencies might exist when following the 28-year optimum nitrogen rate. However, if followed for 28 years, the producer's income would be maximized, and the soil nitrogen target threshold value would be met.

To identify the optimum nitrogen rate for each strategy, the application of 60 different nitrogen rates ranging from 0-300 kg N ha^{-1} (in increments of 5 kg N ha^{-1}) was simulated for each grid and each year of historical weather data. Analogues to Paz et al. (1999) the MNR (€ ha^{-1}) was computed for each grid in each year and afterwards averaged over 28-year period using the following function:

$$MNR_{n,t} = Y_{n,t} * P_C - N_{n,t} * P_N + CP_{n,t} \quad [6]$$

where $Y_{n,t}$ is corn yield (kg ha^{-1}) for grid n and year t, P_C is the price of corn (€ kg^{-1}), $N_{n,t}$ is the nitrogen application rate (kg N ha^{-1}) for grid n and year t, P_N is the price of nitrogen fertilizer (€ kg^{-1}) and $CP_{n,t}$ the compensation payment (165 € ha^{-1}) for grid n and year t, based on the simulated amount of nitrogen left in the soil after harvest (November 15^{th}). Corn yield, nitrogen application rate and compensation payment are a function of t = weather year and n = grid number for VRM, while nitrogen is not a function of grid number for CUM and OUM. According to the SchALVO policy of the State of Baden-Württemberg in grids where the threshold of 45 kg N ha^{-1} was exceeded at November 15^{th}, $CP_{n,t}$ was set to zero (€ ha^{-1}). The price of corn was calculated based on the actual corn prices (0.13 € kg^{-1}) at the stock market in Paris (www.mativ.com, 9 Nov 2004). Three different prices were assumed for the nitrogen (P_{N1} = 0.50 € kg^{-1}, P_{N2} = 0.59 € kg^{-1}, P_{N3} = 0.83 € kg^{-1}). Note, that the computed optimum nitrogen rate on field level and grid level depended on the chosen fertilizer and corn prices.

In order to determine if there might be an economic and ecological advantage of spatially targeted policies leading to a higher MNR for the producer optimum nitrogen prescriptions were also developed for the three different nitrogen applications strategies based on 28 years. The MNR was determined according to function 1, setting CP in all strategies to zero.

Finally, the amount of money a producer could spent on VRM was computed by subtracting the MNR of the producer's current management (CUM) from the MNR for VRM, averaged over all grids using the following function:

$$\Delta MNR = MNR_{VRM} - MNR_{CUM} \quad [7]$$

where MNR_{VRM} is the average MNR for variable-rate management (€ ha^{-1}), and MNR_{CUM} is the average MNR for current management (€ kg^{-1}). Two diagrams presenting the differences in marginal net return for several different corn price and nitrogen fertilizer prizes, indicating the additional profit for shifting from CUM to OUM or VRM, respectively.

8.4 Results and Discussion

8.4.1 Model Calibration Using APOLLO

The APOLLO model was calibrated as described by Link et al. (2004b) using the data from the years 1998-2002 for this field. The model calibration was performed by adjusting soil parameters including maximum potential rooting depth (cm) and available soil water (%) over their expected ranges to minimize error between simulated and observed yield during this 5-year period for each grid. The optimization of these two soil parameters for each grid, resulted in good correlations between simulated and measured grid-level yields of $r^2 = 0.60$ (Figure 31) over the 5-year period.

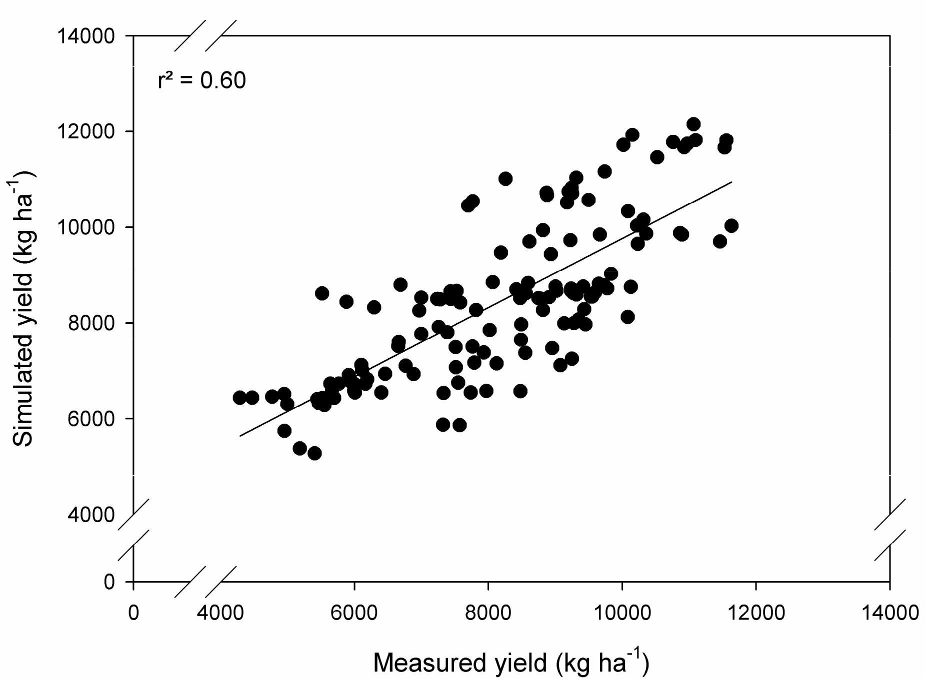

Figure 31. Simulated vs. measured mean grid corn grain yields (kg ha^{-1}) for the 30 grids using 5 years of data (1998-2002).

The mean measured yield over the 5-year period was 8139 kg ha^{-1}, whereas the mean simulated yield was slightly higher with 8244 kg ha^{-1}, resulting in a model error of 2 %. Overall, the model explained approximately 60 % of the yield variability in all grids over five years. This indicates that the adjustments of soil parameters including maximum potential rooting depth (cm) and available soil water (%) accounted for a significant amount of the spatial and temporal yield variability across the field. Thus, the model mimicked historical yield variability adequately to proceed with an economic analysis.

8.4.2 Optimum Nitrogen Prescriptions and Net Return

Table 20 shows the results of the different prescriptions for the three chosen scenarios taking into consideration that the producer would receive a spatially targeted compensation payment of 165 € ha^{-1} if the threshold value of nitrogen in the soil after harvest was below 45 kg N ha^{-1}.

8.4.2.1 Strategy 1: Current Uniform Management (CUM)

The nitrogen application rate actually applied on the field in Weisweil ranged between 70-120 kg N ha^{-1} in the period of 1998-2002. In order to simulate the current uniform management (CUM) a mean nitrogen application rate of 105 N kg ha^{-1} applied at the 4^{th} leaf stage was assumed based on the producer's current practices. The fertilizer prices were assumed at P_{N1} = 0.5 € kg^{-1}, P_{N2} = 0.59 € kg^{-1}, and P_{N3} = 0.83 € kg^{-1}. The mean simulated yield for CUM averaged over 28 years was 5852 kg ha^{-1}. The yield for single grids ranged from 5287 to 6554 kg ha^{-1}.

For the CUM a mean MNR of 828 € ha^{-1} was calculated for the whole field in consideration of the highest nitrogen price (P_{N3} = 0.83 € kg^{-1}). The MNR of single grids ranged between 734 and 947 € ha^{-1} taking into consideration that the producer could receive a grid based compensation payment if the targeted threshold value of nitrogen in the soil after harvest was below 45 kg N ha^{-1}. The mean amount of nitrogen left in the soil after harvest in a depth of 0-90 cm was estimated with 28 kg N ha^{-1} until November 15^{th}. For single grids the mean amount of nitrogen left in the soil varied from 17 to 42 kg N ha^{-1}, indicating that using the CUM resulted on average in nitrogen values below the threshold of 45 kg N ha^{-1}. However, in about 16 % of the grids, the model simulated nitrogen left in the soil above the threshold of 45 kg N ha^{-1}, lowering the mean MNR. The simulated nitrate leached during the growing season was about 28 kg N ha^{-1} (25-35 kg N ha^{-1}) over the 28-year period.

8.4.2.2 Strategy 2: Optimum Uniform Management (OUM)

The optimum uniform management (OUM) resulted in a lower nitrogen application rate at the 4^{th} leaf stage compared to the CUM (Table 20). Depending on the cost of nitrogen, the 28-year optimum nitrogen application rate under OUM ranged between 80 kg N ha^{-1} for P_{N1} and 75 kg N ha^{-1} for P_{N2} and P_{N3}, respectively instead of 105 kg N ha^{-1} for the CUM. The increase of nitrogen prices of about 0.05 € kg^{-1} (P_{N2} of 0.59 € kg^{-1}) or 0.33 € kg^{-1} (P_{N3} of 0.83 € kg^{-1}) lead to a slightly lowered OUM application rate of 75 kg N ha^{-1}. For the OUM of 80 kg N ha^{-1}, a mean yield of 5763 kg ha^{-1} was computed by the model over the 28-year period. Yields in single grids ranged between 5250 kg ha^{-1} and 6435 kg ha^{-1} over the long term.

The mean yield based on the nitrogen application rate of 75 kg N ha^{-1} ranged between 5208 and 6390 kg ha^{-1} for the single grids and the mean yield of the whole field was assumed 5730 kg ha^{-1} over the 28-year period.

The MNR based on the low costs of nitrogen (P_{N1} of 0.50 € kg^{-1}) was computed as 881 € ha^{-1} for the whole field, whereas the MNR for single grids varied between 804 and 978 € ha^{-1}. The mean MNR corresponding to the cost of nitrogen of P_{N2} = 0.59 € kg^{-1} was with 874 € ha^{-1} (807-968 € ha^{-1}) slightly higher than the mean MNR corresponding to the cost of nitrogen of P_{N3} = 0.83 € kg^{-1}, which was 856 € ha^{-1} (789-950 € ha^{-1}) over the long term.

Based on a uniform application rate of 80 kg N ha^{-1} as well as 75 kg N ha^{-1}, the mean amount of nitrogen left in the soil after harvest was simulated with 21 kg N ha^{-1} (14-32 kg N ha^{-1} and 14-31 kg N ha^{-1} for 80 kg N ha^{-1} and 75 kg N ha^{-1}, for different nitrogen prices, respectively). The simulated mean nitrogen leached was 28 kg N ha^{-1} for the low nitrogen price, with a range of 25 to 34 kg N ha^{-1} over a period of 28 years. The same results were found for the other nitrogen prices as well.

However, in about 4-5 % of the grids, a nitrogen amount above the threshold of 45 kg N ha^{-1} was simulated over all years when 80 kg N ha^{-1} or 70 kg N ha^{-1} were applied. Thus the MNR was slightly lowered because of these grids.

8.4.2.3 Strategy 3: Variable-Rate Management (VRM)

For VRM, a mean nitrogen application rate of 71-80 N kg ha^{-1} was found to maximize the 28-year MNR in the 30 grids, depending on the fertilizer price (Table 20).

The grid yields corresponding to a mean nitrogen rate of 80 kg N ha^{-1} (55-100 kg N ha^{-1}) assuming a fertilizer price of P_{N1} = 0.50 € kg^{-1} (scenario 1) varied from 5225 to 6554 kg ha^{-1}, with a mean simulated yield over the 28-year period of 5796 kg ha^{-1}. In this scenario the MNR over the long term was between 819 and 981 € ha^{-1} for individual grids, and the mean MNR for the field was 886 € ha^{-1}.

When the optimum VRM was calculated based on a nitrogen price of P_{N2} = 0.59 € kg^{-1} (scenario 2), the nitrogen application rates were slightly lower compared to P_{N1} = 0.50 € kg^{-1}. The optimum nitrogen rates for the single grids ranged from 55 to 95 kg N ha^{-1}, with a mean N application rate of 78 kg N ha^{-1}. Simulated yields were slightly reduced compared to the previous scenario because less nitrogen was applied. The mean yield of the individual grids ranged from 5225 to 6512 kg ha^{-1}, the mean yield over the whole field was 5786 kg ha^{-1}. The mean MNR corresponding to this scenario was 879 € ha^{-1} for the whole field, the mean MNR for single grids varied between 813 and 973 € ha^{-1}.

When the optimum VRM was calculated based on a nitrogen price of P_{N3} = 0.83 € kg^{-1} (scenario 3), the nitrogen application rates decreased compared to the lower nitrogen prices. The optimum nitrogen application rates for the single grids ranged from 55 to 90 kg N ha^{-1}, resulting in a mean nitrogen application rate of 71 kg N ha^{-1}. Due to less applied nitrogen in almost all grids, the mean yield over the whole field was slightly reduced and was about

Table 20. Mean and range of nitrogen application rate, corn grain yield, marginal net return (MNR), nitrogen left in soil after harvest and nitrate leached during the growing season for three different scenarios: current uniform management (CUM), optimum uniform management (OUM) and variable-rate management (VRM).

	Unit	CUM P_{N1}	CUM P_{N2}	CUM P_{N3}	OUM P_{N1}	OUM P_{N2}	OUM P_{N3}	VRM P_{N1}	VRM P_{N2}	VRM P_{N3}
Nitrogen application rate	**(kg N ha^{-1})**	105	105	105	80	75	75	80 55 - 100	78 55 - 95	71 55 - 90
Yield	**(kg ha^{-1})**	5852 5287 - 6554	5852 5287 - 6554	5852 5287 - 6554	5763 5250 - 6135	5730 5208 - 6390	5730 5208 - 6390	5796 5225 - 6554	5786 5225 - 6512	5747 5225 - 6512
Nitrogen left in soil	**(kg N ha^{-1})**	28 17 - 42	28 17 - 42	28 17 - 42	21 14 - 32	21 14 - 31	21 14 - 31	21 16 - 31	21 15 - 31	20 15 - 28
Nitrate leached	**(kg N ha^{-1})**	28 25 - 35	28 25 - 35	28 25 - 35	28 25 - 34	27 25 - 34	27 25 - 34	27 25 - 33	27 20 - 33	27 20 - 33
MNR	**(€ ha^{-1})**	851 734 - 990	842 725 - 981	828 736 - 947	881 804 - 978	874 807 - 968	856 789 - 950	886 819 - 981	879 813 - 973	860 795 - 952

P_{N1} = 0.50 € kg^{-1}, P_{N2} = 0.59 € kg^{-1}, P_{N3} = 0.83 € kg^{-1}.

5747 kg ha^{-1} when compared to the previous scenarios. Lower yields influenced the MNR which varied between 795 and 952 € ha^{-1} for single grids. The computed mean MNR over the whole the field was 860 € ha^{-1}.

The mean amount of nitrogen left in the soil after harvest in a depth of 0-90 cm did not differ much as a function of nitrogen price. The amount of nitrogen left in upper 0-90 cm of the soil ranged from 16 to 21 kg N ha^{-1} in individual grids for VRM scenario 1, from 16 to 31 kg N ha^{-1} for scenario 2, and from 15 to 28 kg N ha^{-1} for scenario 3. Only small differences concerning the VRM were visible for the mean nitrogen left in soil, which was 21 kg N ha^{-1} for scenario 1 and 2, and 20 kg N ha^{-1} for scenario 3. This means the threshold of 45 kg N ha^{-1} at November 15th was not exceeded in any of the grids in the field.

However, in about 3 % of the grids, a nitrogen amount above the threshold of 45 kg N ha^{-1} was simulated over all years for the VRM scenarios 1 and 3. For VRM based on scenario 2 only about 0.5 % of the grids gave total nitrogen in the top 90 cm at harvest above the threshold of 45 kg N ha^{-1}. Thus for most of the grids, the compensation payments could be realized, which influenced the MNR positively.

8.5 Discussion

Based on the simulation analysis, no advantage of OUM or VRM were determined in comparison to the CUM in terms of the amount of nitrogen leached during the growing season. Management practices CUM, OUM and VRM did not show large differences in the amount of soil available nitrogen left in after harvest and almost no differences in the nitrate leached during the growing season were found based on the simulation (Table 20). These results were similar to studies of Ferguson et al. (2002), who found no significant differences in soil residual nitrate between variable-rate management and uniform management. As in our study, the differences in total applied nitrogen between uniform and variable-rate management were small, thus the corn grain yield in uniform and variable-rate management were about the same level (Ferguson et al., 2002). However, in studies of Eghball et al. (2003) it was found that a reduced nitrogen application (75 % of the recommended nitrogen amount) resulted in similar corn grain yields compared to full rate application, whereas the residual soil nitrate was significantly reduced. Derby et al. (2004) described that an adaptation of nitrogen application rate would not necessarily increase yield but would reduce leaching losses of excess nitrate nitrogen in extremely cool years and increase profits by reducing input costs (Derby et al., 2004). Dampney et al. (1999) found a reduction in nitrate leaching in winter wheat when comparing uniform rate with variable-rate nitrogen management. In studies of Kitchen et al. (1995) variable-rate nitrogen management on corn decreased the amount of nitrogen in the soil at the end of the season compared with uniform nitrogen management.

Table 21 shows the results of the different prescriptions for the three chosen scenarios taking into consideration that no compensation is paid to the producer, and thus the threshold of 45 kg N ha^{-1} were not taken into consideration. In general for the case of no compensation payment over the 28-years, the nitrogen fertilizer rate increased slightly for OUM and VRM, without a significant yields increase. Rates of nitrogen left in soil were similar to the rates computed for the case of a compensation payment to the producer, indicating that for the evaluated field the computed 28-year average optimum nitrogen rate did not endanger the targeted threshold value of 45 kg N ha^{-1}. MNR was generally lower for all three management scenarios because of the missing compensation payment of 165 € ha^{-1}. Thus, the compensation payment creates an economical stimulus for the producer to stay within the limits of environmental legislation.

Furthermore, the costs the government had to pay for each kg of nitrogen, which was not applied in order to get the compensation payments, could be determined by the ratio of compensation payment to the amount of saved nitrogen. In the OUM scenario, 80 or 75 kg N ha^{-1} were applied respectively, resulting a reduction of nitrogen application rate of 25 and 30 kg N ha^{-1} compared to CUM. For the VRM on average 80 kg N ha^{-1}, 78 kg N ha^{-1} or 71 kg N ha^{-1} were applied, resulting in a reduction about maximal 34 kg N ha^{-1}. Thus for strategy OUM the government paid 5.50 € kg^{-1} N, which was saved for corn production (as long as an application rate of 75 kg N ha^{-1} was assumed), for strategy VRM the government had to pay only 4.85 € kg^{-1} N (when an application rate of 71 kg N ha^{-1} was assumed).

This result indicated different possibilities for the German compensation payment policy. In order to establish an equal compensation payment for OUM and VRM two different possibilities seems to be possible. On the one hand the compensation payment could be reduced to 145.5 € ha^{-1}, when the compensation payments would be performed on a grid level basis. Due to the grid level applied nitrogen higher reductions could be achieved and thus the compensation payment per kg of saved nitrogen could be decreased to 4.85 € kg^{-1} following the compensation payment in the VRM. On the other hand the grid level based compensation payment could also increase the economic feasibility of VRM, by paying a specific amount of compensation payments for each kg of N (i.e. 5.50 € kg^{-1} as for the OUM), which was saved for corn production. Such a change of the German policy of compensation payment could counteract the fact, which was described by Thrikawala et al. (1999), that the major advantage of precision technologies is the reduction in the level of polluting residuals, without having any positive benefits for the producer.

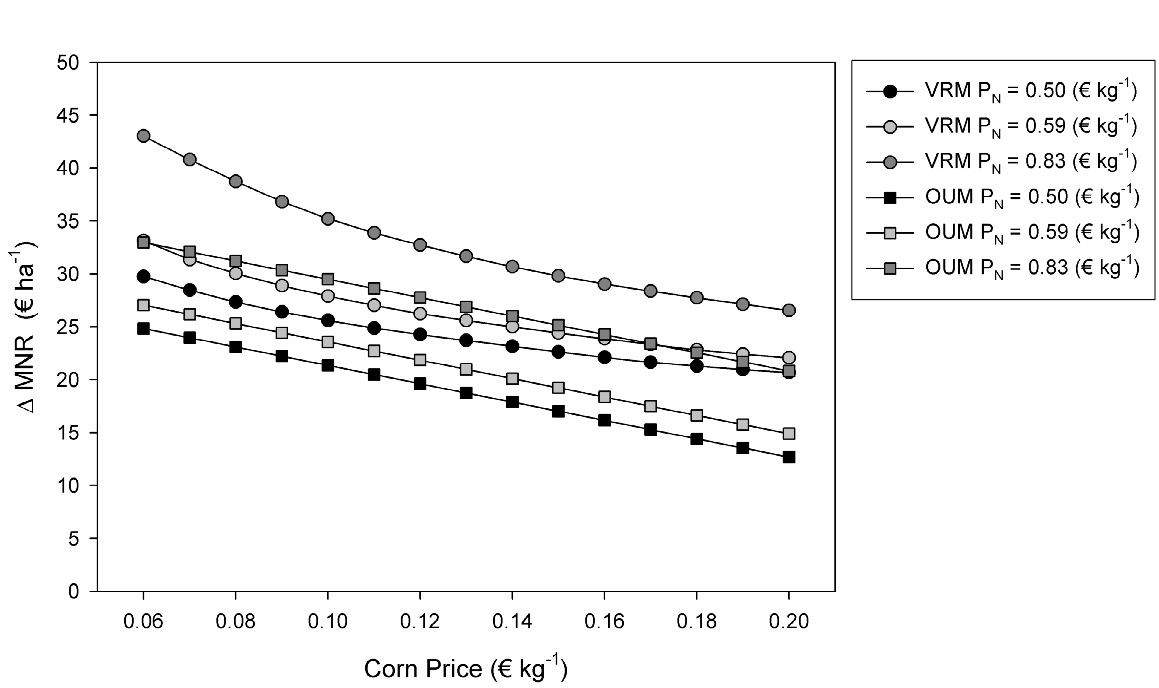

Figure 32. Difference in marginal net return (Δ MNR) between current uniform management (CUM) and the strategies optimum uniform management (OUM) and variable-rate management (VRM) optimized over a 28-year period (1976-2003) for the field Weisweil considering different corn prices and three different nitrogen fertilizer prices (P_{N1} = 0.50 € kg^{-1}, P_{N2} = 0.59 € kg^{-1}, P_{N3} = 0.83 € kg^{-1}). The MNR of CUM was used as benchmark for the calculations.

Table 21. Comparison of nitrogen application rate, yield, marginal net return (MNR), nitrogen left in soil after harvest for three different scenarios: current uniform management (CUM), optimum uniform management (OUM) and variable-rate management (VRM) without compensation payment.

	Unit	CUM P_{N1}	CUM P_{N2}	CUM P_{N3}	OUM P_{N1}	OUM P_{N2}	OUM P_{N3}	VRM P_{N1}	VRM P_{N2}	VRM P_{N3}
Nitrogen application rate	**(kg N ha^{-1})**	105	105	105	85	85	85	88 75 - 110	85 75 - 105	76 60 - 90
Yield	**(kg ha^{-1})**	5755 4997 – 6621	5755 4997 – 6621	5755 4997 – 6621	5705 4983 – 6519	5705 4983 – 6519	5705 4983 – 6519	5750 5015 – 6623	5736 5015 – 6622	5687 4947 – 6580
Nitrogen left in soil	**(kg N ha^{-1})**	27 16 - 41	27 16 - 41	27 16 - 41	22 13 - 33	22 13 - 33	22 13 - 33	23 15 - 33	22 15 - 33	21 14 - 33
MNR	**(€ ha^{-1})**	711 612 - 825	702 603 -816	677 578 - 790	714 620 - 822	707 612 - 814	707 612 - 814	716 622 - 825	708 614 - 816	688 593 - 794

P_{N1} = 0.50 € kg^{-1}, P_{N2} = 0.59 € kg^{-1}, P_{N3} = 0.83 € kg^{-1}.

In our study the calculation of the MNR showed that there is still a potential to increase the income of a producer based on different nitrogen fertilization strategies. In order to get information about the amount of money the producer could spend for investigation in variable-rate technology the additional profit from shifting from CUM to VRM was calculated. Figure 32 and Figure 33 show the additional profit a producer would achieve under VRM calculated after equation [7] considering different corn prices and fertilizer prices. The results indicate that nitrogen prices and nitrogen amount applied in the different grids and scenarios gave different MNR values. Independent of the price for corn, the VRM was more favourable from an economic point of view than the OUM and CUM, respectively. Results of Koch et al. (2004) also suggested that variable-rate nitrogen application utilizing site-specific management zones are more economically feasible than conventional uniform nitrogen application.

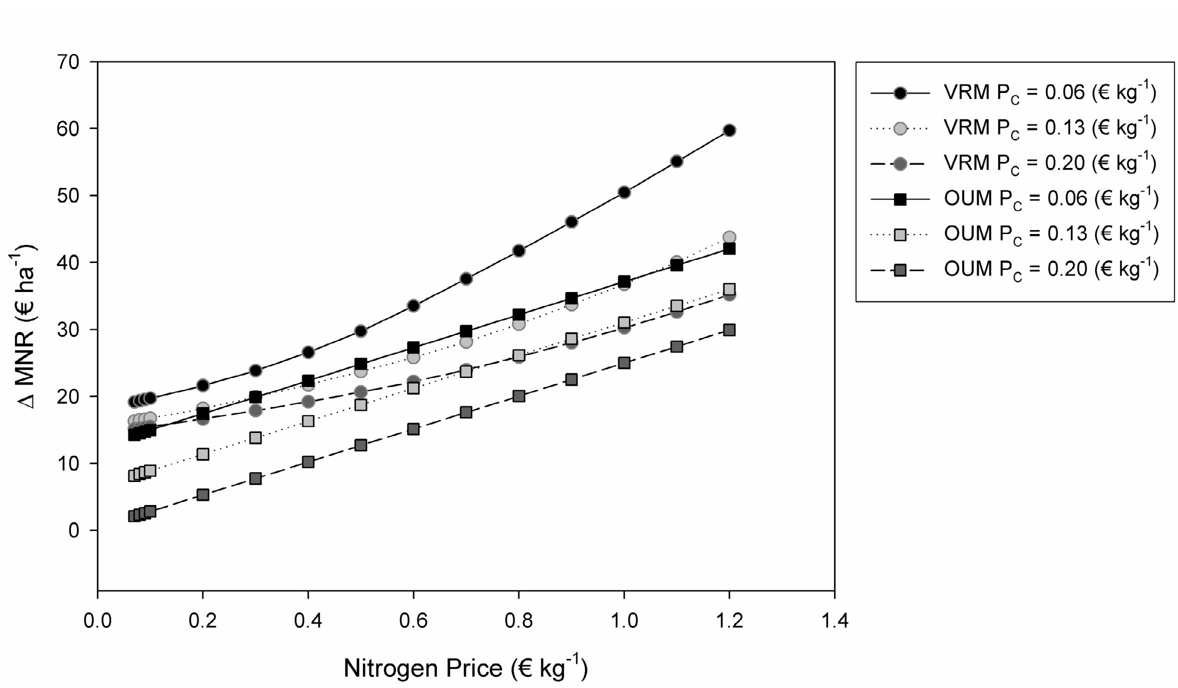

Figure 33. Difference in marginal net return (Δ MNR) between current uniform management (CUM) and the strategies optimum uniform management (OUM) and variable-rate management (VRM) optimized over a 28-year period (1976-2003) for the field Weisweil considering different nitrogen fertilizer prices fertilizer prices and three different corn prices P_{C1} = 0.06 € kg^{-1}, P_{C2} = 0.13 € kg^{-1}, P_{N3} = 0.2 € kg^{-1}). The MNR of CUM was used as benchmark for the calculations.

However, Swinton et al. (2002a) found that the added revenue from site-specific nitrogen application was generally insufficient to cover the costs of site-specific data acquisition and the variable-rate fertilizer application. Koch et al. (2004) showed that variable-rate technology for nitrogen application was most profitable on farms with a total size of approximately 500 ha, especially when it was adapted to site-specific management zones and based on variable yield goals within the management zones.

To maximize the difference between the efficiency gains from fertilizer and the cost of information and application, the optimal management size unit is required (Thrikawala et al., 1999). In this connection Babcock and Pautsch (1998) found that less productive fields possessed more yield variability than productive fields and therefore they assumed that the value of variable-rate technology will be greater for less productive fields.

8.6 Conclusion

Nitrogen management can be improved and nitrogen leaching be reduced in continuous corn cropping systems through the insight provided by comprehensive crop growth models such as DSSAT or APOLLO. As a continually evolving tool such models have the potential to help researchers and producers to better understand, how soil, crop, weather, and management factors interact and affect crop nitrogen demand and fertilizer use efficiency on a site-specific scale. Different management scenarios can be examined and compared for their impact on economic returns and potential for excessive leaching of nitrates.

The results of this study showed, that the MNR of a producer could be maximized over the long-term by reducing nitrogen application rates. The results indicated a potential to increase the MNR, by shifting from CUM to OUM and to VRM. Due to the small differences in the nitrogen application rate between OUM and VRM the advantage of VRM was not as distinct as expected. However, when economic and environmental risks due to uncertain weather were taken into consideration VRM reduced the risk of nitrogen losses to a distinct amount. Thus, the results underline the relevance of managing temporal and spatial variation on fields for groundwater protection applying dynamic nitrogen management strategies.

In the previous paper a crop growth model was used to evaluate uniform and variable nitrogen management strategies. The results indicated that nitrogen management can be improved and nitrogen leaching can be reduced in continuous corn cropping systems through the application of adapted nitrogen fertilization strategies. Thus, the main scope in this study was to assess the relevance of managing temporal and spatial variation on fields for groundwater protection applying dynamic nitrogen management strategies. Further on, the implementation of a variable-rate management was able to improve the marginal net return for the producer, when compared to the current uniform management of the producer. Therefore including a crop growth model for developing an adapted nitrogen fertilization strategy seems to be useful.

9 General Discussion

The general discussion of this study is organized on three levels. First of all the basic principles and the aim of the study are displayed. Based on the aim of the study, to investigate and model the potential to optimize nitrogen fertilization strategies, the necessary preconditions and the realization are discussed in the following section. The last section provides an estimation of the potential to optimize nitrogen fertilization strategies for the corn cropping systems in general and assesses the possible mitigation of environmental nitrogen losses due to site-specific nitrogen management.

9.1 Basic Principles and Aim of the Study

"Sustainable agriculture implies not only securing the supply of food and other products from agricultural production for a growing world population, but also that its environmental impacts are recognized and accounted for within national development plans" (FAO, 1996). In the decades ahead improved farming systems to protect and enhance environmental quality will become a greater need (Power et al., 2001). Worldwide the intensification of the agricultural production enforced the discussion on the trade-off between insuring adequate food supply and the protection of the environment. Several studies indicated a negative impact of agricultural land use to the environment. In Chapter 2 the environmental pollution by agricultural land use was discussed. It was obvious, that current nitrogen fertilizer strategies contribute highly to nitrate leaching and nitrous oxides emission. In order to reduce the nitrogen losses from agricultural land use, on a national and international level, several laws were implemented to protect the environment. Currently, nitrogen fertilizer strategies are primarily uniform rates across the field. As fields can be highly variable both spatially and temporally in the growth conditions it has been shown that the nitrogen utilization does not have to be homogenous across the field, especially if yield patterns, including high and low yielding zones were visible (Chapter 4).

The implementation of precision farming (PF) technologies was expected to influence and to reduce the amount of nitrogen losses because of a spatial and temporal adaptation of nitrogen application to the crop nitrogen demand. Thus, it was expected that the nitrogen utilization efficiency could be improved (Chapter 4). Several attempts have shown that it may be very difficult to compute the optimum nitrogen fertilization strategy to obtain a high yield with minimum environmental impact. Several attempts based on historical data only have failed or had limited success (Welch et al., 1999; Ferguson et al., 2002; Derby et al., 2004).

In this study, the main focus was to investigate and model the optimization of variable-rate nitrogen fertilization strategies in corn cropping systems with regard to minimize nitrogen losses. In this study the method of precision farming (PF) technology was selected to optimize the nitrogen fertilization strategy. Thus, the contribution of PF to the minimization of nitrogen losses will be discussed in the following parts of this chapter.

The investigations were performed on three farm fields in the Upper Rhine Valley, which is characterized as a region of intense agricultural production (Chapter 3). The three fields were small-scaled and represented the agricultural structure of this region. In order to estimate the feasibility of PF technologies and the associated optimization of nitrogen fertilization strategies, the occurrence of spatial variability has to be identified (Chapter 5). Yield mapping is the most common approach to determine yield pattern within fields. Afterwards the correlation between those yield patterns and measured plant and soil parameters could lead to insights into possible yield-limiting factors. A reduction in crop yield could be caused by many factors, including water stress, nutrient deficiency, chemical and physical soil properties, pests and diseases (Chapter 5). Yield-limiting factors might vary across fields and/or years and thus increase the spatial yield variability. Due to the interaction of many factors, the magnitude of yield-limiting factors might be different from year to year. In order to account for the various and complex interactions, linear and multiple regressions as well as crop growth models were implemented in the analysis process. Both approaches identified soil characteristics as the most important yield-limiting factors for all three fields (Chapter 5). Following the suggestion of the literature, developing an adapted nitrogen fertilization strategy has to be based on the insight of yield-limiting factors. In this study the adapted nitrogen fertilizer strategies were developed by implementing a crop growth model on a site-specific scale (Chapter 7 and 8).

9.2 Spatial Variability

For PF to be a viable method it is important to identify yield patterns within a field, describing zones in a field that give stable yields over multiple seasons and possible reasons for yield differences. In order to optimize nitrogen fertilization strategies based on PF methods, the spatial structure of a field has to be determined. The investigation of the variability and stability of crop yield is a common method to get a first impression about the level of variability within a field. Thus, similar to studies of Taylor et al. (1998), Jaynes and Colvin (1997) and Lamb et al. (1997) as a first step in this study the spatial variability and temporal stability of corn grain yield on the Weisweil fields were investigated over five years of yield data.

The investigation of spatial variability and temporal stability of corn yields over the 5-year period was performed for different grid sizes. The results were slightly different depending on the grid sizes imposed on each field. In general, larger grids were able to adequately describe temporal yield stability, but not spatial yield variability across seasons. Smaller grids were able to describe spatial yield variability, but not temporal yield stability across seasons (Chapter 5). These results are consistent with studies of Long (1998) and

Ping and Dobermann (2003), who found that increasing the grid size may create larger and more continuous yield classes. According to Wong (1995) and Long (1998), there appeared to be a direct trade-off between maintaining spatial structure using a small-scaled grid network and maintaining temporal stability by selecting a coarser grid network. Long (1998) postulated that an agronomist will need to consider the scale at which the spatial variability of site-specific yield data has to be analyzed. Based on the results of the literature and of this study the grid size should be selected in regard of the existing variability within the field and the underlying yield-limiting factors. Some of the underlying factors may have a high range of variability or continuity, whereas other factors might have a low range of variability or continuity. Due to the scale of variability of the underlying factor, different grid sizes should be selected to capture the spatial variability and stability within different sites and to delineate management zones.

The reasons for yield variability can be diverse and include biotic and abiotic factors (Mulla and Schepers, 1997; Braum et al., 1998). Spatial variability of nutrients result in most cases from spatial variations in underlying soil chemical and physical properties, organic matter, pH and, in some cases may be induced by management practices (Batchelor et al., 2002). Many studies describe the relationship between yield pattern and soil properties (Penney et al., 1996; Kravchenko and Bullock, 2000). However, the identification of yield-limiting factors might be difficult because of the complex interactions that create variable stresses or limitations of nutrients that reduce yield in different ways during different seasons.

In this study a good relationship between soil properties and yields was determined. Strong multiple correlations were found between combinations of soil nutrient levels, soil characteristics and yield. However, some of the spatial variability in yield remained unexplained, which suggested, that other factors may have influenced yield. However, developing this knowledge is imperative to designing optimum environmentally sound nitrogen prescriptions. In order to identify more of the underlying processes affecting the measured yield variability beside linear and multiple regression, complex methods like crop growth models were used in this study.

Based on this consideration, the APOLLO model, developed by Batchelor et al. (2004a) was used to asses the impact of grid size on simulated spatial yield variability in four different cases. The model was calibrated in consideration of ten soil parameters. The accuracy of the calibration changed in dependency on grid size and selected soil parameters. Whereas some soil parameters failed to explain the spatial yield variability, other gave good estimations of the spatial yield variability. Especially the assumption of a varying restrictive layer accounted for most of the spatial yield variability. Thus, the soil fertility, the root distribution and the restrictive layer were identified as the primary factors that explained spatial yield variability in the investigated fields. However, not only the selection of soil parameters influenced the performance of the model. The accuracy of the model improved when yield associated with larger grids was used for calibration. In general the APOLLO model performed well in simulating spatial yield variability of the three fields and therefore demonstrated the value of using a crop growth model in quantifying individual as well as combined effects of factors leading to spatial yield variability.

When the yield patterns in a field are obvious, it is important to adapt the nitrogen fertilization strategy to minimize the environmental impact. Otherwise, the uniform nitrogen application rate could easily result in overfertilization or underfertilization and thus increase the risk of nitrogen losses. The identification of soil properties as yield-limiting factors could be used as underlying information to adapt the nitrogen fertilization rate. Most soil properties are stable over time and thus could be implemented for the demarcation of different management zones. In management zones with less favorable growth conditions (due to soil characteristics, low yielding zones) the nitrogen uptake by the plant is expected to be lowered and thus the nitrogen application rate should be reduced. Otherwise the amount of nitrogen, which is left in the soil after harvest, would increase the risk of nitrate leaching. Contrary, in management zones with more favorable growth conditions (high yielding zones) the nitrogen uptake by the plant is expected to be increased. In order to avoid nitrogen deficiencies in such high yielding areas, more nitrogen needs to be applied. However, the application rate should still match the demand of the plant.

The applicability of the APOLLO model can be extended by developing prescriptions for different management strategies, like plant population, and especially nitrogen fertilization rates, which could enhance the possibilities of successfully implementing site-specific management strategies. The following section deals with the possibility to use the crop growth model to develop an optimum nitrogen fertilization strategy.

9.3 Nitrogen Prescription

General guidelines for rates and application times were published by IFA (1992). Up to now, the economical optimum nitrogen fertilizer strategies were determined by the relationship between the expected crop yield and the amount of nitrogen the crop will need to achieve a certain yield level. This relationship implied that high yielding locations will respond to higher rates of nitrogen while low-yielding location should require less (Doerge, 2004). A typical example to determine the nitrogen recommendation is shown by Doerge (2004) by the following formula used in the Midwestern United States:

$$\text{N recommendation (lb A}^{-1}\text{)} = \text{target yield x 1.2} - \text{N credits} \quad [8]$$

with target yield (bu A^{-1}) is the average yield in the field over a specific period (5 years) plus 5 percent and nitrogen credits (lb A^{-1}) include additions of nitrogen in legume residue, starter or other fertilizers, manures, herbicides carrier nitrogen solution and irrigation water.

Several agronomists suggest that spatial and temporal nitrogen management should not be linked to yield variation only, it should also take other spatial information, like soil type and water availability into consideration. As high-yielding sites with low nitrogen requirements and low-yielding sites that respond to unexpectedly high rates of nitrogen are quite common (Doerge, 2004), fertilizer strategies need to be considered from the three angles: need for fertilizer use, fertilizer soil-plant interaction and environmental related factors (Misra and Mani, 1994). The management practice should be selected in consideration of how it affects risks associated with net income and environmental quality (Power et al., 2001).

For a long time, nitrogen recommendations were normally developed on a field level basis for a uniform nitrogen application. However, the nitrogen response patterns showed temporal variability, even if yield patterns were similar across the years (Doerge, 2004). However, nitrogen applications should be performed on a site-specific level. Producers, who want to use variable-rate management, have several choices. On the one hand they could determine the optimum nitrogen application rate on a site-specific level by such simple methods as the equation by Doerge (2004) described above. On the other hand they could investigate the nitrogen availability within the field by measuring the amount of nitrogen in the soil and use equations to compute the amount of nitrogen to apply based on the yield goal for different grids in a field. This is similar to the late spring nitrogen approach supported by Binford et al. (1992) for the Midwestern United States. However, grid soil sampling to generate nitrogen rate maps is less common commercially because of the cost required for more frequent sampling for nitrogen status (Ferguson et al., 2002) and it is labor intensive and time consuming (Fleming and Westfall, 2001; Koch and Khosla, 2003). In studies of Eghball et al. (2003) it seemed that spatial variability of corn grain yield was not significantly influenced by soil nitrate distribution, indicating non-effectiveness of using soil nitrate spatial distribution for managing corn yield variability unless some areas in the field are severely nitrogen deficient. Alternatively, producers can use a spectral N-sensor mounted on an nitrogen applicator to determine the optimum nitrogen needed to maximize yield, as provided by Agri Con (Jahna, Germany). However the innovative method based on a N-sensor still implies difficulties for cereals (Pedersen, 2003), for corn something equivalent it is not available yet. Thus, only a minor percentage of the total nitrogen application can be applied according to real-time sensing and canopy management and the majority must be distributed according to previous years yield or soil maps (Pedersen, 2003). While all of these approaches are in use today, they do not account for the risk of weather on optimum nitrogen rate. Weather influences soil temperature and moistures and consequently affect nitrogen cycling, transformation, and movement that complicate the nitrogen management (Westerman et al., 1999). Not only the nitrogen in the soil is affected, weather conditions can also directly and indirectly affect the nitrogen requirement by the plant (Power et al., 2001).

Blackmer et al. (1997), McBratney and Whelan (1999), and Swinton et al. (2002a) emphasized that beside the soil texture, weather conditions also have a major impact on yields and nitrate leaching, and for this reason should be considered for an optimized nitrogen fertilization strategy, especially in order to increase the environmental advantage of variable-rate management.

9.4 Case Study

In previous results (Chapter 8) it was shown that utilizing the strategies optimum uniform management (OUM) and variable-rate management (VRM) have the potential to reduce nitrogen left in the soil compared to the current uniform management (CUM). However, all strategies did not show major differences concerning the amount of available nitrogen left in the soil after harvest and almost no differences in the amount of nitrate leached during the growing season. Thus, the positive environmental improvement from variable-rate nitrogen application seems to be relatively modest compared to uniform treatment, which is similar to results of Pedersen (2003). However, in studies of Eghball et al. (2003) and Derby et al. (2004) it was found that a reduced nitrogen application rate resulted in basically similar corn grain yields compared to a full rate application but reduced amounts of residual soil nitrogen. Thus, the risk of nitrogen leaching due to excess nitrate was minimized and profits of the producer increased by a reduction of input costs.

As indicated in the international literature, weather patterns have a major impact on the optimum nitrogen fertilization strategy (Blackmer et al., 1997; McBratney and Whelan, 1999; Mamo et al., 2003). Therefore in the following approach in addition to yield expectations, management, soil properties, and weather conditions were integrated into the development of an optimum nitrogen prescription for the experimental site Weisweil in the Upper Rhine Valley.

The Upper Rhine Valley belongs to one of the most important drinking water areas in Germany. The intense agricultural land use had negative effects on the quality of drinking water in this region (BUND, 2003). In order to implement a European law (EC-Council Directive, 1991), which was passed to protect the groundwater body against pollution from agriculture, the Government of Baden-Württemberg passed a law in 1987 (SchALVO, Ministerium für Umwelt Baden-Württemberg, 1987) and determined a threshold for nitrogen left in the soil after harvest of about 45 kg N ha^{-1}. For the development of adapted nitrogen fertilization strategies, the regulations of the SchALVO were taken into consideration, as well as were the local weather conditions.

The mean annual precipitation in the Weisweil region varied between 696 and 1110 mm over the 28-year period (1976-2003). Due to temporal changes in weather patterns over such a long period in some years only 76 % of the mean precipitation occurred, whereat in other years more than 122 % of the mean precipitation was obtained. Taking the differences in these weather patterns into account, an optimum nitrogen fertilization strategy was developed based on different ranges of annual precipitation. A case study was carried out dividing the 28-years of weather data into a) dry years with a annual precipitation less than 800 mm, b) normal years with an annual precipitation in a range from 800-1000 mm and c) wet years with an annual precipitation above 1000 mm. Optimum nitrogen prescriptions were developed for the three types of weather scenarios, taking the two different nitrogen application strategies current uniform management (CUM) and variable-rate management (VRM) into consideration. The CUM was developed based on actual management strategies on the field in Weisweil, whereas the VRM was designed in consideration of maximizing the marginal net return (MNR) for each grid over the whole field (Chapter 8). Thus different nitrogen application rates were simulated for each grid.

9.4.1 Nitrate Leaching

The mean nitrogen application rate of 140 kg N ha^{-1} was assumed for CUM over all three different weather scenarios. In contrast the optimum nitrogen fertilization strategies for the VRM depended on the weather pattern. Generally, the optimum nitrogen application rate of the VRM was lower for dry seasons, compared to normal or wet seasons. For a dry season the optimum VRM was 100 kg N ha^{-1} on average. Within the field the optimum VRM would imply nitrogen application rates from 75 up to 110 kg N ha^{-1} (Table 22). For a normal season the optimum VRM was 101 kg N ha^{-1} on average, whereat for single grids the optimum nitrogen application rate would range between 85 kg N ha^{-1} and 125 kg N ha^{-1} (Table 22). However, the optimum VRM for a wet season required nitrogen application rates for single grids in a range of 110 kg N ha^{-1} to 145 kg N ha^{-1} (Table 22). On average 127 kg N ha^{-1} were applied for the optimum VRM. The results support the studies of Mamo et al. (2003) who showed that variable-rate nitrogen recommendations might vary depending on the growing season, which means the knowledge of the existing environmental conditions and possible future weather is very important.

The different nitrogen application rates of CUM and VRM also affected corn grain yield (Table 22). The difficulty of a reduction in nitrogen application rate without reducing yield substantially was discussed by Welch et al. (1999). In general the simulated mean corn grain yield for dry seasons was lower than for normal and wet seasons, whereupon the mean corn grain yield of the CUM was increased compared to the mean corn grain yield in the VRM. However, “crop producers with a high degree of spatial soil variation on their fields might be able to both improve yields and reduce nitrate leaching on their fields with PF but the majority of producers are likely to make little or no improvements of nitrate leaching with variable-rate treatment” (Pedersen, 2003).

Table 22. Current uniform management (CUM) and variable-rate management (VRM) in consideration of the three weather scenarios and the resulting corn grain yield, amount of nitrogen left in soil after harvest and marginal net return (MNR).

	Weather scenario	Nitrogen application rate	Yield	Nitrogen left in soil in 0-90 cm	MNR
		(kg N ha^{-1})	(kg ha^{-1})	(kg N ha^{-1})	(€ ha^{-1})
CUM	**Dry**	140	4879 4084 - 5942	31 20 - 44	687 537 - 866
VRM	**Dry**	100 75 - 110	4741 3800 - 5838	21 16 - 28	730 591 - 877
CUM	**Normal**	140	5641 4990 - 6314	26 16 - 38	799 684 - 915
VRM	**Normal**	101 85 - 125	5589 5001 - 6314	15 13 - 19	847 776 - 924
CUM	**Wet**	140	6951 5791 - 7944	25 13 - 56	996 857 - 1131
VRM	**Wet**	127 110 - 145	6916 5757 - 7980	24 13 - 53	997 857 - 1131

P_{N3} = 0.83 € kg^{-1}

In this case study it was obvious, that the amount of nitrate left in the soil after harvest could be reduced tremendously, when VRM was implemented instead of CUM (Table 22). However, because of only small differences concerning the mean nitrogen application rate of CUM and VRM in wet years, this effect was narrowed. In wet years the mean amount of nitrogen left in the soil under CUM and VRM was 25 kg N ha^{-1} on average and 24 kg N ha^{-1} on average, respectively. For single grids the values ranged from 13 to 56 kg N ha^{-1} in the CUM and from 13 to 53 kg N ha^{-1} in the VRM. For seasons with normal precipitation, the mean amount of nitrogen left in the soil for CUM was slightly increased compared to wet seasons (26 kg N ha^{-1}). In contrast the VRM led to a reduction of nitrogen in the soil of about 10 kg N ha^{-1}, resulting in a mean of 15 kg N ha^{-1} after harvest (Table 22). Similar to the normal season, the difference in nitrogen left in the soil between CUM and VRM was about 10 kg N ha^{-1} in a dry season. The mean amount of nitrogen left in the soil, was simulated as 31 kg N ha^{-1} for a dry season in the CUM, ranging from 20-40 kg N ha^{-1}. In the VRM the mean simulated amount was 21 kg N ha^{-1}. For single grids the nitrogen left in the soil varied between 16 and 28 kg N ha^{-1}. Similar results were determined by Mavromatis et al. (2002), who found greater nitrogen leaching when the growing season was followed by a wet season (El Niño), compared to drier seasons (La Niña). Therefore Mavromatis et al. (2002) proposed that adapted nitrogen fertilization strategy might be most advantageous in wet seasons, resulting in higher yields and lower nitrate leaching when compared to the other nitrogen fertilization strategies. At the same time, the response to nitrogen fertilization strategies was found to be little in drier years. These results support the suggestion of several other studies, who pointed out the importance of knowledge about the weather conditions in order to optimize production, to improve yield response and to minimize the negative environmental impact (Pedersen, 2003; Dobermann et al., 2004).

In this study it was also obvious, that there is still potential to increase the income for the producer. The calculation of marginal net return (MNR) for each scenario showed that, the VRM was more favorable from an economic point of view than the CUM. As long as the additional costs are below the additional gain in yield or reduction in fertilizer application the variable-rate management will be economically feasible (Ferguson and Hergert, 1999; Thrikawala et al., 1999). In order to determine if the producer is able to spend money for investigation in variable-rate technology at all, the differences in MNR between the CUM and VRM were computed. The additional profit provided a clear picture of the level of profitability that a producer can achieve given a particular prescription. For this case the advantageous of VRM was mainly during dry and normal seasons, but not for the wet seasons. In a dry or normal season, the additional profit was 43 € ha^{-1} and 48 € ha^{-1}, respectively. For a wet season the additional profit from VRM compared to the CUM was only about 1-2 € ha^{-1}, which hardly can warrant the additional costs associated with the VRM.

In order to conduct grid soil sampling, the producer is faced with yearly expenses of about 7 € ha^{-1} (Pedersen, 2003). Performing advanced technologies, like the use of the N-sensor, would total about 9 € ha^{-1} $year^{-1}$ (Pedersen, 2003). This calculation includes the costs for gathering the information, but does not include cost for the dGPS receivers, the variable-rate management and the costs for additional software. The total costs of implementing variable-rate management on a farm with 100 ha is stated by Pedersen (2003) as about 66 € ha^{-1} $year^{-1}$. According to Pedersen (2003) for a farm with a total size of 500 ha arable land, the total cost of implementing variable-rate management would lead to yearly expenses of about 32 € ha^{-1} $year^{-1}$. Due to this, the possibility of VRM did not seem to be feasible for producers in this region with small-scaled fields, and an average farm size of less than 20 ha. Building cooperation between the producers to share the costs and the equipment could increase the economic feasibility of VRM in such a region. However, the amount of soil available nitrogen left in the soil was reduced in VRM compared to CUM, which would argue for the implementation of VRM on this field.

9.4.2 Nitrous Oxide Emissions

In this study we were not able to measure nitrogen fluxes in the on-farm study. Measurements of nitrous oxides fluxes are complicated, time consuming and require the installation of closed-chambers. Discontinuous measurements of nitrous oxide fluxes often result in overestimation (Brumme and Beese, 1992) or underestimation (Scott et al., 1999) of the total nitrous oxide emissions. In order to determine the impact of PF and especially adapted nitrogen fertilizer strategies on gaseous nitrogen losses, the cumulative denitrification (kg N ha^{-1}) was simulated. To determine the optimization potential of nitrogen application concerning gaseous nitrogen losses, different strategies (CUM and VRM) were simulated in consideration of three different weather patterns. The simulation was performed using the DSSAT 4.0 model, which provides a detailed output for denitrification and ammonia volatilization in the field. In studies of Sehy (2004), the denitrification was indicated as the main source for nitrous oxide, and therefore cumulative denitrification was used in this study as dimension of possible nitrous oxides emissions.

In order to estimate the potential reduction of gaseous nitrogen losses by implementing VRM instead of CUM, the denitrification rate was simulated for both strategies. The CUM was assumed to consist of a constant nitrogen rate of 140 kg N ha^{-1} over all weather pattern, whereas the nitrogen rate in VRM was adapted to dry, normal and wet growing seasons, as described above. The mean denitrification rate on field level for both strategies and different weather pattern is shown in the following section, whereas single years (1990, 1986, 2001) were selected in order to demonstrate dry, normal and wet growing seasons.

Figure 34 shows the simulated cumulative denitrification in a dry season for the CUM and the VRM, respectively. The denitrification rose slowly for both scenarios until July, and increased to about 50 % over the following period, which might be caused by the second fertilizer application in June mainly. The mean application rate of CUM (140 kg N ha^{-1}) and VRM (100 kg N ha^{-1}) differed by 40 kg N ha^{-1}. These differences between the two application strategies were visible in the denitrification rate.

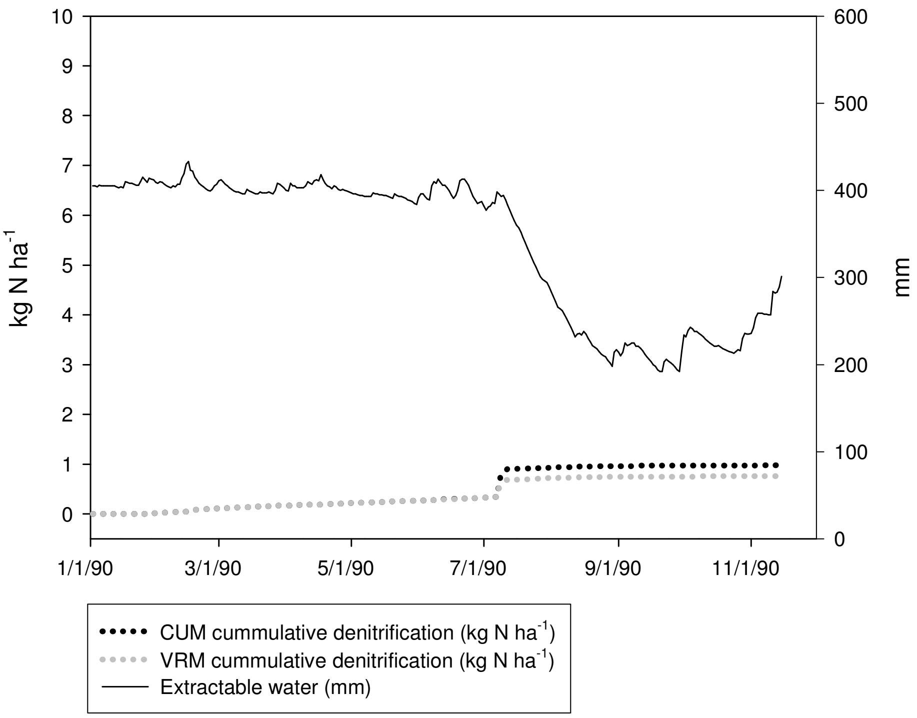

Figure 34. Simulation of cumulative denitrification (kg N ha^{-1}) over the growing season 1990 for current uniform management (CUM) and variable-rate management (VRM), which was adapted to a dry season (annual precipitation < 800 mm).

Due to missing precipitation the availability of extractable water decreased dramatically. Decreased soil water content was associated with higher oxygen content in the soil, resulting in a lower denitrification rate at the end of the season. Thus, the simulated cumulative denitrification in the dry growing season 1990 was assumed with 0.98 kg N ha^{-1} for CUM and 0.76 kg N ha^{-1}.

The year 1986 was selected to demonstrate the cumulative denitrification for a growing season with an annual precipitation of 800–1000 mm, representing a normal season (Figure 35). Compared to the dry season the denitrification rate in a normal season rose steeper over the whole year. Similar to the previous results a leap was shown in July, about three weeks after the second fertilizer application. Similar as in the previous results the denitrification rate increased obviously after the fertilizer application. The application rate for CUM was 140 kg N ha^{-1}, in contrast the mean application rate for VRM was 101 kg N ha^{-1} for a normal season. The difference of 39 kg N ha^{-1} applied, resulted in different denitrification rates from the beginning of July. However, the trend of denitrification was similar for both strategies. The simulated cumulative denitrification for a normal season constituted 2.28 kg N ha^{-1} for CUM and 2.04 kg N ha^{-1} for VRM.

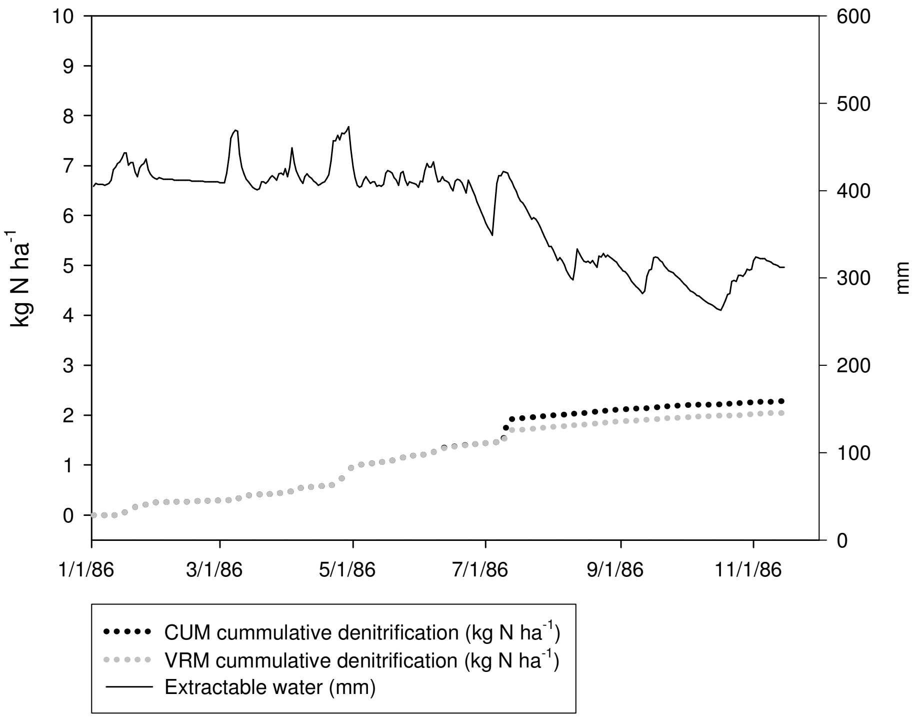

Figure 35. Simulation of cumulative denitrification (kg N ha^{-1}) over the growing season 1986 for current uniform management (CUM) and variable-rate management (VRM), which was adapted to a normal season (annual precipitation of 800-1000 mm).

The simulated cumulative denitrification for a wet year, in this case year 2001, is shown in Figure 36. The denitrification rate for the year 2001 rose continuously from the beginning of the simulation start, whereat the rise was steeper than in the calculations for dry and normal seasons. Due to the higher level of denitrification the leap after the nitrogen application was less intense, compared to previous results. At the same time the differences between the two management strategies were less distinctive. This was expected, because the mean nitrogen application rates for CUM and VRM were almost the same, with totally 140 kg N ha^{-1} and totally 127 kg N ha^{-1}, respectively. The negligible differences between the nitrogen rates of both application strategies, led to small differences of cumulative denitrification. For CUM about 5.25 kg N ha^{-1} were transformed via denitrification, whereas for VRM about 5.04 kg N ha^{-1} were build over the growing season 2001. In studies of Sehy (2004) measured cumulative nitrous oxide emissions in the field reached values of 4.0 kg N ha^{-1} $year^{-1}$ and 8.0 kg N ha^{-1} $year^{-1}$. Thus, the simulated values of denitrification were in the range of measured values indicating the suitability of a modeling approach for the estimation of gaseous nitrogen losses.

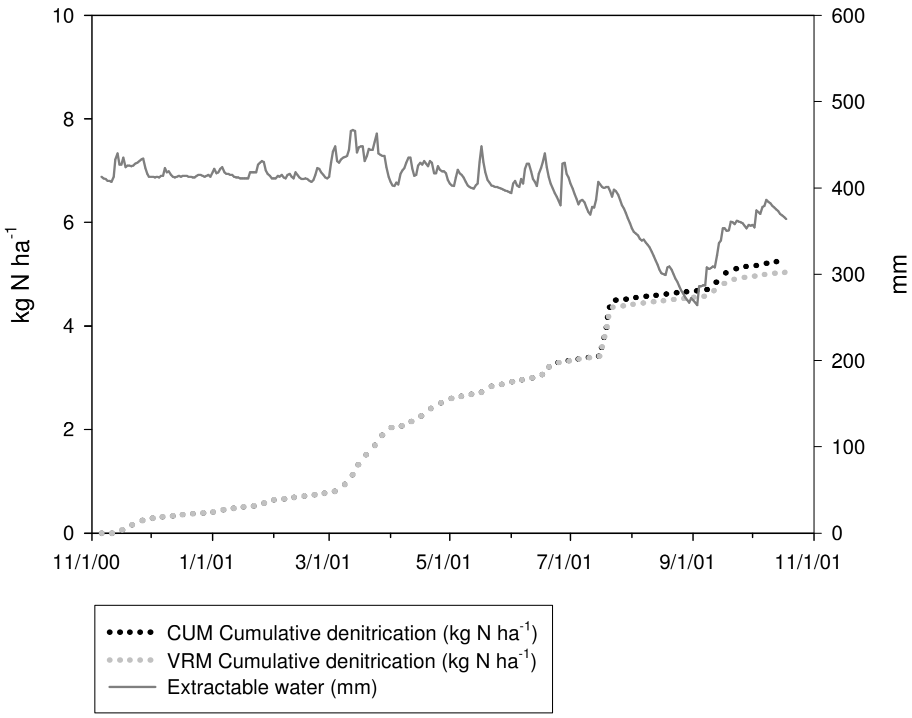

Figure 36. Simulation of cumulative denitrification (kg N ha^{-1}) over the growing season 2001 for current uniform management (CUM) and variable-rate management (VRM), which was adapted to a wet season (annual precipitation > 1000 mm).

These results indicated different cumulative denitrification rates in dependency of the weather pattern, which is widely described in the international literature. In general lower denitrification rates were found in drier seasons, when the soil oxygen content was increased. In a dry year about 0.8 % of the applied nitrogen was transformed by denitrification to nitrous oxide for CUM and VRM. Similar results were found by Flessa et al. (2002), who declared the annual nitrous oxide emissions of applied nitrogen from arable land with 0.5 kg N_2O-N ha^{-1} $year^{-1}$ in Bavaria, Germany. However, in the normal and wet years the percentage rate was increased. In the normal year about 1.8 % and 2.1 % of the applied nitrogen was built into nitrous oxide for CUM and VRM, respectively. In the scenario for a wet season the values was doubled and constituted for CUM 4.0 % and for VRM 4.1 %.

However, the cumulative denitrification rate was found to be reduced for VRM. Sehy (2004) attributed the lowered cumulative denitrification in VRM to the reduced denitrification in the low yielding areas of a field (up to 34 %), whereas in high yielding areas the emission rate of site-specific and conventional fertilization were almost at the same level. Sehy (2004) attributed this effect to higher water availability in the high yielding areas. Otherwise, when the nitrate concentration exceeds a specific threshold it does not directly influence the amount of nitrous emissions anymore (Limmer and Steele, 1982). Thus, denitrification rates above values of 10.0 mg NO_2-N kg^{-1} (Mosier et al., 1983) and 25.0 mg NO_2-N kg^{-1} (Limmer and Steele, 1982), respectively were independent of the available nitrate in the soil.

9.5 Potential to Optimize Nitrogen Fertilization Strategies

Recapitulating the results this case study indicated a positive impact of variable-rate management on the environmental quality compared to current uniform management. However, the region of the Upper Rhine Valley does not posses the typical agricultural structure to implement PF technologies. Normally, each of the numerous small-scaled fields is managed uniformly and fertilizer application rates could be adapted among the fields. Thus, the implementation of PF technologies seems to be less economic feasible for such an agricultural structure. However, all three experimental sites in Weisweil offered high and low yielding areas within the field, indicating spatially variable response to nitrogen. Due to the spatial and temporal variability of corn grain yield, different nitrogen rates were found for each grid to be optimum. In this case study the VRM was developed on a grid basis. At the same time it was not followed by maximizing the yield in each grid, but by maximizing the MNR for each grid. Based on this assumption the optimum VRM was associated with lower mean nitrogen application rates than the CUM. Although the mean CUM on the three fields did not reach as high nitrogen inputs as shown in other regions with intense agricultural production, shifting the nitrogen application strategy from CUM to an optimum VRM affected the environmental quality. For VRM the nitrogen application rate was adapted to the spatial yield variability within the field, matching the demand of the plants with the supply of nitrogen fertilizer. The positive effect of VRM was pointed out enhanced, when the nitrogen application rate was developed in consideration of different weather patterns. As shown in the case study, the implementation of VRM decreased the potential of nitrogen leaching by up to 30 % (in dry years).

A positive effect of VRM was also obvious, when the cumulative denitrification was taken into consideration. According to the nitrogen amount the contribution of VRM to a reduction of cumulative denitrification was less. In contrast to CUM a positive impact of VRM was obvious. In the dry season, due to VRM the cumulative denitrification over the growing season was decreased by about 22 %. In a normal season the potential reduction of cumulative denitrification was simulated with 11 % and 4 %, respectively.

Thus, the results of this case study suggest, that implementing VRM could lead to a reduction of nitrogen losses, as long as nitrogen leaching and nitrogen emission could be minimized. Therefore even in regions with small-scaled fields and moderate nitrogen application rates the additional requirements and costs for VRM to be warrantable, especially in the view of the described potential of adapted fertilization strategies to minimize nitrogen losses to groundwater and atmosphere.

It is obvious that the optimization potential of a nitrogen fertilization strategy depends on the cropping system it was built for. In 2004 the area of corn production in entire Germany was extended to about 1710165 ha, which equals and increase of 4.5 % compared to the previous year 2003 (Deutsches Maiskomitee, 2005). In the entire area of Germany silage was produced on about 1248468 ha and corn for grain yield on about 370022 ha in 2004 (Deutsches Maiskomitee, 2005). Corn for grain yield is mainly produced in the southwestern part of Germany, whereas silage is grown all over the country.

In general the optimization potential due to site-specific management would be lowered for regions with more homogenous fields and increased for heterogeneous field structure. This is simply based on the fact, that on a homogenous field structure the magnitude of low yielding and high yielding areas can not be as distinctive as expected for a heterogeneous field. For the same reason the advantageousness of optimized nitrogen fertilization strategies could easily be increased on large-scaled fields compared to small-scaled fields. Due to this fact and the economic point of view, the PF technology is mainly implemented on large-scaled fields, like in the Eastern part of Germany. Although there might be an optimization potential for small-scaled fields, the implementation of PF technology is less common.

Due to the nitrogen sensitive area in the Upper Rhine Valley, the nitrogen application rates had to be reduced over the last decades. Thus the current nitrogen application rate is somehow about 120 kg N ha^{-1}, whereat in other regions in Germany or all over the world nitrogen applications rates are twice as much. Under high input conditions the risk of nitrogen losses is increased and thus the optimization potential for site-specific nitrogen application rates, too. Ferguson et al. (2002) reported target nitrogen application rates of 202 kg N ha^{-1} for Nebraska, which belongs to the corn belt of the United States. However, an adaptation of nitrogen application rates in the study of Ferguson et al. (2002) did not significantly reduce amount of nitrogen left in the soil.

The optimization potential also depends on the soil type. On soils with coarser soil texture, nitrogen losses to groundwater are more likely, whereat on soils with finer soil texture the transport of nitrogen into the deeper soil layers is less intense. Thus the implication of an optimized nitrogen fertilization strategy seems to be more useful for soils with coarser soil texture.

In this study it also was obvious, that the weather patterns strongly influenced the optimization potential for adapted nitrogen fertilization strategies to reduce nitrogen losses. When the nitrogen application strategy in a normal season is splitted and thus matches the nitrogen demand of the plant, the optimization potential for adapted fertilization strategies was less pronounced. However, especially in dry seasons, when the nitrogen uptake of the plant is reduced due to e.g. water stress, a current nitrogen application strategy could lead to increased risks for nitrate leaching, because much of the applied nitrogen remains in the soil. Aside, an optimized nitrogen application strategy could be able to avoid increased amounts of nitrogen left in the soil after harvest.

Overall, those considerations imply that the optimization potential of nitrogen fertilization strategies might vary across different corn cropping systems. In dependency of the management practices, soil and weather the possibilities to optimize the nitrogen fertilization strategy in order to reduce nitrogen losses might be increased or reduced. Thus, up scaling the effect of optimized nitrogen fertilization strategies has to be done in consideration of the cropping system and of site characteristics. Both vary widely across regional, national and international scales. Overall, the results of this study indicated that there exists a potential for nitrogen fertilization strategies to be optimized, leading to lower nitrogen losses and more environmentally sound corn cropping systems.

9.6 Recommendation for Further Research

The results of this study pointed out the possibility to use crop growth models in order to develop variable-rate fertilizer strategies. The implementation of the crop growth model formed the basis of developing adapted nitrogen fertilization strategies in consideration of underlying yield-limiting factors. However, modeling complex systems requires good and valuable information about the basis securities. In this context the plausibility of the model needs to be tested in further research. One focus should be drawn on the developed nitrogen fertilization strategies, whereat the other focus should be drawn on the indicated yield-limiting factors.

Thus, in future research the developed nitrogen fertilization strategies using the crop growth model should be realized and tested with regard to the reduction of nitrogen losses. Additionally, there is a need to validate the model in consideration of the indicated yield-limiting factors, like a restrictive layer or a bounded rooting depth. Because the results of this study indicated an increased optimization potential for nitrate leaching, the main attention should be on this topic. The positive effects of variable-rate nitrogen fertilization strategies on reducing nitrous oxides emissions seem to be limited.

10 Summary

The aim of this study was the "Investigation and Modeling of the Optimization Potential of Adapted Nitrogen Fertilization Strategies in Corn Cropping Systems with Regard to Minimize Nitrogen Losses". The background for the investigation could be seen in the increasing number of environmental pollution by agricultural land use. The dissertation was embedded in the context of the Graduiertenkolleg "Strategies to Reduce the Emission of Greenhouse Gases and Environmental Toxic Agents from Agriculture and Land Use" at the University of Hohenheim. The objective of this Graduiertenkolleg was to develop methods for quantifying and modeling the origin and the emission of greenhouse gases and environmentally toxic agents from agriculture and land use and for assessing them economically in the sense of practicable avoidance strategies. In order to determine the optimization potential of adapted nitrogen fertilization strategies in corn the study was organized in the following parts:

1. Investigation of the spatial variability and temporal stability of corn grain yield on three fields in the Upper Rhine Valley (Chapter 5 and 7),
2. Determination of underlying yield-limiting factors in each field by the use of simple and complex models (Chapter 7),
3. Development of adapted nitrogen fertilization strategies in consideration of the yield variability and the underlying yield-limiting factors (Chapter 8).

The area of investigation was located in the Upper Rhine Valley, which is characterized as a region with intense corn cultivation. At the same time this region belongs to the most important water protection areas in Europe. Thus, a conflict between agricultural land use associated with high fertilizer inputs on one hand and the protection of water bodies on the other hand rose, because measured nitrate concentrations in the groundwater increased constantly within the last decades (Chapter 1).

The study was conducted on three farm fields (I1, I2, I3) in the boundary of Weisweil, which is located northwest of Freiburg, Germany (Chapter 3). Since 1998 the three fields were planted continuously with corn. In a 7-year field experiment spatial variability and stability of yield could be indicated (Chapter 5). The determined yield pattern in each field raised assumptions about varying growth conditions within and among the fields. Thus, on the one hand the corn yield seemed to be influenced by temporal variations in cultivar, climate and management and by spatial and temporal variation of possible yield-limiting factors like nutrient availability or water supply on the other hand. In order to optimize management strategies (i.e. nitrogen application) the underlying yield-limiting factors causing the spatial and temporal yield variability needed to be determined in these three fields (Chapter 5 and 7).

Whereas plant yield parameters did not explain the existing yield variability very well, soil characteristics were identified as the major factors affecting the observed yield

variability in all three fields. Significant relationships were found between combinations of soil nutrient levels, soil characteristics and yield (Chapter 5). Based on these results, it appeared that soil characteristics were the primary factor affecting spatial yield variability in the three farmer fields in the Upper Rhine Valley. However, some of the spatial yield variability remained unexplained by simple regression analysis (Chapter 5).

In a more complex approach crop growth models were implemented to simulate the spatial yield variability within the field and to get information about the underlying yield-limiting factors (Chapter 7). Therefore the process-oriented crop growth model APOLLO was implemented to evaluate the causes of spatial yield variability of corn in the three fields. APOLLO (Application of Precision Agriculture for Field Management Optimization) is a precision farming decision support system, which is based on the CERES and CROPGRO family of crop growth models and includes different soil parameter to calibrate the model. In general the APOLLO model performed well in simulating spatial yield variability in the fields. The results indicated that the spatial yield variability was mainly affected by a varying restrictive layers and reduction of root growth within the three fields (Chapter 7). The correlation between simulated and measured yields provided information about the strength of the soil parameter affecting the yield within these fields. The calibration results were influenced by the grid size. Whereas smaller grids provided more random monitor yield data, larger grids provided a more representative set of yield monitor data, due to the coverage of a larger area. Consequently, the APOLLO model performed better when yields belonging to larger grids were used for model calibration (Chapter 7).

The applicability of the APOLLO model can be extended by developing prescriptions for different management strategies and thus enhancing the possibilities of successfully implementing site-specific management strategies. Thus, APOLLO was used to simulate the current uniform nitrogen management strategy of the producers in Weisweil over a 28-year period. Additionally an optimum uniform management and an optimum variable-rate management were developed and simulated. For these strategies also the different weather pattern were taken into account. All three strategies were evaluated based on the simulated yield, the simulated leaching potential and the simulated economics (Chapter 8). It was obvious, that variable-rate nitrogen fertilization strategies were most advantageous compared to the other strategies, especially, when the nitrogen application rates were differentiated for dry, normal and wet weather scenarios. Adapted nitrogen fertilization strategies, as optimum uniform management and variable-rate management indicated a potential to reduce the amount of nitrogen, which is left in the soil after harvest, and associated that the potential nitrate leaching was reduced. In a case study the cumulative denitrification under these weather and fertilization scenarios over the growing season was simulated. The results indicated a reduction of cumulative denitrification under adapted fertilization strategies when compared to current uniform management (Chapter 8 and 9).

Summarizing, the results of this study suggest, that the implementation of adapted fertilization strategies (especially the variable-rate management of nitrogen) could lead to a reduction of nitrogen losses, as nitrogen leaching and nitrogen emissions could be minimized. Generally, the optimization potential for adapted nitrogen fertilizer strategies (optimum uniform management and variable-rate management) could be improved for cropping systems that were associated with higher risk for nitrogen losses.

11 Zusammenfassung

Das Ziel der Arbeit war die "Untersuchung und Modellierung des Optimierungspotentials von angepassten Stickstoff-Düngungsstrategien in Mais Anbausystemen in Hinblick auf Stickstoffverluste". Der Hintergrund der Arbeit liegt in der steigenden Umweltbelastung durch die Landbewirtschaftung. Aus diesem Grund war die Dissertation in den Kontext des Graduiertenkollegs „Strategien zur Vermeidung der Emission klimarelevanter Gase und umwelttoxischer Stoffe aus Landwirtschaft und Landschaftsnutzung" an der Universität Hohenheim eingegliedert. Die Zielsetzung des Graduiertenkollegs war die Entwicklung von Methoden zur Quantifizierung und die Modellierung der Entstehung und der Emission von klimarelevanten Gasen und umwelttoxischen Stoffen aus der Landwirtschaft und Landnutzung und die ökonomische Bewertung praktikabler Vermeindungsstrategien. Um das Optimierungspotential von angepassten Stickstoff-Düngungsstrategien in Mais zu ermitteln, wurde die Arbeit wurde folgendermaßen gegliedert:

1. Untersuchung der räumlichen Variabilität und zeitlichen Stabilität von Maiserträgen auf drei Schlägen im Oberrheingraben (Kapitel 5),
2. Ermittlung der zu Grunde liegenden ertragslimitierenden Faktoren in allen Schlägen mittels einfacher und komplexer Modelle (Kapitel 7),
3. Entwicklung angepasster Stickstoffdüngestrategien unter der Berücksichtigung von Ertragsvariabilität und den ertragslimitierender Faktoren (Kapitel 8).

Das Untersuchungsgebiet war im Oberrheingraben angesiedelt, welches als eine Region intensiver Maisproduktion gekennzeichnet ist. Gleichzeitig gehört die Region entlang des Rheins zu den bedeutendsten Trinkwassergebieten Europa. Daraus ergaben sich in den letzten Jahrzehnten der Konflikt zwischen intensiver Landbewirtschaftung verbunden mit hohen Einträgen an Düngemitteln auf der einen Seite und der Schutz der Grundwasservorkommen auf der anderen Seite (Kapitel 1).

Die Untersuchungen wurden auf drei Praxisschläge bei Weisweil nordwestlich von Freiburg, Deutschland, durchgeführt (Kapitel 3). Auf allen drei Schlägen wurde seit 1998 Mais in Monokultur angebaut. In den Untersuchungen im Oberrheingraben konnte eine räumliche und zeitliche Variabilität der Kornerträge ermittelt werden (Kapitel 5). Die unterschiedlichen Ertragsmuster in jedem Schlag lassen ertragslimitierende Wachstumsbedingungen vermuten. Einerseits schien der Ertrag beeinflusst durch die zeitliche Variation von Sorte, Klima und Management, sowie durch räumlich Variation möglicher ertragslimitierender Faktoren, wie Nährstoff- und Wasserverfügbarkeit auf der anderen Seite. Um die Managementstrategien (Stickstoffdüngung) anzupassen, müssen die zu Grunde liegenden ertragslimitierenden Faktoren innerhalb der drei Schläge ermittelt werden (Kapitel 5 und 7).

Über die erfassten Pflanzenparameter konnte die gemessene Ertragsvariabilität nicht erklärt werden, wohingegen Korrelationen zwischen Bodeneigenschaften und den ermittelten Ertragsvariabilitäten innerhalb der drei Schläge gezeigt werden konnten. Signifikante Zusammenhänge wurden zwischen Bodennährstoffen, Bodeneigenschaften und dem Ertrag ermittelt (Kapitel 5). Aufgrund dieser Ergebnisse scheinen die Bodeneigenschaften die Haupteinflussfaktoren für die gemessene Ertragsvariabilität auf den drei Schlägen im Oberrheingraben zu sein. Trotz allem konnte über einfache Regressionsmodelle nur ein Teil der Ertragsvariabilität erklärt warden (Kapitel 5).

In einem nächsten Schritt wurden komplexe Wachstumsmodelle eingesetzt, um die Ertragsvariabilität innerhalb der Schläge zu simulieren und die zu Grunde liegenden Faktoren zu ermitteln (Kapitel 7). Das eingesetzte prozess-orientierte Modell APOLLO (Application of Precision Agriculture for Field Management Optimization) wurde auf Grundlagen von CERES und CROPGRO entwickelt. Innerhalb des Modells könnten unterschiedliche Bodeneigenschaften angepasst werden und somit das Modell kalibriert werden. Die Ergebnisse haben gezeigt, dass mittels APOLLO die Ertragsvariabilität gut wider gegeben werden kann. Als Ursachen für die Variabilität wurden vor allem Unterschiede in der Bodenverdichtung und der Durchwurzelbarkeit des Bodens angenommen (Kapitel 7). Die Korrelationen zwischen simuliertem und gemessenem Ertrag geben Auskunft über die Ausprägung der ertragslimitierenden Faktoren. Die Kalibrierung war unter anderem abhängig von der gewählten Größe der Grids. Kleine Grids konnte die Ertragsvariabilität stärker abbilden, wohingegen größere Grids die Ertragsmuster deutlich wiedergaben. Infolge dessen konnte eine bessere Kalibrierung des Modells erzielt werden, wenn die Erträge aus größeren Grids zu Grunde gelegt wurden (Kapitel 7).

Das APOLLO-Modell wurde des Weiteren auch zur Entwicklung der Stickstoff-Düngeempfehlung eingesetzt. Über einen Zeitraum von 28 Jahren wurde die aktuelle Stickstoff Düngestrategie der Landwirte simuliert. Zusätzlich wurden über das APOLLO-Modell auch eine optimierte einheitliche und eine optimierte variable Stickstoff-Düngestrategien entwickelt. Die Düngestrategien wurden unter Berücksichtigung von langjährigen Wetterverhältnissen (28 Jahre) untersucht. Die Strategien wurden anhand von simuliertem Ertrag, simulierter Nitratauswaschung und simulierten ökonomischen Gesichtspunkten bewertet (Kapitel 8). Dabei wurde deutlich dass die angepassten Düngestrategien (optimiertes einheitliches Management und variable angepasstes Management) gegenüber der aktuellen Düngestrategie von Vorteil waren. Insbesondere dann, wenn die Düngestrategien für unterschiedliche Wetterbedingungen (Trocken, normal und nasse Jahre) entwickelt wurden. Die angepassten Düngestrategien führten zu einer Reduzierung des Reststickstoffes im Boden und somit zu einem verringerten Risiko der Nitratauswaschung. Auch für die gasförmigen Stickstoffverluste konnte in Optimierungspotential ermittelt werden. Die Ergebnisse zeigten eine verringerte kumulative Denitrifizierungsrate unter angepasster Düngestrategie verglichen mit der aktuellen Düngestrategie (Kapitel 8 and 9).

Zusammenfassend kann gesagt werden, dass die Anwendung einer angepassten Düngestrategie (optimiertes einheitliches Management und variable angepasstes

Management) zu einer Reduzierung von Stickstoffverlusten, in Form von Nitratauswaschung und Stickstoffemissionen führen kann. Generell, ist das Optimierungspotential aber abhängig vom jeweiligen Anbausystem und damit größer, wenn ein Anbausystem einem gesteigerten Verlustpotential für Stickstoff unterliegt.

12 References

Addiscott, T.M. 1993. Simulation modeling and soil behavior. Geoderma. 60, 15-40.

Addiscott, T.M., Whitmore, A.P., Powlson, D.S. 1991. Farming, Fertilizers and the Nitrate Problem. CAB International, Wallingford UK. 170 pp.

Angus, J.F., Bowden, J.W., Keating, B.A. 1993. Modeling nutrient responses in the field. Plant Soil. 155/156, 57–66.

APSRU. 2004. http://www.apsru.gov.au/apsru/Products/apsim.htm

Arah, J.R.M., Smith, K.A. 1990. Factors influencing the fraction of the gaseous products of soil denitrification evolved to the atmosphere as nitrous oxide. In: Bouwman, A.F. (Ed.), Soils and the Greenhouse Effect. John Wiley and Sons, New York. pp. 475–480.

Arslan, S., Colvin, T.S. 2002. Grain yield mapping: Yield sensing, yield reconstruction, and errors. Presic. Agric. 3, 135-154.

Arvidsson, J., Håkansson, I. 1996. Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. Soil Tillage Res. 39, 175-197.

Asmus, F. 1993. Anwendung von Festmist und Jauche im Pflanzenbau. In: Umweltverträgliche Verwertung von Festmist, KTBL-Arbeitspapier Nr 182. pp. 32-44.

Babcock, B.A., Pautsch, G.R. 1998. Moving from uniform to variable fertilizer rates on Iowa corn: Effects on rates and returns. J. Agr. and Resour. Econ. 23 (2), 385-400.

Bach, M. 1987. Die potentielle Nitratbelastung des Sickerwassers durch die Landwirtschaft in der Bundesrepublik Deutschland. Gött. Bodenkd. Ber. 93, 1-186.

Batchelor, W.D., Paz, J.O., Thorp, K.R. 2004a. Development and evaluation of a decision support system for precision farming. In: Proceedings of the 7th International Conference on Precision Agriculture. July 25-28, 2004. Minneapolis, MN. ASA, CSSA, and SSSA, Madison, WI, USA.

Batchelor, W.D., Link, E.J., Thorp, K.R., Graeff, S., Paz, J.O. 2004b. The role of crop growth models in precision farming. Workshop Precision Farming, May 13, Renningen, Germany. Pp. 11-16.

Batchelor, W.D., Basso, B., Paz, J.O. 2002. Examples of strategies to analyze spatial and temporal yield variability using crop models. Europ. J. Agron. 18, 141-158.

Behrendt, H., Bach, M., Kunkel, R., Opitz, D., Pagenkopf, W.-G., Scholz, G., Wendland, F. 2002. Quantifizierung der Nährstoffeinträge der Flussgebiete Deutschlands auf der Grundlage eines harmonisierten Vorgehens. UFO-Plan des BMU Forschungsberichts 29922285, Abschlussbericht.

Benbi, D.K., Nieder, R. 2003a. Introduction. In: Benbi, D.K., Nieder, R. (Eds.), Handbook of Processes and Modeling in the Soil-Plant System, Haworth Press, Inc., New York. pp. 1-4.

Benbi, D.K., Richter, J. 2003b. Nitrogen Dynamics. In: Benbi, D.K., Nieder, R. (Eds.), Handbook of Processes and Modeling in the Soil-Plant System, Haworth Press, Inc., New York. pp. 409-481.

Bernardos, J.N., Viglizzo, E.F., Jouvet, V., Lértora, F.A., Pordomingo, A.J., Cid, F.D. 2001. The Use of EPIC Model to Study the Agroecological Change During 93 Years of Farming Transformation in the Argentine Pampas. Agric. Syst. 69, 215-34.

Binford, G.D., Blackmer, A.M., Cerrato, M.E. 1992. Relationships between corn yields and soil nitrate in late spring. Agron. J. 84, 53-59.

Blackmer, A.M., Voss, R.D., Mallarino, A.P. 1997. N fertilizer recommendations for corn in Iowa. PM-1714. Iowa State Coop. Ext., Iowa. State. Univ., Ames, IA, USA.

Blackmore, B.S. 2000. The interpretation of trends from multiple yield maps. Comput. Electron. Agric. 26, 37-51.

Blackmore, B.S., Moore, M. 1999. Remedial correction of yield map data. Precis. Agric. 1, 53-66.

Booltink, H.W.G., van Alphen, B.J., Batchelor, W.D., Paz, J.O., Stoorvogel, J.J., Vargas, R. 2001. Tools for optimizing management of spatially-variable fields. Agric. Syst. 70, 445-476.

Boote, K.J., Jones, J.W., Hoogenboom, G.J, Pickering, N.B. 1998. The GROPGRO model for grain legumes. In: Tsuji, G.Y., Hoogenboom, G.J., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 99-128.

Böttcher, J., Strebel, O. 1985. Räumliche Variabilität der Stoffanlieferung an das Grundwasser bei Gley-Podsolen aus Fein- bis Mittelsand unter Acker. Mitteilng. Dt. Bodenkundl. Ges. 43/1, 199-204.

Bouma, J. 1997a. Precision agriculture: introduction to the spatial and temporal variability of environmental quality. In: Lake, J.V., Bock, G.R., Goode, J.A. (Eds.), Precision Agriculture: Spatial and Temporal Variability of Environmental Quality. Proc. Ciba Foundation Symposium Wageningen, The Netherlands, 21-23, Jan 1997, John Wiley and Sons, New York, USA. pp. 5-17.

Bouma, J. 1997b. General reflections. In: Lake, J.V., Bock, G.R., Goode, J.A. (Eds.), Precision Agriculture: Spatial and Temporal Variability of Environmental Quality. pp. 231-235.

Bouniols, A., Cabelguenne, M., Jones, C.A., Chalamet, A., Charpenteau, J.L., Marty, J.R. 1991. Simulation of soybean nitrogen nutrition for a silty clay soil in southern France. Field Crop Res. 26, 19–34.

Bouwman, A.F., Taylor, J.A., Kroeze, C. 2000. Testing hypothesis on global emissions of nitrous oxide using atmospheric models. Global Change Science. 2 (2-3), 475-492.

Bouwman, A.F. 1990. Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In: Bouwman, A.F. (Ed.), Soils and the Greenhouse Effect. Wiley, Chichester. pp. 100–120.

Bouwman, A.F. 1998. Nitrous oxides and tropical agriculture. Nature. 392, 866-867.

Bouwman, A.F. 1996. Direct emission of nitrous oxide from agricultural soils. Dordrecht, The Netherlands, Boston, Kluwer. Nutr. Cycl. Agroecosyst. 46 (1), 53-70.

Bowen, W.T., Baethgen, W.E. 1998. Simulation as a tool for improving nitrogen management. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 193-208.

Bowen, W.T., Jones, J.W., Carsky, R.J., Quintana, J.O. 1993. Evaluation of the nitrogen submodel of CERES-Maize following legume green manure incorporation. Agron. J. 85, 153-159.

Boydell, B.C., McBratney, A.B. 2002. Identifying potential within-field management zones from cotton-yield estimates. Precis. Agric. 3, 9-23.

Braden, J.B., Johnson, G.V., Bouzaher, A., Miltz, D. 1989. Optimal spatial management of agricultural pollution. Amer. J. Agr. Econom. 71, 404-413.

Braum, S.M., Hinds, P., Maltzer, G.L., Bell, J., Mulla, D., Robert, P.C. 1998. In: Proceedings of the 4^{th} International Conference on Precision Agriculture. July 19-22 1998. St. Paul, MN. ASA, CSSA and SSSA. Madison, WI, USA.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H. 2003. An overview of the crop model STICS. Eur. J. Agr. 18, 309-332.

Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M.H., Ruget, F., Nicoullaud, B., Gate, P., Devienne-Baret, F., Antonioletti, R., Durr, C., Richard, G., Beaudoin, N., Rescous, S., Tayot, X., Plenet, D., Cellier, P., Machet, J.-M., Meynard, J.M., Delécolle, R. 1998. STICS: A generic model for simulation of crops and their water and nitrogen balances: I. Theory and parameterization applied to wheat and corn. Agron. 18, 311-346.

Brouwer, R., de Witt, C.T. 1968. A simulation model of plant growth with special attention to root growth and its consequences. In: Proceedings of the 15^{th} Easter School of Agricultural Sciences. Nottingham, United Kingdom, University of Nottingham. pp. 224-242.

Brown, R.A., Rosenberg, N.J. 1997. Sensitivity of crop yield and water use to change in a range of climatic factors and CO_2 concentrations: a simulation study applying EPIC to the central USA. Agric. For. Meteorol. 83, 171-203.

Brumme, R., Beese, F. 1992. Effect of liming and nitrogen fertilization on emissions of CO_2 and N_2O from a temperate forest. J. Geophys. Res. 97, 12851-12858.

BUND. 2003. http://vorort.bund.net/suedlicher-oberrhein/projekte/irp/zusammenfassung_wasser.htm

Bundesregierung. 2004a. Mitteilung der Regierung der Bundes Republik Deutschland, August 2004. 3. Bericht gemäß Artikel 10 der Richtlinie 91/676/EWG des Rates vom 12. Dezember 1991 zum Schutz der Gewässer vor Verunreinigungen durch Nitrat aus landwirtschaftlichen Quellen. http://www.lawa.de/pub/kostenlos/gw/ Nitratbericht-2004.pdf

Bundesregierung, 2004b. Am 16. Februar tritt das Kyoto-Protokoll in Kraft. phttp://www.bundesregierung.de/Politikthemen/Kyoto-Protokoll,12005.722593/artikel/Am-16.-Februar-2005-tritt-das-.htm

Bundesregierung. 2004c. Climate change – a major challenge of our time. http://www.bundesregierung.de/en/-,10001.756263/artikel/Climate-change-major-challenge.htm

Cambardella, C.A., Moorman, T.B., Jaynes, D.B., Hatfield, J.L., Parkin, T.B., Simpkins, W.W., Karlen, D.L. 1999. Water quality in Walnut Creek watershed: Nitrate-nitrogen in soils, subsurface drainage water, and shallow groundwater. J. Environ. Qual. 28, 25–34.

Cambardella, C.A., Clovin, T.S., Karlen, D.L., Logsdon, S.D., Berry, E.C., Radke, J.K., Kaspar, T.C., Parkin, T.B., Jaynes, D.B. 1996. Soil property contribution to yield variation pattern. In: Proceedings of the 3rd International Conference on Precision Agriculture. June 23-26, 1996. Minneapolis, MN. ASA, CSSA, SSSA, Inc., Madison, WI, USA.

Chang, J., Clay, D.E., Carlson, C.G., Reese, C.L., Clay, S.A., Ellsbury, M.M. 2004. Defining yield goals and management zones to minimize yield and nitrogen and phosphorous fertilizer recommendation errors. Agron. J. 96, 825-831.

Chang, J., Clay, D.E., Carlson, C.G., Clay, S.A., Malo, D.D., Berg, R., Kleinjan, J., Wiebold, W. 2003. Different techniques to identify management zones impact on nitrogen and phosphorus sampling variability. Agron. J. 95, 1550-1559.

Claupein, W. 1994. Zwischenfruchtanbau und Untersaaten zu Verminderung des Stickstoffaustrages – Möglichkeiten und Grenzen. In: Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (Ed.), Strategien zur Verminderung der Nitratauswaschung in Wasserschutzgebieten. pp. 51-60.

Dampney, P., Mason, P., Goodlass, G., Hillman, J. 2002. Methods and measures to minimise diffuse pollution of water from agriculture: a critical appraisal. Report for Defra, Project NT2507.

Dampney, P.M.R., Goodlass, G., Froment, M.A., Stafford, J.V. 1999. Environmental and production effects from variable rate nitrogen fertilizer to winter wheat in England. In: Proceedings of the 4th International Conference on Precision Agriculture. July 19-22, 1998. St. Paul, MN. ASA, CSSA, SSSA, Madison, WI, USA.

Deutsches Maiskomitee. 2005. Maisanbaufläche 2004 in Deutschland. http://www.maiskomitee.de/

De Wit, C.T., Goudriaan, J., van Laar, H.H., Penning de Vries, F.W.T., Rabbinge, R., van Keulen, H., Louwerse, W., Sibma, L., de Jonge, C. 1978. Simulation of assimilation 1978. Simulation of assimilation, respiration and transpiration of crops. Simulation Monograph Series, PUDOC, Wageningen, The Netherlands. 141 pp.

De Wit, C.T., Brouwer, R., Penning de Vries, F.W.T. 1970. The simulation of photosynthetic systems. In: Setlik, I. (Ed.), Prediction and Measurement of Photosynthetic

Productivity. Proceeding IBP/PP Technical Meeting Trebon 1969. PUDOC, Wageningen, The Netherlands, pp. 47–50

Derby, N.E., Casey, F.X.M., Knighton, R.E., Steele, D.D. 2004. Midseason N fertility management for corn based on weather and yield prediction. Agron. J. 96, 494-501.

Di, H.J., Cameron, K.C. 2004. Effective reductions in nitrate leaching and nitrous oxide emissions by the use of a nitrification inhibitor, dicyandiamide (DCD), in a grazed and irrigated grassland. In: Hatch, D.J., Schadwick, D.R., Jarvis, S.C., Roker, J.A. (Eds.), Controlling Nitrogen Flows and Losses. Wageningen Academic Publishers. pp. 431-433.

Diepenbrock, W. 1996. Zum N-Haushalt der Maispflanze. 10. Maiskolloqium. Halle/Saale.

Dinnes, D.L., Karlen, D.L., Jaynes, D.B., Kaspar, T.C., Hatfield, J.L., Colcin, T.S., Cambardella, C.A. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. 94, 153-171.

Dobermann, A., Blackmore, S., Cook, S.E., Adamchuck, V.I. 2004. Precision Farming: Challenges and Future Directions. In: Proceedings of the 4th International Crop Science Congress, 29 Sept – 1 Oct 2004, Brisbane, Australia.

Dobermann, A., Arkebauer, T., Cassman, K.G., Drijber, R.A., Lindquist, J.L., Specht, J.E., Walters, D.T., Yang, H., Miller, D., Binder, D.L., Teichmeier, G., Ferguson, R.B., Wortmann, C.S. 2003a. Understanding corn yield potential in different environments. In: L.S. Murphy (Ed.), Fluid Focus: The Third Decade. Proceedings of the 2003 Fluid Forum, Vol. 20. Fluid Fertilizer Foundation, Manhattan, KS, USA.

Dobermann, A., Ping, J.L., Adamchuk, V.I., Simbahan, G.C., Ferguson, R.B. 2003b. Classification of crop yield variability in irrigated production fields. Agron. J. 95, 1105-1120.

Doerge, T.A. 2004. Variable-rate nitrogen management for corn production - Success proves elusive. In: Site-specific Management Guidelines. http://www.ppi-far.org/ppiweb/ppibase.nsf/b369c6dbe705dd13852568e3000de93d/a42f148e2bc89621 85256ab5006adf42/$FILE/SSMG36.pdf

Doerge, T., Kitchen, N.R., Lund, E.D. 2002. Soil Electrical Conductivity mapping, Site specific Management Guidelines. www.ppi-far.org

Doerge, T. 1999. Soil Electrical Conductivity Mapping, Crop Insights, Vol. 9, No. 19.

Dowdell, R.J., Burford, J.R., Cress, R. 1979. Losses of nitrous oxide dissolved in drainage water from agricultural land. Nature. 278, 342-343.

Easterling, W.E., Chen, X., Hays, C., Brandle, J.R., Zhang, H. 1996. Improving the validation of model-simulated crop yield response to climate change: an application to the EPIC model. Climate Research. 6, 263-273.

EC-Council Directive 1991. Council Diretice 91/676/EEC Concerning the protection of waters against pollution caused by nitrates from agricultural sources.

Edwards, D.R., Benson, V.W., Williams, J.R., Daniel, T.C., Lemunyon, J., Gilbert, R.G. 1994. Use of the EPIC model to predict runoff transport of surface-applied animal manure constituents. Trans. ASAE. 37 (2), 403-409.

Eghball, B., Schepers, J.S., Negahban, M., Schlemmer, M.R. 2003. Spatial and temporal variability of soil nitrate and corn yield: Multifractal analysis. Agron. J. 95, 339-346.

Eghball, B., Varvel, G.E. 1997. Fractal analysis of temporal yield variability of crop sequences, implications for site-specific management. Agron. J. 89, 851-855.

Ehlers, W., Goss, M. 2003. Water Dynamics in Plant Production. CABI Publishing, Cambridge, U.S.A. pp.304.

Eichner, M.J. 1990. Nitrous oxide emissions from fertilized soils: Summary of available data. J. Environ. Qual. 19, 272-280.

Enquête-Kommission "Schutz der Erdatmosphäre" des deutschen Bundestages. 1994. Schutz der Grünen Erde. Klimaschutz durch umweltgerechte Landwirtschaft und Erhalt der Wälder. Economica Verlag, Bonn. 702 pp.

Ess, D., Morgan, M. 1997. An introduction to precision farming. In: Clapp, S. (Ed.), The Precision Farming Guide for Agriculturists. pp. 2-9.

FAO. 1996. Control of Water Pollution from Agriculture. FAO Irrigation and Drainage Paper 55, Food and Agriculture Organization of the United Nations, Rome.

Ferguson, R.B., Lark, R.M., Slater, G.P. 2003. Approaches to management zone definition for use of nitrification inhibitors. Soil Sci. Soc. Am. J. 67, 937-947.

Ferguson, R.B., Hergert, G.W., Schepers, J.S., Gotway, C.A., Cahoon, J.E., Peterson, T.A. 2002. Site-specific nitrogen management of irrigated maize: Yield and soil residual nitrate effects. Soil Sci. Soc. Am. J. 66, 544-533.

Ferguson, R.B., Hergert, G.W. 1999. Sampling and Spatial Analysis Techniques for Quantifying Soil Map Unit Composition. In: Corwin, D.L., Loague, K., Ellsworth, T.R. (Eds.), Application of GIS, Remote Sensing, Geostatistical and Solute Transport Modeling to the Assessment of Nonpoint Source Pollution in the Vadose Zone. American Geophysical Union. pp. 79-91.

Firestone, M.K., Davidson, E.A. 1989. Microbiological Basis of NO and N_2O Production and Consumption in Soil. In Andreae, M.O., Schimel, D.S. (Eds.), Exchange of Trace Gases between Terrestrial Eco-systems and the Atmosphere. John Wiley and Sons Ltd. pp. 7-21.

Fleming, K.L., Westfall, D.G. 2001. Evaluating management zone technology and grid soil sampling for variable N application. In: Proceedings of the 5th International Conference on Precision Agriculture, July 16-19, 2000, Minneapolis, MN. ASA, CSSA, and SSSA, Madison, WI, USA.

Fleming, K.L., Westfall, D.G., Bausch, W.C. 2000. Evaluating management zone technology and grid soil sampling for variable rate nitrogen application. In: Proceedings of the 5th International Conference on Precision Agriculture, July 16-19, 2000, Minneapolis, MN. ASA, CSSA, and SSSA, Madison, WI, USA.

Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M.A., Munch, J.C., Beese, F. 2002. Integrated evaluation of greenhouse gas emission (CO_2, CH_4, N_2O) from two farming systems in southern Germany. Agric. Ecosyst. Environ. 91, 175-189.

Focht, D. 1978. Methods for analysis of denitrification in soils. In: Nielsen, D., MacDonald, J. (Eds.), Nitrogen in the Environment. Academic Press. 2, 433-490.

Forcella, F. 1993. Value of managing within-field variability. In Robert, P.C., Rust, R.H., Larson, W.E (Eds.), Soil Specific Crop Management - A Workshop on Research and Development Issues. Am. Soc. Agron., Crop Sci. Soc. Am., Soil Sci. Soc. Am., Madison, WI, USA.

Forrester, J.W. 1961. Industrial dynamics. Cambridge, Massachusetts, USA. Massachusetts Institute of Technology Press.

Fraisse, C.W., Sudduth, K.A., Kitchen, N.R. 2001. Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity. Trans ASEA. 44, 155-166.

Fraisse, C.W., Sudduth, K.A., Kitchen, N.R. 1998. Evaluation of crop models to simulate site-specific crop development and yield. In: Proceedings of the 4th International Conference on Precision Agriculture. July 19-22, 1998. St. Paul, MN. ASA, CSSA, SSSA, Inc., Madison, WI, USA.

Franzen, D.W., Hopkins, D.H., Sweeney, M.D., Ulmer, M.K., Halvorson, A.D. 2002. Evaluation of soil survey scale for zone development of site specific nitrogen management. Agron. J. 94, 381-389.

Franzen, D.W., Peck, T.R. 1995. Field soil sampling density for variable rate fertilization. J. Prod. Agric. 8, 568-574.

Frasier, W.M., Whittlesey, N.K., English, M. 1999. Economic impacts of irrigation application uniformity in controlling nitrate leaching. In: Proc. ASCE, International Water Resource Engineering Conference, August 1999, Seattle. Water Resour. Publ., Highlands Ranch, CO, USA.

Friedmann, A. 2000. Die Spät- und postglaziale Landschafts- und Vegetationsgeschichte des südlichen Oberrheintieflands und Schwarzwaldes. In: Goßmann, H. (Ed.), Im Selbstverlag des Institutes für Physische Geographie, des Albert-Ludwigs-Universität Freiburg i. Br. pp. 222.

Garrison, M.V., Batchelor, W.D., Kanwar, R.S., Ritchie, J.T. 1999. Evaluation of the CERES-Maize water and nitrogen balances under tile-drained conditions. Agric. Syst. 62, 198-200.

Gerdes, G. 1993. Calibration of the soybean growth simulation model SOYGRO for Central Portugal. Verlag Ulrich E. Grauer, Wendlingen.

Godwin, D.C., Singh, U. 1998. Nitrogen balance and crops response to nitrogen in upland and lowland cropping systems. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic, Boston. pp. 55-77.

Godwin, D.C., Jones, C.A. 1991. Nitrogen dynamics in soil-plant systems. In: Hanks, J., Ritchie, J.T. (Eds.), Modeling Plant and Soil Systems. American Society of Agronomy, Inc. Madison, Wi. No. 31, pp. 287-321.

Godwin, D.C., Vlek, P.L.G. 1985. Simulation of Nitrogen Dynamics in Wheat Cropping Systems. In: Day, W. (Ed.), Wheat Growth and Modeling. NATO Advanced Research Series. pp 311-332.

Götz, A., Fautz, B. 1962. Mittleres Oberrhein-Tiefland. In: Meyen, E., Schmithüsen, J., Gellert, J., Müller-Miny, H., Schultze, J.H. (Eds.), Handbuch der naturräumlichen Gliederung Deutschlands. Bundesanstalt für Landeskunde und Raumforschung, Bad Godesberg.

Graduiertenkolleg. 2004. http://www.uni-hohenheim.de/~wwwgkoll/english.htm

Granli, T, Bøckman, O.C. 1994. Nitrous oxide from agriculture. Norw. J. of Agric. Sci. Suppl., 12, 1-128.

Gutser, R., Hauk, S. 1994. Pflanzenbauliche Maßnahmen zur Verringerung des Stickstoffaustrages aus landwirtschaftlich genutzten Flächen. In: Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (Ed.), Verminderung des Stickstoffaustrages aus landwirtschaftlich genutzten Flächen in das Grundwasser – Grundlange und Fallbeispiele. pp. 345-362.

Haag, D., Kaupenjohann, M. 2001. Landscape fate of nitrate fluxes and emissions in Central Europe – A critical review of concepts, data, and models for transport and retention. Agric. Ecosyst. Environ. 86, 1-21.

Hammer, G., Porter, J., Sinclair, T., Kropff, M. 2001. Are we making progress in crop modeling? Can we do better?. In: Bindi, M., Donatelli, M., Porter, J., Van Ittersum, M.K. (Eds.), Proceedings. 2nd International Symposium Modeling Cropping Systems. 16-18 July, 2001. Florence, Italy. pp. 3-4.

Hanks, R.J., Ritchie, J.T. 1991. Modeling plant an soil systems. Agron., 31, 545.

Hanks, R.J., Hill, R.W. 1980. Modeling crop responses to irrigation in relation to soils, climate, and salinity. International Irrigation Information Center Pub. No. 6. pp 66.

Hatch, D., Goulding, K., Murphy, D. 2002. Nitrogen. In: Haygarth, P.M., Jarvis, S.C. (Eds.), Agriculture, Hydrology, and Water Quality. CABI Publishing, New York, NY. pp. 7-28.

Haynes, R.J. 1986. Nitrification. In: Haynes, R.J. (Ed.), Mineral nitrogen in the plant–soil system. Orlando, FL. Academic Press, pp. 127-165.

Heathwaite, A. L. 1993. Nitrogen cycling in surface waters and lakes. In: Burt, T. P., Heathwaite, A. L., Trudgill, S. T. (Eds.), Nitrate: Processes, Patterns and Management. John Wiley & Sons, Chichester. pp. 99-144.

Hodges, T. 1991. Modeling and programming philosophies. In: Hodges, T. (Ed.), Predicting Crop Phenology. Boca Raton, Fl., CRC Press. pp. 101-105.

Hoogenboom, G. 2003. Crop growth and development. In: Bendi, D.K., Nieder, R. (Eds.), Handbook of Processes and Modeling in the Soil-Plant System. The Haworth Press, Binghamton, New York. pp. 655-691.

Houghton, J. 1997. Global Warming: the Complete Briefing, 2nd Edn. Cambridge University Press, Cambridge, UK.

http://bioag.byu.edu/aghort/514pres/denitrif/sld002.htm, 2004

http://eco.wiz.uni-kassel.de/ecobas.html, 2004.

http://eco.wiz.uni-kassel.de/model_db/mdb/cropsyst.html, 2004.

http://eco.wiz.uni-kassel.de/model_db/mdb/dssat.html, 2004.

http://eco.wiz.uni-kassel.de/model_db/mdb/epic.html, 2004.

http://oberrheingraben.de/Grabenfuellung/Grabenfuellung.htm, 2004.

http://oberrheingraben.de/Morphologie/Morphologie.htm, 2004.

http://www.agrarprojekte.de/fotos-zf.htm, 2004.

http://www.envirotools.org/glossary.shtml, 2004.

http://www.epa.gov/maia/html/glossary.html, 2004.

http://www.soilerosion.net/sen/doc/report_6/EPICmod.htm, 2004.

http://www.soils.org/cgi-bin/gloss_search.cgi, 2004.

http://www.statistik.baden-wuerttemberg.de, 2004.

Hutchinson, G.L., Davidson, E.A. 1993. Processes for production and consumption of gaseous nitrogen oxides in soil. In: Harper, L.A., Mosier, A.R., Duxbury, J.M., Rolston, D.E (Eds.), Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. ASA Spec. Publ. 55, Madison, WI. pp. 79-93.

Huttenlocher, F. 1972. Kleine geographische Landeskunde. G. Braun (Ed.), Karlsruhe. 222 pp.

IFA and FAO. 2001. Global estimates of gaseous emissions of NH_3, NO and N_2O from agricultural land (based on work by Bouwman, A.F., Boumans, L.J.M., Batjes, N.H.). International Fertilizer Industry Association and Food and Agriculture Organization of the United Nations, Rome. 106 pp.

IFA. 1992. IFA World Fertilizer Use Manual. International Fertilizer Industry Association, Paris.

IPCC. 2004. Intergovernmental Panel of Climate Change. http://www.ipcc.ch/.

IPCC. 2001. Climate change 2001. The Scientific Basis. IPCC Third Assessment Report, Intergovernmental Panel of Climate Change. Summary for Policy Makers. http://www.ipcc.ch/pub/guide/htm

IPCC. 1997. Revised 1996 IPCC Guidelines for national greenhouse gas inventories. The Organisation for Economics Co-operation and Development, Paris.

Irmak, A., Jones, J.W., Batchelor, W.D., Paz, J.O. 2001. Estimating spatially variable soil properties for application of crop models in precision farming. Trans. ASAE. 44 (5), 1343-1353.

Jackson, D.R, Smith, K.A. 1997. Animal manures slurries as a source of nitrogen for cereals; effect of application tie in efficiency. Soil Use Manage. 13, 75-81.

Jarvis, S.C., Stockdale, E.A., Shepherd, M.A., Powlson, D.S. 1996. Nitrogen mineralisation in temperate agricultural soils: process and measurement. Advances in Agron., 57, 187-237.

Jaynes, D.B., Kaspar, T.C., Colvin, T.S. James, D.E. 2003. Cluster Analysis of Spatiotemporal Corn Yield Patterns in an Iowa Field. Agron. J. 95, 574-586.

Jaynes, D.B., Colvin, T.S. 1997. Spatiotemporal Variability of Corn and Soybean Yield. Agron. J. 89, 30-37.

Jensen, E.S. 1992. The release and fate of nitrogen from catch crops materials decomposing under field conditions. J. Soil Sci. 43, 335-345.

Johnson, PA., Shepherd, M.A., Smith, P.N. 1997. The effects of crop husbandry on nitrate leaching from shallow limestone soil growing a five course combinable crop rotation. Soil Use Manage. 13, 17-24.

Jones, C.A., Kiniry, J.R. 1986. CERES-Maize: a simulation model of maize growth and development. Texas A&M Univ. Press. College Station, Texas. 194 pp.

Jones, J.W., Hoogenboom, G.J., Porter, C., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A., Ritchie, J.T. 2003. DSSAT Cropping System Model. Special Edition of Europ. J. Agron. 18, 235-265.

Jørgensen, R.N. 2002 Study on Line Imaging Spectroscopy as a Tool for Nitrogen Diagnostics in Precision Farming. Risø National Laboratory, Roskilde.

Kanwar, R.S., Stoltenberg, D.E., Pfeiffer, R.L., Karlen, D.L., Colvin, T.S., Simpkins, W.W. 1993. Transport of nitrate and pesticides to shallow groundwater system as affected by tillage and crop rotation practices. Soil and Water Conserv. Soc., February 21-24 1993, Ankeny, IA, USA. pp. 270-273.

Kanwar, J.S. 1972. Fertile. News. 17,17.

Katsvairo, T.W., Cox, W.J., Van Es, H.M. 2003. Spatial growth and nitrogen uptake variability of corn at two nitrogen levels. Agron. J. 95, 1000-1011.

Kauppi, P., Sedjo, R. 2001. Technological and economic potential of options to enhance, maintain, and manage biological carbon reservoirs and geo-engineering. In: Metz, B., Davidson, O., Swart, R., Pan, J. (Eds.), Climate Change 2001: Mitigation. Cambridge Univ. Press, Cambridge, UK. pp. 301-343.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.

Keating, B.A., Godwin, D.C., Watiki, J.M. 1991. Optimizing nitrogen inputs in response to climatic risk. In: Muchow, R.C., Bellamy, J.A. (Eds.), Climatic Risk in Crop

Production: Models and Management for the Semiarid Tropics and Subtropics. CAB International, Wallingford, UK. pp. 329–358.

Kitchen, N.R., Drummond, S.T., Lund, E.D., Sudduth, K.A., Buchleiter, G.W. 2003. Soil electrical conductivity and topography related to yield for three contrasting soil–crop systems. Agron. J. 95, 483-495.

Kitchen, N.R., Hughes, D.F., Sudduth, K.A., Birrell, S.J. 1995. Comparison of variable rate to single rate nitrogen fertilizer application: Corn production and residual soil NO_3^--N. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Site-Specific Management for Agricultural Systems. ASA Misc. Publ., ASA, CSSA and SSSA, Madison WI, USA. pp. 427-441.

Koch, B., Khosla, R., Fraisier, W.M., Westfall, D.G., Inman, D. 2004. Economic feasibility of variable-rate nitrogen application utilizing site-specific management zones. Agron. J. 96, 1572-1580.

Koch, B., Khosla, R. 2003. The role of precision agriculture in cropping systems. J. Crop Prod. 8, 361-381.

Krauss, A. 1999. Regional nutrient balances in view of sustainability of soil fertility and safeguarding natural sources. In: Van Cleemput, O., Haneklaus, S. Hofman, G., Schnug, E., Vermoesen, A. (Eds.), 11th international World Fertilizer Congress of Fertilization for Sustainable Plant Production and Soil Fertility. Get, Belgium. International Science Centre of Fertilizers (CIEC). Braunschweig, Vol. 1, pp. 312-324.

Kravchenko, A.N., Bullock, D.G. 2000. Correlation of grain yield with topography and soil properties. Agron. J. 92, 75–83.

Kues, J. 1994. Bodenkundliche Standortkartierung in Grundwassergewinnungsgebieten. In: Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (Ed.), Verminderung des Stickstoffaustrages aus landwirtschaftlich genutzten Flächen in das Grundwasser – Grundlange und Fallbeispiele. pp. 95-111.

Kuntze, H. 1983. Zur Stickstoffdynamik in landwirtschaftlich genutzten Böden. In: Arbeiten der DLG, Bd. 177: Nitrat – ein Problem für unsere Trinkwasserversorgung?

Lægreid, M., Bøckman, O.C., Kaarstad, O. 1999a. Global challenge – to feed the people. In: Agriculture, Fertilizer and the Environment. Norsk hydro ASA, Porsgrunn, Norway. No 12, pp. 25-75.

Lægreid, M., Bøckman, O.C., Kaarstad, O. 1999b. Concerns related to fertilizer use. In: Agriculture, Fertilizer and the Environment. Norsk hydro ASA, Porsgrunn, Norway. No 12, pp. 77-182.

LaFrance, J.T., Watts, M.J. 1995. Public grazing in the west and rangeland reform '94. Amer. J. Agr. Econom. 77, 447-461.

Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V. 1998. The potential of U.S. Cropland to sequester carbon and mitigate the greenhouse effect. Ann Arbor Press.

Lamb, J.A., Dowdy, R.H., Anderson, J.L., Rehm, G.W. 1997. Spatial and temporal stability of corn grain yields. J. Prod. Agric. 10 (3), 410-414.

Lambert, R., Van Bol, V., Maljean, J.-F., Peeters, A. 2002. Project pilote pour la protection des eauc de la nappe des sables bruxelliens. Rapport d'activité final (Project controls for the protection of groundwater of bruxellian's sands. Final report).

Larson, W.E., Lamb, J.A., Khakural, B.R., Ferguson, R.B., Rehm, G.W. 1997. Potential of site-specific management for nonpoint environmental protection. In: Pierce, F.J., Sadler, E.J. (Eds.), The state of site-specific management for agriculture. ASA, Madison, WI. pp. 337–367.

Lewan, L. 1994. Effects of a catch crop on leaching of nitrogen from a sandy soil - Simulations and measurements. Plant Soil. 166, 137–152.

Liebler, J. 2003. Feldspektroskopische Messungen zur Ermittlung des Stickstoffstatus von Winterweizen und Mais auf heterogenen Schlägen. Herbert Utz Verlag, 192 pp.

Limmer, A.W., Steele, K.W. 1982. Denitrification potentials: measurement of seasonal variation using a short-term anaerobic incubation technique. Soil Biol. Biochem. 14, 179-184.

Lindstrom, M.J., Voorhees, W.B. 1994. Response of temperates crops in North America to soil compaction. In: Soane, B.D., van Ouverkerk, C. (Eds.), Soil Compaction in Crop Production, Elsevier, Amsterdam. pp. 265-286.

Link, E.J., Graeff, S., Batchelor, W.D., Claupein, W. 2004a. Spatial variability and temporal stability of corn (*Zea mays* L.) grain yields in the Upper Rhine Valley (Germany) – relevance of grid size. Europ. J. Agron. (submitted).

Link, E.J., Graeff, S., Batchelor, W.D., Paz, J.O., Thorp, K.R., Claupein, W. 2004b. Procedure to Evaluate Spatial Corn (*Zea mays* L.) Yields in the Upper Rhine Valley (Germany) Using a Crop Growth Model. Europ. J. Agron. (submitted).

Lipiec, J., Simota, C. 1994. Role of soil and climated factors in influencing crop response to soil compaction in Central and Eastern Europe. In: Soane, B.D., van Ouverkerk, C. (Eds.), Soil Compaction in Crop Production, Elsevier, Amsterdam. pp. 365-390.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L., Leslie, J.K. 1992. Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. Australian Journal of Soil Research. 30, 757-774.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L. 1989. PERFECT - A computer simulation model of Productivity, Erosion, Runoff Functions to Evaluate Conservation Techniques. Queensland Department of Primary Industries, Bulletin QB89005. 119 pp.

Long, D.S. 1998. Spatial autoregression modeling of site-specific wheat yield. Geoderma. 85, 181-197.

Ma, L., Schaffer, M.J. 2001.A Review for carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. In: Schaffer, M.J., Ma, L., Hansen, S. (Eds.), Modeling Carbon and Nitrogen Dynamics for Soil Management. Lewis Publishers. 651 pp.

Machado, S., Bynum, E.D., Archer, T.L., Lascano, R.J., Wilson, L.T., Bordovsky, J., Segarra, E., Bronson, K., Nesmith, D.M., Xu, W. 2002. Spatial and temporal variability of corn growth and grain yield: implications for site-specific farming. Crop Sci. 42, 1564-1576.

Mäckel, R. 1998. Wandel der Geo-Biosphäre in den letzten 15000 Jahren - Allgemeine Projektbeschreibung und Forschungstätigkeit der Arbeitsgruppe Freiburg. -In: Mäckel, R., Friedmann, A. (Eds.), Wandel der Geo-Biosphäre in den letzten 15000 Jahren im südlichen Oberrheintiefland und Schwarzwald. Freiburger Geogr. Hefte 54, pp. 5-30.

Maier, A. 2003. http://vorort.bund.net/suedlicher-oberrhein/projekte/irp/zusammenfassung_wasser.htm.

Mamo, M., Malzer, G.L., Mulla, D.J., Huggins, D.R., Strock, J. 2003. Spatial and Temporal Variation in Economically Optimum N Rate for Corn. Agron. J. 95, 958-964.

Mapp, H.P., Bernardo, D.J., Sabbagh, G.J., Geleta, S., Watkins, K.B. 1994. Economic and environmental impacts of limiting nitrogen use to protect water quality: A stochastic regional analysis. Amer. J. Agr. Econom. 76, 889-903.

Marschner, H. 1986. Mineral Nutrition of Higher Plants. 2nd edition. Academic Press. 889 pp.

MATIF. 2004. Marche de Terme Internationel de France. http://www.matif.com

Mavromatis, T., Jagtap, S.S., Jones, J.W. 2002. ENSO Effect on Peanuts yield and nitrogen leaching. Clim. Res. 22, 129-140.

McBratney, A.B., Whelan, B.M. 1999. The null hypothesis of precision agriculture. In: Proceedings of the 2nd European Conference on Precision Agriculture, 1999, Odense, Denmark. Sheffield Academic Press, Sheffield, England. pp. 947-958.

McElroy, M.B., Woofsy, S.C. 1985. Nitrous oxide sources and sinks: atmospheric ozone. Vol. 1. NASA, Washington, 81 pp.

McKenna, P. 1998. Report on the Commission Reports on the Implementation of Council Directive 91/676/EEC. Committee on the Environment, Public Health and Consumer Protection (A4-0284/98), EC, Brussels.

Mearns, L.O., Mavromatis, T., Tsvetsinskaya, E., Hays, C., Easterling, W.E. 2001. Comparative Responses of EPIC and CERES Crop Models to High and Low Spatial Resolution Climate Change Scenarios. J. Geophys. Res. 104, 6623–6646.

Meisinger, J.J., Randall, G.W. 1991. Estimating nitrogen budgets for soil-crop systems. In: Follett, R.F., Keeney, D.R., Cruse R.M. (Eds.), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Science Society of America, Madison, Wisconsin. 357 pp.

Ministerium für Umwelt Baden-Württemberg. 1987. Verordnung des Ministeriums für Umwelt über Schutzbestimmungen in Wasser- und Quellenschutzgebieten und die Gewährung von Ausgleichsleistungen (Schutzgebiets- und Ausgleichsverordnung – SchALVO). Stuttgart.

Misra, S.G., Mani, D. 1994. Pollution through fertilizer. In: Nangia, S.B. (Ed.), Agricultural Pollution. Ashish Publishing House, Punjabi Bagh, New Delhi. pp. 15-29.

Mohamed, S.B., Evans, E.J., Shield, R.S. 1996. Mapping techniques and intensity of soil sampling for precision farming. In: Proceedings of the 3rd International Conference on Precision Agriculture, June 23-26, 1996, Minneapolis, MN. ASA, CSSA, and SSSA, Madison, WI, USA.

Monteith, J.L. 1965. Evaporation and environment. In: 19th Symposia of the Society for Experimental Biology 19, University Press, Cambridge. pp. 205–234.

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A. 1993. Soil attribute prediction using terrain analysis. Soil Sci. Soc. Am. J. 57, 443-452.

Moran, M.S., Humes, K.S., Pinter, P.J.Jr. 1997. The scaling characteristics of remotely-sensed variables for sparsely-vegetated heterogeneous landscapes. J. Hydrol. 190, 337-362.

Mosier, A.R., Kroeze, C., Navison, C., Oenema, O., Seitzinger, S., van Kleemput, O. 1998. Closing the global atmospheric N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutrient cycling Agroecosystems. 52, 225-248.

Mosier, A.R., Parton, W.J., Hutchinson, G.L. 1983. Modeling nitrous oxide evolution from cropped and native soils. Ecol. Bull. Stockholm. 35, 229-241.

Motulsky, H.J., Christopoulos, A. 2004. Fitting models to biological data using linear and nonlinear regression. Oxford University Press, New York, USA. 351 pp.

Motz, I. 2002. Einfluss von Bodenbearbeitung, Düngung und Fruchtfolge auf die Lachgasemission aus Ackerflächen. Institut für Agrartechnik, Dissertation Universität Hohenheim.

Mulla, D.J., Schepers, J.S. 1997. Key processes and properties for site-specific soil and crop management. In: Pierce, F.J., Sadler, E.J. (Eds.), The State of Site-Specific Management for Agriculture. ASA, CSSA and SSSA, Madison, WI. Amer. Soc. Agron. pp. 1-18.

Mulla, D.J., Bhatti, A.U., Hammond, M.W., Benson, J.A. 1992. A comparison of winter wheat yield and quality under uniform versus spatially variable fertilizer management. Agriculture, Ecosystems and Environment. 38,301-311.

Nehmdahl, H., Greve, M.H. 2001. Using soil electrical conductivity measurements for delineating management zones on highly variable soils in Denmark. In: Proceedings of the 3rd European Conference on Precision Agriculture, 2001, Montpellier. pp. 461-464.

Nielsen, D.R., Wendroth, O., Pierce, F.J. 1999. Emerging concepts for solving the enigma of precision farming research. In: Proceedings of the 4th International Conference on Precision Agriculture. July 19-22, 1998. St. Paul, MN. ASA, CSSA, and SSSA, Madison, WI, USA. pp. 303-318.

Oenema, O., Velrhoff, G.L., Yamulki, S., Jarvis, S.C. 1997. Nitrous oxide emissions from grazed grassland. Soil Use and Management. 13, 288-295.

Overman, A.R., Scholtz III, R.V. 2002a. Introduction. In: Dekker, M. (Ed.), Mathematical Models of Crop Growth and Yield. New York. pp.1-34.

Overman, A.R., Scholtz III, R.V. 2002b. Growth response model. In: Dekker, M. (Ed.), Mathematical Models of Crop Growth and Yield. New York. pp. 95-185.

Paz, J.O., Batchelor, W.D., Jones, J.W. 2003. Estimating potential economic return for variable soybean variety management. Trans. ASAE 46 (4), 1225-1233.

Paz, J.O., Batchelor, W.D., Tylka, G.L. 2001. Method to use crop growth models to estimated potential return for variable-rate management in soybeans. Trans. ASAE. 44, 1335-1341.

Paz, J.O., Batchelor, W.D., Babcock, B.A., Colvin, T.S., Logsdon, S.D., Kaspar, T.C., Karlen, D.L. 1999. Model-based technique to determine variable rate N for corn. Agric. Syst. 61, 69-75.

Paz, J.O., Batchelor, W.D., Colvin, T.S., Logsdon, S.D., Kaspar, T.C., Karlen, D.L. 1998a. Analysis of water stress effects causing spatial yield variability in soybeans. Agric. Syst. 61, 69-75.

Paz, J.O., Batchelor, W.D., Colvin, T.S., Logsdon, S.D., Kaspar, T.C., Karlen, D.L., Babcock, B.A., Pautsch, G.R. 1998b. Model-based technique to determine variable rate nitrogen for corn. In: Proceedings of the 4th International Conference on Precision Agriculture. July 19-22, 1998. St. Paul, MN. ASA, CSSA, and SSSA, Madison, WI, USA.

Paz, J.O., Batchelor, W.D., Colvin, T.S. 1997. Calibration of a crop growth model to predict spatial yield variability. ASAE Paper No. 97-1031. American Society of Agricultural Engineers, St. Joseph, MI, USA.

Pedersen, S.M. 2003. Precision farming – Technology assessment of site-specific input application in cereals. Diss. Department of Manufacturing, Engineering and Management, Technical University of Denmark.

Penney, D.C., Noland, S.C., McKenzie, R.C., Goddard, T.W., Kryzanowski, L. 1996. Yield and nutrient mapping for site-specific fertilizer management. Communications of Soil Science and Plant Analysis. 27, 1265-1279.

Pierce, F.J., Sadler, J.D. 1997. In: Pierce, F.J., Sadler, J.D. (Eds.), The State of Site-Specific Management for Agriculture. Madison, WI: Agronomy Society of America, Crop Science Society of America, and Soil Science Society of America, 1997.

Ping, J.L., Dobermann, A. 2003. Creating spatially continuous yield classes for site-specific management. Agron. J. 95, 1121-1131.

Power, J.F., Wiese, R., Flowerday, D. 2001. Managing farming systems for nitrate controll: a research review from management systems evaluation areas. J. Environ. Qual. 30 (6), 1866-1880.

Priestley, C.H.B., Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weath. Rev. 100, 81–92.

Rambow, J., Schindler, R. 1994. Transportmechanismen im Boden und Grundwasser – Eine Übersicht. In: Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (Ed.), Verminderung des Stickstoffaustrages aus landwirtschaftlich genutzten Flächen in das Grundwasser – Grundlange und Fallbeispiele. pp. 33-57.

Randall, G.W., Huggins, D.R., Russelle, M.P., Fuchs, D.J., Nelson, W.W.,. Anderson, J.L. 1997. Nitrate losses through subsurface tile drainage in CRP, alfalfa, and row crop systems. J. Environ. Qual. 26, 1240-1247.

Ritchie, J.T. 1998. Soil water balance and plant water stress. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic, Boston. pp. 41-54.

Ritchie, J.T., Singh, U., Godwin, D.C., Bowen, W.T. 1998. Cereal growth, development and yield. In: Tsuji, G.Y., Hoogenboom, G.J., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp 79-88.

Ritchie, J.T. 1972. Model for Predicting Evaporation from a Row Crop with Incomplete Cover, Water Resour. Res. 8, 2104-2113.

Robert, P.C., Rust, R.H., Larson, W.E. (Eds.). 1996. Precision Agriculture: Proceedings of the 3rd International Conference. Madison, WI: Agronomy Society of America -Crop Science Society of America - Soil Science Society of America, 1996.

Robert, P.C., Rust, R.H., Larson, W.E. (Eds.). 1995. Site-Specific Management for Agricultural Systems. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 1995.

Roel, A., Plant, R.E. 2004. Spatiotemporal analysis of rice yield variability in two California fields. Agron. J. 96, 77-90.

Rohmann, U., Rödelsperger, M. 1994. Maßnahmenkombinationen und Varianten zur Sanierung des nitratbelasteten Trinkwassers der Gemeinde Weisweil. Technologie-zentrum Wasser Karlsruhe.

Ross, P.J., Bristow, K.L. 1990. Simulating water movement in layered and gradational soils using the Kirchhoff transform. Soil Sci. Soc. Am. J. 54, 1519–1524.

Russel, E.J. 1912. Soil Conditions and Plant Growth. 1st Ed. Longmans, Green and Co., London.

Sadler, E.J., Bauer, P.J., Busscher, W.J. 2000. Site-specific analysis of a droughted corn crop: I. Growth and corn yield. Agron. J. 92, 395-402.

Sadler, E.J., Busscher, W.J., Bauer, P.J., Karlen, D.L. 1998. Spatial scale requirements for precision farming: A case study in the south-eastern USA. Agron. J. 90, 191-197.

Sadler, E.J., Russell, G. 1997. Modeling crop yield for site-specific management. In: Pierce, F.J., Sadler, E.J. (Eds.), The State of Site-Specific Management for Agriculture. Madison, WI. ASA, CSSA, SSSA, Madison, WI. pp. 69-80.

Sadler, E.J., Busscher, W.J., Karlen, D.L. 1995. Site-specific yield histories on SE coastal plain field. In: Proceedings of the 2nd International Conference of Precision Agriculture. Minneapolis, MN, March 27-30, 1994. ASA, CSSA and SSSA, Madison, WI. pp 154-166.

Sattelmacher, B. 1990. Nährstoffversorgung der Pflanzen. In: Blume, H-P. (Ed.), Handbuch des Bodenschutzes. 2 Aufl., Ecomed-Verlag, Landsberg/Lech. pp. 81-84.

Sattelmacher, B., Stoy, A. 1990. Düngung von Böden. In: Blume H.-P., (Ed.), Handbuch des Bodenschutzes. Ecomed-Verlag, Landsberg/Lech. pp. 217-244.

Scheffer, F., Schachtschabel, P. 1989. Lehrbuch der Bodenkunde. Ferdinand Enke Verlag Stuttgart.

Schepers, A., Shanahan, J.F., Liebig, M.A., Schepers, J.S., Johnson, S., Luchiari, A. 2004. Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years. Agron. J. 98, 195-203.

Schmidt, U. 1998. Einfluss von Bewirtschaftungsmaßnahmen und Umweltfaktoren auf Lachgas-Emissionen aus landwirtschaftlich genutzten Lössböden. Dissertation Universität Hohenheim. Hohenheimer Bodenkundliche Hefte, Heft 45.

Schmidt, I., Bock, E. 1998. Anaerobic ammonia oxidation by cell-free extracts of Nitrosomonas eutropha. Antonie Leeuwenhoek 73, 271-278.

Schröder, J.J., Neeteson, J.J., Oenema, O., Struik, P.C. 2000. Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Res. 66, 151–164.

Schröder, J.J., van Dijk, W., de Groot, W.J.M. 1996. Effects of cover crops on the nitrogen fluxes in a silage maize production system. Netherlands Journal of Agricultural Science. 44, 293-315.

Schulze, R. 2001. Die Schutzgebiets- und Ausgleichs-Verordnung – Praktische Umsetzung im Ackerbau und auf Grünland. In: Landesanstalt für Pflanzenbau (Ed.), Merkblätter für die Umweltgerechte Landbewirtschaftung (Nr. 20, Wasserschutz, SchALVO, Juli 2001). pp 1-12.

Scott, A., Crichton, I.J., Ball, B.C. 1999. Long-term monitoring of soil gas fluxes with closed chambers using automated and manual systems. J. Environ. Qual. 28, 1637-1643.

Sehy, U. 2004. N_20-Freisetzung aus Ackerböden – Der Einfluss der Bewirtschaftung des Standortes. Ökom. Verlag, München. 129 pp.

Seligman, N.C., van Keulen, H. 1981. PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen. In: Frissel, M.J., van Veen, J.A. (Eds.), Simulation of Nitrogen Behavior of Soil-Plant Systems, PUDOC, Wageningen, Netherlands. pp. 191-221.

Sick, W.-D. 1994. Die Agrarwirtschaft in Grenzbereich dreier Länder, Südbaden, Oberelsass, Nordostschweiz. In Berichte zur deutschen Landeskunde, Trier. Bd. 68. Heft 1, 111-133.

Smaling, E.M.A., Oenema, O., Fresco, L.O. 1999. Nutrient disequilibria in agroecosystems: Concepts and case studies. CAB International, Wallingford. pp. 322.

Smil, V. 1999. Nitrogen in crop production: an account of global flows. Global Biochem. Cycl. 13, 647-662.

Spalding, R.F., Exner, M.E. 1993. Occurrence of nitrate in groundwater - a review. J. Environ. Qual. 22 (3), 392-402.

Stafford, J.V., Clark, R.M., Bola, H.C. 1998. Using yield maps to regionalize fields into potential management units. In: Proceedings of the 4th International Conference on Precision Agriculture. July 19-22, 1998. St. Paul, MN. ASA, CSSA and SSSA, Madison, WI, USA. pp. 225-237

Statistisches Landesamt Baden-Württemberg. 2004. www.statistik.baden-wuerttemberg.de

Stöckle, C.O., Donatelli, M., Nelson, R. 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18, 289-307.

Stöckle, C.O., Campbell, G.S. 1989. Simulation of crop response to water and nitrogen: an application example using spring wheat. Trans. ASAE. 32, 66–74.

Stoorvogel, J.J., Smaling, E.M.A. 1998. Research on soil fertility decline in tropical environments: integration of spatial scales. Nutrient Cycling in Agroecosystems. 50, 151-158.

Sudduth, K.A., Drummond, S.T., Birrell, S.J., Kitchen, N.R. 1996. Analysis of spatial factors influencing crop yield. In: Proceedings of the 3rd International Conference on Precision Agriculture. June 23-26, 1996. Minneapolis, MN. ASA, CSSA, SSSA, Inc., Madison, WI, USA. pp. 129-140.

Swinton, S.M., Liu, Y., Miller, N.R. 2002a. Is Yield Response Site-specific? Revisiting N Recommendations on Corn. Selected paper. American Agricultural Economics Association annual meeting, July 28-31, 2002, Long Beach, CA, USA.

Swinton, S., Jones, K., Miller, N., Brook, R., Warncke, D., Schabenberger, O. 2002b. Site-specific versus whole-field fertility and lime management in Michigan soybeans and corn. In: Proceedings of the 6th International Conference on Precision Agriculture. July 14-17, 2002. Minneapolis, MN. ASA, CSSA, SSSA, Inc., Madison, WI, USA.

Tanner, C.B., Sinclair, T.R. 1983. Efficient water use in crop production: research or re-search?. In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), Limitations to efficient water use in crop production, Amer. Soc. Agron., Madison, WI, USA.

Taylor, R.K., Kluitenberg, G.J., Schrock, M.D., Zhang, N., Schmidt, J.P., Havlin, J.L. 1998. Using yield monitor data to determine spatial crop production potential. ASAE International Meeting. July 12-16, 1998, Disney's Coronado Springs Resort, Orlando, FL, USA.

Ten Berge, H.F.M., Burgers, S.L.G.E., Hack-ten Broeke, M.J.D., Smit, A., de Gruijter, J.J., Velthof, G.L., Schröder, J.J., Oenema, J., de Ruijter, F.J., Radersma, S., Hoving, I.E., Boels, D. 2004. Nitrogen rate, surplus or residue? Performance of selected indicators for nitrate leaching. In: Hatch, D.J., Schadwick, D.R., Jarvis, S.C., Roker, J.A. (Eds.), Controlling Nitrogen Flows and Losses. Wageningen Academic Publishers. pp. 397-405.

Thornley, J.H.M., Johnson. I.R. 1990. Dynamic modeling. In: Thornley, J.H.M., Johnson. I.R. (Eds.), Plant and Crop Modeling - A Mathematical Approach to Plant and Crop Physiology. Oxford Science Publications. 669 pp.

Thornton, P.K., Hoogenboom, G., Wilkens, P.W., Bowen, W.T. 1995. A computer program to analyze multiple-season crop model outputs. Agron. J. 87, 131–136.

Thorp, K.R., Batchelor, W.D., Paz, J.O., Steward, B.L. 2004. Estimating Yield and Environmental Risks Associated With Variable Rate Nitrogen Management for Corn Using Apollo. Proceedings of the 7th International Conference on Precision Agriculture. July 25-26, 2004. Minneapolis, MN. ASA, CSSA, SSSA Inc., Madison, WI, USA.

Thrikawala, S., Weersink, A., Kachanoski, G., Fox, G. 1999. Economic feasibility of variable-rate technology for nitrogen on corn. Amer. J. Agr. Econ. 81, 914-927.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Horwarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D. 2001. Forecasting agriculturally driven global environmental change. Science 292, 281-284.

Tomer, M.D., Anderson, J.L. 1995. Field evaluation of a soil water-capacitance probe in a fine sand. Soil Sci. 159, 90-98.

Torstensson, G. 1992. Nitrogen delivery and utilization by subsequent crops after incorporation of leys with different plant composition. Biological Agriculture and Horticulture. 16, 129-143.

Umweltinformationssystem Baden-Württemberg, 2004. http://www.umwelt-bw.de/lfu/abt4 /monit/de/5Oberrheingraben/

UN. 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. UN Publications, New York. http://unfccc.int/files/essential_background/back ground_ publications_htmlpdf/application/pdf/conveng.pdf

UNEP/IETC. 2002. Planning and Management of Lakes and Reservoirs: An Integrated Approach to Eutrophication. United Nations Environment Programme. www.unep.or.jp /ietc/publications/techpublications/techpub-11

UNFCCC. 2004a. Kyoto Protocol. http://unfccc.int/essential_background/ kyoto_protocol/ items/ 2830.php

UNFCCC. 2004b. http://unfccc.int/files/essential_background/application/pdf/beginner_02 _en.pdf

UNFCCC. 1998. Review of the implementation of commitment and of other provisions of the convention. Review of information communicated under Article 12. National Communication from parties included in the annex 1 to the convention. Summary compilation of annual greenhouse gas emissions inventory data from Annex I Parties. Note by the secretariat. United Nations Framework Convention on Climate Change. Conference of the Parties. http://unfccc.de

UNFCCC. 1992. United Nations Framework Convention on Climate Change, http://www.unfccc.de / resource/conv/index.htm

Van Alphen, B.J., Stoorvogel, J.J. 2000. A functional approach to soil characterization in support of precision agriculture. Soil Sci. Soc. Am. J. 64, 1706-1713.

Van der Paauw. 1952. Critical remarks concerning the validity of the Mitscherlich effect law. Plant and Soil. 4, 97-106.

Van der Ploeg, R.R., Machulla, G., Ringe, H. 1995. Ein Mischzellenmodell zur Abschätzung der Nitratauswaschung aus landwirtschaftlich genutzten Böden im Winterhalbjahr. Z. Pflanzenernähr. Bodenk. 158, 365-373.

Van Dijk, W., Dekker, P., van der Schoot, J.R. 2004. Nitrate leaching on loess soils as affected by N fertilisation and crop rotation. In: Hatch, D.J., Schadwick, D.R., Jarvis, S.C., Roker, J.A. (Eds.), Controlling Nitrogen Flows and Losses. Wageningen Academic Publishers. pp. 459-460.

Van Ittersum M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J. 2003. On approaches and applications of the Wageningen crop models. Europ. J. Agron. 18, 201-234.

Van Ittersum, M.K., Donatelli, M. 2003. Modeling cropping systems – highlights of the symposium and preface to the special issues. Europ. J. Agron. 18, 187-197.

Varvel, G.E., Schlemmer, M.R., and Schepers, J.S. 1999. Relationship between spectral data from an aerial image and soil organic matter and phosphorus levels. Precis. Agric. J. 1, 291-300.

Veldkamp, E., Keller, M. 1997. Fertilizer-induced nitric oxide emissions from agricultural soils. Nutrient cycling in Agroecosystems. 48, 69-77.

Verhagen, A.J., Bouma, J. 1998. Defining threshold values for residual soil N levels. Geoderma. 85, 199-211.

Verhagen, A.J., Bouma, J. 1997. Modeling soil variability. In: Pierce, F.J., Sadler, E.R. (Eds.), The state of site-specific mangement for agriculture. ASA, Misc. Publ., ASA, CSSA, SSSA, Inc., Madison, WI, USA.

Verhagen, A., Booltink, H.W.G., Bouma, J. 1995. Site-specific management: Balancing production and environmental requirements at farm level. Agric. Syst. 49, 369-384.

Vetter, R., Rühling, I., Lasserre, D. 2001. Abschlussbericht zum Projekt 1.1.1. Nutzbarmachung von Verfahren der Präzisionslandwirtschaft am Oberrhein – Analyse und Interpretation der Variabilität von Ackerflächen in der Rheinebene. http://www.itada.org/download.asp?id=111abDkf.pdf, 2004.

Vinten, A.J.A., Howard, R.S., Redman, M.H. 1991. Measurements of nitrate leaching losses from arable plots under different nitrogen input regimes. Soil Use Manage. 7, 3-14.

Wallgren, B., Lindén, B. 1994. Effects of catch crops and ploughing times on soil mineral nitrogen. Swedish J. agric. Res. 24, 67-75.

Weed, D.A.J., Kanwar, R.S. 1996. Nitrate and water present in and leaching from root-zone soil. J. Environ. Qual. 25 (4), 709-719.

Welch, J.P., Woog, G.A., Godwin, J.C., Taylor, J.C., Earl, R., Blackmore, B.S., Spoor, G., Thomas, G. 1999. Developing strategies for spatially variable nitrogen application. In: Proceedings of the 2nd European Conference on Precision Agriculture. July 11-15, 1999. Odense, Denmark. pp. 729-738.

Werner, W., Wodsak, H.-P. (Eds.). 1994. Stickstoff- und Phosphoreintrag in die Fließgewässer Deutschlands unter besonderer Berücksichtigung des Eintragsgeschehens im Lockergesteinsbereich der ehemaligen DDR. Schriftenreihe Agrarspektrum. 22, 243 pp.

Westerman, R.L., Raun, W.R., Johnson, G.V. 1999. Nutrient and water use efficiency. In: Sumner, M.E. (Ed.), Handbook of Soil Science. CRC Press, Inc. Boca Raton, FL. pp. 175-189.

Wibawa, W.D., Dludlu, D.L., Swenson, L.J., Hopkins, D.G., Dahnke, W.D. 1993. Variable fertilizer application based on yield goal, soil fertility, and soil map unit. J. Prod. Agric. 6, 255-262.

Williams, J.R. 1995. The EPIC model. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications. pp. 909-1000.

Williams, J.R., Putman, J.V., Dyke, P.T. 1985. Assessing the effect of soil erosion on productivity with EPIC. Proc. Nat. Symp. Erosion and Soil Productivity. ASAE Publ. 8-85.

Williams, J.R., Dyke, P.T., Jones, C.A. 1983. EPIC: a model for assessing the effects of erosion on soil productivity. In: Laurenroth, W.K., Skogerboe, G.V., Flug, M. (Eds.), Analysis of Ecological Systems: State-of-the-Art in Ecological Modeling. Elsevier, Amsterdam, pp. 553-572.

Wollenhaupt, N.C., Wolkowski, R.P., Clayton, M.K. 1994. Mapping soil test phosphorus and potassium for variable-rate fertilizer application. J. Prod. Agric. 7, 441-448.

Wong, D.W.S. 1995. Aggregation effects in geo-referenced data. In: Arlinghaus, S.L., Griffith, D.A. (Eds.), Practical Handbook of Spatial Statistics. CRC Press, Boca Raton, FL. pp 83-106.

Zhang, W.L., Tian, Z.X., Zhang, N., Li, X.Q. 1996. Nitrate Pollution of Groundwater in Northern China. Agric. Ecosyst. Environ. 59, 223-31.

Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Arbeit selbst und nur unter Verwendung der angegebenen Hilfsmittel und Quellen angefertigt habe. Wörtlich und inhaltlich übernommene Stellen sind als solche gekennzeichnet.

Die Arbeit ist in gleicher oder ähnlicher Form noch keiner anderer Prüfungsbehörde vorgelegt worden und noch nicht veröffentlicht.

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