Precision Manure Management across Site-Specific Management Zones: Grain Yield and Economic Analysis

M. E. Moshia, R. Khosla,* L. Longchamps, R. Reich, J. G. Davis, and D. G. Westfall

ABSTRACT

Precision manure management is a relatively new concept that merges the best agronomic and manure management practices along with precision agricultural techniques, such as site-specific management zones (MZs), for agricultural productivity and environmental quality. The objective of the study was to assess the influence and compare the economic efficiency of variable-rate applications of animal manure on grain yield in maize (Zea mays L.) fields across MZs in limited irrigation cropping systems.

The study was conducted on furrow-irrigated maize fields in northeastern Colorado, USA. Fields were classified into low, medium, and high yielding MZs, based on soil color, elevation, and yield history. Experimental strips were 4.5 m wide and 540 m long spanning all MZs with manure and N fertilizer management strategies nested within MZs. Variable-rate manure applications of 22, 44, and 67 Mg ha⁻¹ were considered for variable yield goal (VYG) and constant yield goal (CYG) manure management strategies. The results of this study indicates that maize grain yield was significantly different across MZs a majority of times, however, not always consistent with the MZ productivity level. For instance, the low MZ showed a significantly (P ≤ 0.05) higher grain yield under a CYG manure management strategy. The enterprise budget analysis indicated that application of animal manure alone was economically inefficient for maize grain production. The study suggests that variable-rates of manure can be used in conjunction with synthetic N fertilizer to ensure that crop N requirements are met at early growth stages of maize.

Precision manure management is a relatively new concept that combines the best manure management practices with precision agricultural techniques, such as production-level site-specific management areas (MZs). Management zones are subregions of a field that express a homogeneous combination of yield limiting factors (Doerge, 1999). Application of nutrients to soil using MZs has shown to improve nutrient use efficiency, maintain or increase grain yield, and potentially reduce environmentally sensitive nutrient loading (Khosla et al., 2002; Hornung et al., 2003). The use of MZs in managing spatial variability has been proposed as a cost effective approach to using spatial information for improved crop management (Fleming et al., 1999; Luchiari et al., 2001; Koch et al., 2004).

ISSUES WITH MANURE MANAGEMENT AND THE ENVIRONMENT

In the western Great Plains of the United States, animal agriculture is an important contributor to the agricultural economy, and many livestock farms are located close to bodies of water (Davis et al., 1997). With the increased concentration of livestock, there are many confined-animal feeding operations (CAFOs) and associated manure stocks (Fleming and Long, 2002). Agricultural producers who focus on making economic management decisions regarding manure utilization in their production systems are often in conflict with environmental interests (Fleming and Long, 2002). Livestock farmers have recycled manure on the land where it was produced primarily because of high transportation costs to offsite areas (Janzen et al., 1999; Kellogg et al., 2000).

The challenge with agricultural lands receiving manure is worsened when manure is applied uniformly on spatially variable fields over long periods of time (Fleming and Long, 2002). It has been widely documented that because of the inherent spatial variability of soil, not all areas of a field may require the same level of nutrient inputs. Uniform application of inputs, such as manure, often results in some areas of the field receiving greater nutrient inputs than is necessary.

M.E. Moshia, Dep. of Crop Science, Tshwane Univ. of Technology, Pretoria, 0001, South Africa; R. Khosla, L. Longchamps, J.G. Davis, and D.G. Westfall, Dep. of Soil and Crop Sciences, Colorado State Univ., Fort Collins, CO 80523-1170; R. Reich, Dep. of Forest, Rangeland and Watershed Stewardship, Colorado State Univ., Fort Collins, CO 80523-1472. Received 19 Aug. 2013. *Corresponding author (raj.khosla@colostate.edu).

Published in Agron. J. 106:2146–2156 (2014) doi:10.2134/agronj13.0400 Available freely online through the author-supported open access option. Copyright © 2014 by the American Society of Agronomy, 5585 Guilford Road, Madison, WI 53711. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Abbreviations: CAFOs, concentrated animal feeding operations; CYG, constant yield goal; DGPS, differentially corrected global positioning system; EPA, Environmental Protection Agency; MZs, site-specific management zones; VYG, variable yield goal.
When the nutrient supplied by manure or conventional fertilizer is not given accurate credit, or when manure or conventional fertilizer is applied at excessive rates to soil, the excess nutrients may contribute to pollution of the environment through transport to surface water and groundwater (Burkart and James, 1999; Smith et al., 2001a, 2001b). The nutrients in animal manure that are of greatest environmental concerns are N and P. Runoff and leachate from overfertilized areas may contaminate water supplies, whereas crop yield may be restricted in under-fertilized areas (Cahn et al., 1994). When manure is applied annually to meet N requirements of a crop, P accumulation may occur in the soil (Eghball and Power, 1999). Any P that is not taken up by crops accumulates in soil, potentially to levels that far exceed the amounts needed for optimal crop growth (Toth et al., 2006). As a result, concerns have arisen that crops are not fully assimilating nutrients present in the applied manure (Ribaudo et al., 2003). Unlike N, P is relatively immobile in the soil system. Perhaps one of the greatest opportunities for modern agriculture lies in the challenge of effectively incorporating best manure management practices into cropping systems that will minimize environmental risks (Schepers et al., 2000). Site-specific manure application may potentially lead to decreased environmental risks and thus evolve into being part of best management practices.

**Apparent Nitrogen Budget**

Nitrogen budgets have been used as a quantitative means of assessing soil and cropping system N use for over 100 yr (Lawes et al., 1882; Watson and Atkinson, 1999), and the approach is still common (Bremboek et al., 1996). Repeated N applications to field crops, either as inorganic fertilizers or animal manures, can lead to N buildup in soils and potential long-term environmental hazards (Munoz et al., 2003). Nitrogen in excess of 50 to 100 kg N ha\(^{-1}\) over the agronomic rate has been proposed as a limit beyond which the environment will be degraded, particularly by agricultural activities (Paris-Convention for the Prevention of Marine Pollution, 1993).

Both for economic and environmental reasons, the use of fertilizer N should be as efficient as possible (Van Cleemput et al., 1981). By quantifying both the inputs and outputs for a given system, N budgets can identify surplus N within the system (Watson and Atkinson, 1999). Such an approach will help ensure that the non-efficient part of the fertilizer should be as small as possible and in such a form that pollution of the environment is limited (Van Cleemput et al., 1981). Although studies on N budget and balances have been published, the present study assesses manure management across spatially variable soils classified into MZs on fields planted to maize under limited irrigation conditions.

**Precision Manure Management on Spatially Variable Soils**

To make informed decisions concerning the application of animal manure on crop fields, farmers must consider several parameters, such as manure quality, where to apply, when to apply, and how much manure to apply in specific areas of the field (Morris et al., 1999). Variable-rate technology is a major element of precision agriculture that allows for the different application of crop inputs throughout a field in a cost-effective way. Precision agriculture is an integrated information- and technology-based agricultural management system, with the intent to manage spatial and temporal variability associated with all aspects of agricultural production for optimum profitability, sustainability, and protection of the environment (Robert et al., 1995; Pierce and Nowak, 1999). Bouma (1999) suggested that variable-rate application practices could avert environmental effects by reducing the loss of agricultural chemicals. Studies have emphasized the potential of variable-rate application of nutrients in protecting the environment because no nutrients would be applied to field areas with above optimum levels of nutrients for crop production (Mulla, 1993; Franzen and Peck, 1995; Schepers et al., 2000).

Previous studies have shown the potential of site-specific management using liquid manure and have highlighted the need for further research (Ess et al., 2001; Lambert et al., 2003, 2004). However, a review of the literature indicates that there are no published sources that have previously investigated the utilization, agronomic use efficiency, and economic effectiveness of solid animal manure applied across MZs as a part of best manure management practices. Even though most costs associated with manure management are on loading, transportation, and application, Massey and Payne (2013) and Ribaudo et al. (2003) stated that solid manures are the least expensive to transport because most of the bulk transported is dry organic matter containing nutrients. The U.S. Environmental Protection Agency (EPA) regulations under the Clean Water Act of Concentrated Animal Feeding Operations (CAFOs) are driving the need for improved record keeping and accountability of manure applications (Ribaudo et al., 2003). There is a need to investigate whether traditional (uniform) manure management practices can be improved by taking advantage of a site-specific management zone approach.

**Economic Analysis**

Irrigated maize and livestock farming are major agricultural activities broadening and strengthening the economy of the state of Colorado (Ribaudo et al., 2003). The economic efficiency of utilizing animal manure from livestock farms as a nutrient source for maize production across MZs has not been previously investigated. One tool that can be used for economic analysis and planning purposes is an enterprise budget (Bitzer and Herbek, 2001). Enterprise budgets can be used to estimate net return by incorporating quantities and prices of all costs associated with production. Likewise, sensitivity analysis can also be used to create a set of scenarios to determine how changes in grain yield and maize price could impact the net return (Saltelli et al., 2008). The hypothesis of this study was that variable-rate application of animal manure based on the productivity potential of MZs will economically enhance grain yield of low producing MZs and maintain or improve the grain yield of medium and high yielding MZs over time. The objectives of the study were (i) to assess the influence of variable-rate applications of animal manure on grain yield under continuous maize production across MZs in limited furrow-irrigated cropping systems, and (ii) to compare the economic efficiency of variable and constant yield goal manure management strategies across MZs for maize production under limited furrow-irrigated conditions.
MATERIALS AND METHODS

Experimental Sites

This study was conducted over 3 yr on one site about 2.7 ha in size during the crop growing seasons of 2006, 2007, and 2008 as part of a large multi-disciplinary MZs project (Khosla et al., 2008). The study site was located in the proximity of 40°39′N, 104°59′W in northeastern Colorado near Fort Collins, CO, and has been under continuous maize production for the previous three growing seasons to initiation of the study. The soil series of the study site was classified as fine-loamy, mixed, mesic, Aridic Haplustralfs with a 1 to 2% slope (Soil Survey Staff, 1980). The two soil series in this site are a Kim loam (fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthents) and Nunn clay loam (fine, smectitic, mesic Aridic Argiustolls). Maize was planted at a density of 89,000, 84,000, and 81,500 seeds ha⁻¹ on 17 May 2006, 4 May 2007, and 12 May 2008. Row spacing was 0.76 m. Maize hybrids were GARST 88-81 for 2006 and 2007 and NK N40T-GT/CA/LL for 2008. Soil was tilled in the fall and manure was incorporated in the spring just before the preparation of the seed beds.

Management Zone Delineation

Productivity level MZs were previously delineated as a part of a large multi-disciplinary project (Fig. 1). The MZs delineation process involved the commercially available AgriTrak Professional Software to delineate the MZs boundaries (AgriTrak, 1998). A gray-scale bare soil aerial image of the field, the farmer’s perception of the topography data and the farmer’s past crop and soil management experiences were included in the delineation process (Hornung et al., 2006). Regions of darker color on the aerial image, areas of low-lying topography, and areas of historic high yields as reported by the farmer were designated as high MZs and vice-versa (Hornung et al., 2006). The majority of the low and medium MZ are comprised in the Kim loam series whereas the majority of the high MZ is in the Nunn clay loam. The details of the MZs delineation process can be found in Khosla et al. (2002, 2008).

Irrigation was applied for a period of 12 h every other week through a furrow-irrigation system using 3.8-cm diameter siphon tubes. Irrigation water was delivered at a rate of approximately 4.54 m³ h⁻¹ in every other maize row, which is equivalent to about 67 mm applied per irrigation. It is important to understand two aspects of the study under furrow-irrigation: (i) the weather conditions during the three growing seasons in this study were variable, and (ii) the availability of irrigation water was limited, meaning this was a limited irrigation study. At the experimental sites, maize was irrigated only on certain days contingent on the availability of water. Irrigation water was available once every other week for a limited time (about 12-h time blocks) and was applied uniformly across the entire experimental area.

Soil Sampling and Manure Applications

Preplant soil samples were collected each year using a stratified systematic unaligned sampling design at depth intervals of 0 to 20 cm and 20 to 60 cm. Soils were sampled precisely at the same locations throughout the study using MZs map for stratification and a differential global positioning system (DGPS) Trimble AgGPS 114 (Trimble Navigation Ltd., Sunnyvale, CA). Soil samples were collected using a JMC Backsaver probe (Clements Assoc., Newton, IA). Soil samples were sent to a commercial laboratory (AgSource Harris Lab., Lincoln, NE) for routine soil analysis, which included soil pH (by 1:1 soil/H₂O slurry), electrical conductivity (by saturated paste extraction), organic matter (OM) (by weight loss on ignition), NO₃⁻N (by cadmium reduction), P (by Olsen extraction), and particle-size distribution (by hydrometer) (Table 1).

Dairy animal manure was applied to the field each year in spring before planting using a tractor-drawn Hesston S320 (Hesston Corporation, Inc., Hesston, KS) manure spreader calibrated using the tarp calibration method (Davis and Meyer, 1999) (Fig. 1). Manure was incorporated into the soil on the same day as application using a Lely 300.35 rotary cultivator (Lely USA, Inc., Naples, FL). Manure samples were collected at the time of application and transported immediately to a commercial laboratory for analysis (Colorado Analytical Lab., Brighton, CO) of total N (by combustion, Test Methods for the Examination of Composting and Compost (TMECC) 04.02-D), P (total P TMECC 04.03-A), OM (by loss on ignition, TMECC 05.07-A), ash (by loss on ignition, TMECC 04.11-A) and C/N ratio (calculated) in manure (Table 2).

![Fig. 1. Map of the study site illustrating the treatments (synthetic N and manure) and management zones (UAN, urea ammonium nitrate).](image-url)
Grain Yield and Manure Management Strategies

The experimental strips in this study were 4.5 m wide (i.e., 6 rows of maize) and 540 m long spanning the entire length of the field across low, medium, and high MZs (Fig. 1). In addition, there were eight rows of buffer strips of maize giving experimental strips a distance of 5 m away from the borders. The management strategies were nested within MZs. The management strategies evaluated in this study were:

(i) Variable manure applications based on MZs using a constant yield goal (CYG) strategy. The CYG manure management strategy was suggested by the cooperating farmers in this project. In this strategy it is assumed that grain yield can be increased in low-yielding areas (low MZs) of the field to the same levels as that of high MZs by additional applications of manure to the low MZs. Hence, the expected yield is kept at a constant for the entire field.

(ii) Variable manure applications based on MZs using a variable yield goal (VYG) strategy. In the VYG management strategy, manure applications are based on the productivity potential of the MZs, high, medium, and low. Hence, a higher rate of manure is applied on the high MZs and a lower rate of manure is applied on the low MZs.

(iii) Variable commercial N fertilizer applications based on MZs using the VYG N management strategy. The N fertilizer rate was determined using Eq. [1] based on the soil samples acquired from within each MZ, with a unique yield goal for each MZ. In 2006, 2007, and 2008, yield goals for the VYG N fertilizer management strategy were 11.3, 10.0, and 8.8 Mg ha$^{-1}$ for the high, medium, and low-yielding MZs, respectively.

The manure rates in this study were selected to provide a wide range of application rates, encompassing rates equivalent to, lower, and higher than those used by farmers. Variable-rate manure applications were 22, 45, and 67 Mg ha$^{-1}$ for the VYG strategy and 67, 45, and 22 Mg ha$^{-1}$ for CYG strategy across the low, medium, and high MZs, respectively. The variable manure rates were independent of soil analysis results across MZs and crop response functions to manure application. Manure applications were made on experimental strips across MZs such that every manure rate passed through each MZ at least once (Fig. 1).

Application of N fertilizer in the VYG management strategy was based on the N-rate algorithm presented in Davis and Westfall (2009).

$$\text{N rate (kg ha}^{-1}) = 40 + \left[20 \text{EY (Mg ha}^{-1})\right] - \left[8 \times \text{avg. (mg kg}^{-1}) \text{NO}_3-N \text{in soil}\right] - \left[2.3 \times \text{EY (Mg ha}^{-1}) \times \% \text{OM}\right] - \text{other N credits (kg ha}^{-1})$$

where EY is the expected yield and OM is the organic matter. The N fertilizer was injected in the soil as undiluted Urea–NH$_4$NO$_3$ of 32% (UAN 32). Based on the yield goals and the residual N from variable sources, 0, 174, and 128 kg UAN ha$^{-1}$ was applied to the high, medium, and low zones, respectively (Fig. 1).

Maize was harvested in the month of November (contingent on weather conditions) using a Massey Ferguson combine.

### Table 1. Selected soil properties of soil samples acquired at 0- to 20- and 20- to 60-cm depth before planting in 2006 across the low, medium, and high management zones.

<table>
<thead>
<tr>
<th>Management zones</th>
<th>Sampling depth</th>
<th>Soil properties</th>
<th>Soil textural class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-20 cm</td>
<td>pH 7.4</td>
<td>EC† 0.9</td>
</tr>
<tr>
<td>High</td>
<td>20–60 cm</td>
<td>7.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Medium</td>
<td>0-20 cm</td>
<td>7.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Low</td>
<td>20–60 cm</td>
<td>7.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

† EC is soil electrical conductivity.
‡ OM is soil organic matter.
§ Soil nitrate nitrogen.
¶ Olsen soil phosphorus.

### Table 2. Characteristics of dairy cattle manure (DCM) applied in 2006, 2007, and 2008. Nutrients, organic matter, and ash contents are reported on a dry weight basis.

<table>
<thead>
<tr>
<th>Year and source</th>
<th>Total N g kg$^{-1}$</th>
<th>Total P mg kg$^{-1}$</th>
<th>Organic matter g kg$^{-1}$</th>
<th>Ash g kg$^{-1}$</th>
<th>Water content mg kg$^{-1}$</th>
<th>NO$_3$–N† mg kg$^{-1}$</th>
<th>NH$_4$–N‡ mg kg$^{-1}$</th>
<th>EC§ dS m$^{-1}$</th>
<th>pH§</th>
<th>C/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006 DCM</td>
<td>21.72</td>
<td>6.28</td>
<td>626</td>
<td>374</td>
<td>418</td>
<td>33.5</td>
<td>2111</td>
<td>7.83</td>
<td>7.08</td>
<td>15</td>
</tr>
<tr>
<td>2007 DCM</td>
<td>9.8</td>
<td>2.47</td>
<td>392</td>
<td>608</td>
<td>604</td>
<td>22.3</td>
<td>1171</td>
<td>4.75</td>
<td>7.25</td>
<td>21</td>
</tr>
<tr>
<td>2008 DCM</td>
<td>4.03</td>
<td>1.1</td>
<td>129</td>
<td>871</td>
<td>409</td>
<td>53.1</td>
<td>610.2</td>
<td>4.42</td>
<td>6.86</td>
<td>17</td>
</tr>
</tbody>
</table>

† NO$_3$–N is nitrate nitrogen.
‡ NH$_4$–N is ammonium nitrogen.
§ Electrical conductivity (EC) and pH were determined on 5:1 water/dry manure ratio.
harvester equipped with a batch yield and load monitor (HarvestMaster HM-500 Yield and Load Monitor, Logan, UT). Weight of the harvested grain was corrected to a moisture content of 155 g kg⁻¹ for determining grain yield.

**Apparent Nitrogen Budget**

The apparent N budgets were calculated for CYG and VYG manure management strategies for each MZ based on total N inputs from animal manure, residual soil N, and N supplied through organic matter. The total available pre-season N for each MZ was calculated as follows:

\[
(N_{\text{res}} + N_{\text{min}}) = N_{\text{tot}}
\]

where \(N_{\text{res}}\) is the residual soil NO₃–N before planting, \(N_{\text{min}}\) is the N mineralization in soil during the growing season (kg N ha⁻¹), and \(N_{\text{tot}}\) is the total available N (kg N ha⁻¹). The N mineralization rate used in this study was 35 kg ha⁻¹ for every 1% of soil organic matter (Waskom, 1997; Waskom and Davis, 1999).

Required N for yield goal was calculated using the N-rate algorithm presented in Eq. [1] (Davis and Westfall 2009) without including any contributions from NO₃–N and OM in soil. Recommended N was calculated by subtracting the pre-season soil-available N from the required N for yield goal. Total N applied in manure was calculated on a dry-matter basis. A credit of 100% from ammonium and nitrate N, and a credit of only 40% from organic N was estimated for Year 1. A credit of 20 and 10% of organic N was estimated for Year 2 and 3, respectively (Waskom and Davis, 1999). Estimate of excess N was calculated by subtracting N required for actual yield (based on Davis and Westfall, 2009) from total N applied in manure. The estimate of excess N represents a partial figure, as in this study, not all N sources and sinks were accounted for.

**Economic Analysis of Manure Management Strategies**

The economic analysis of this precision manure management study builds on a previous study conducted by Koch et al. (2004) on the economic analysis of nutrient management across MZs. To determine the levels of grain yield at which one can realize positive net returns at maize prices prevailing at the time of planting. No significant spatial auto-correlation was detected in the residuals from the analysis of variance for each management strategy and each year. Therefore, no further adjustments were needed in the analysis of the yield data. Limited irrigation, therefore, should have affected the treatments equally and without biasing the results of the study.

**Results and Discussion**

The climate in this region is classified as semiarid with mean annual temperatures of this region of 10.9, 9.9, and 9.5°C in 2006, 2007, and 2008, respectively. The 2006 mean annual temperature was almost 2°C above the long-term averages (8.9°C), making 2006 the second warmest recorded year in the state of Colorado since 1889 (Doesken, 2006). The cumulative growing degree days from planting to harvest for maize in 2006, 2007, and 2008 were 1449, 1590, and 1318°C, respectively. The months of June, July, and August in 2006 were under extreme drought conditions (Miskus, 2006). The cumulative precipitation from planting to harvest recorded during 2006, 2007, and 2008 from a nearby weather station were 76.7, 201.4, and 238.8 mm, respectively (Fig. 2). A significant portion of seasonal precipitation occurred in the month of August in 2007 and 2008 (31 and 47%, respectively) as compared with 10% in 2006. This amount of precipitation in 2007–2008 helped the crop in a positive manner because drought, or any form of environmental stress 2 wk before or after silking, can result in a large yield reduction (McWilliams et al., 1999). Whenever furrow irrigation was applied, water was distributed uniformly over the study area. Limited irrigation, therefore, should have affected the treatments equally and without biasing the results of the study.

**Effects of Spatial Auto-Correlation on the Outcome of the Experiment**

No significant spatial auto-correlation was detected in the residuals from the analysis of variance for each management strategy and each year. Therefore, no further adjustments were needed in the analysis of the yield data.

**Variable Yield Goal Manure Management Strategy**

Grain yield for VYG manure management strategies was significantly different (\(P \leq 0.05\)) between low and high MZs in 2006 and 2008 with high MZ producing higher yields than low MZ. The medium MZ was significantly different from both low and high management. While keeping the total cost of production constant, the price of maize or maize grain yield, which were the variables in the model, were changed incrementally. We simulated grain yields from 10.0 to 13.8 Mg ha⁻¹ under limited irrigation conditions. Likewise, we simulated maize grain prices from US$78.8 to US$295.5 Mg⁻¹ at increments of US$19.7 Mg⁻¹. These maize prices are typical of the U.S. maize trading market for the last 2 yr.
zones in 2006, but was not significantly different from high zone in 2008 (Fig. 3). It is logical to observe higher grain yield in high MZ areas of the field because of higher level of fertility (Table 1). In addition, the high MZ in this furrow-irrigated field happens to be in the lower elevation part of the field and acts as a natural sink for translocated N and P. This was also observed and reported by Mzuku et al. (2005). Mzuku et al. (2005) used the same method of zone delineation, observed significant differences in soil compaction, soil organic C, texture, and soil moisture among others between the low and the high zones. They reported that the medium zone was sometimes significantly different from the low zone, sometimes significantly different from the high zone, and sometimes significantly different from both low and high zones, which may be attributed to the transitional characteristic of the medium zone. Across all MZs, there was a substantial increase in grain yield in 2007 and 2008 as compared with the drought-affected growing season of 2006 (Fig. 3). Inman et al. (2008) measured yield in this particular field for the 2002 and 2003 growing seasons across all three zones using uniform N fertilization and irrigation. Total precipitation (from November to October) for these years, as measured by the local weather station, was 165 and 277 mm for 2002 and 2003, respectively. The yield reported by Inman et al. (2008) was 8.1, 9.3, and 9.1 Mg ha$^{-1}$ in 2002 for low, medium, and high MZs, respectively, and was 11.0, 11.9, and 12.4 Mg ha$^{-1}$ in 2003 for low, medium, and high MZs, respectively. In 2002, yield was not significantly different across zones whereas yield from 2003 was significantly different between each zone. It is important to point out that considering agronomic differences in grain yield is sometimes either equally important or perhaps more important than statistical significance alone. Studies involving limited number of field observations may not show statistical difference, even when mean difference makes logical agronomic significance due to low statistical power (for example, mean difference of 1.0 Mg ha$^{-1}$ between treatments showing no statistical significance). Spatial auto-correlation in the data set further reduces the statistical power (Type I error) of the experimental design. In the case of spatial auto-correlation, classical ANOVA should not be performed because the model’s residuals are not independent, thus not meeting the assumption of independence. For an experimental design such as the one in this study, it is therefore important to use spatial statistical methodologies to correctly verify the presence or absence of spatial auto-correlation in the field observations and use the appropriate statistical analysis. In this study, residuals of the ANOVA were not spatially auto-correlated, and thus, classical ANOVA was used for analysis. Severe drought in the months of June, July, and August during the growing season of 2006 could have had a negative impact on grain yield; for example, 2.5 Mg ha$^{-1}$ on low MZ in 2006 within VYG manure management strategy. The months of June, July, and August are considered the critical months for N mineralization from manure in Colorado (Waskom and Davis, 1999). Koelsch (2005) and Bacon (1995) reported that soils that are dry throughout most of the growing season have low mineralization and nitrification rates. However, microbial activities in manure-amended soils that are dry during most of the growing season are reported to be greatest immediately after rainfall or irrigation events, as may be the case in the present study (Koelsch, 2005). This observation can be linked to increased grain yield from manure application in 2007 when weather and precipitation were close to normal (Fig. 2). The grain yield increased from 2006 to 2007 and then decreased in 2008. Although this decrease in grain yield may partially be attributed to a hail storm that occurred at the V17 maize crop growth in 2008, which perhaps negatively impacted the grain yield across all MZs and may be the cause of observed low grain yields as compared to previous year of 2007. However, a decrease in grain yield was not observed on VYG N fertilizer management strategy in the same field, showing that hail was not a primary cause of significant decrease ($P \leq 0.05$) in grain yields on manure management strategies. A complete assessment of nutrient balance and review of literature indicates that repeated application of manure can negatively impact crop grain yield.

**Constant Yield Goal Manure Management Strategy**

Under the CYG manure management strategy, grain yield for the low MZ was significantly different and higher than medium and high MZs in 2006 (Fig. 3). Historically,
areas classified as low MZs generally produce lower grain yields compared with high MZs when nutrients are applied uniformly across an agricultural field (Inman et al., 2005; Hornung et al., 2006), but with the CYG manure management strategy, low MZs produced 2 Mg ha\(^{-1}\) grain yield higher than that of the high MZs in the first year of this study (Fig. 3). In two out of 3 yr (i.e., 2006 and 2008), higher applications of manure on the low MZs increased grain yield levels to a level higher than those of the high MZs (\(P \leq 0.05\)). The higher grain yields on the low MZ than that of the high MZ in 2008 can be associated with increased precipitations in this limited irrigation study that potentially promoted N mineralization and nitrification (Fig. 2; Bacon, 1995).

**Variable Yield Goal Nitrogen Fertilizer Management Strategy**

In the first year (2006) of VYG commercial N fertilizer management strategy, grain yields were higher than the yields of CYG and VYG manure management strategies (Fig. 3). This was expected as animal manure was applied in the spring before planting and manure needs time to mineralize before nutrients are released for crop availability. Adequate environmental conditions, such as adequate soil moisture for effective N mineralization, did not prevail in 2006 during the crop growing season. In 2007, all manure management strategies produced grain yields that were equivalent to that of VYG N fertilizer management strategy. But in 2008, grain yields declined for manure management strategies whereas the VYG N fertilizer

---

Fig. 3. Mean grain yield across low, medium, and high management zones for variable yield goal manure, constant yield goal manure, and variable yield goal N management strategies under limited irrigation conditions. Within a year, bars with different letters are significantly different at \(P \leq 0.05\) level of significance as per Tukey-Kramer method.
management strategy produced higher grain yields than VYG and CYG manure management strategies.

Comparing the three management strategies (two manure and one N fertilizer), while manure application may have potential to improve grain yields of low producing areas of the field, it does have agronomic and environmental limitations. Although manure management strategies failed to positively impact grain yield under limited irrigation, N fertilizer management strategy succeeded to continuously improve grain yield. Perhaps there is a 2-yr threshold for using weight-based manure management strategies for maize grain yield across MZs in the Colorado environment, beyond which a positive impact on grain yield will not be realized. Therefore, it may be logical to combine manure management with N fertilizer management such that manure applications continuously impact soil properties/quality slowly over time, while in-season N fertilizer management provides enough impetus to boost the grain yield of crops each year without negatively impacting the environment and grain yield. One source of nutrient, either manure or N fertilizer alone, may not optimize environmental and agronomic goals needed for sustainability of crop production.

**Apparent Nitrogen Budget**

The goal of determining the apparent N budget was to evaluate the amount of N that could be supplemented through animal manure application for enhancing maize grain yield.

When the apparent N budget was calculated, it was used to assess the potential damage to the environment as a result of over application of nutrients from manure. The excess N ranged from –126 (a deficit) to 223 kg ha\(^{-1}\) and from –122 to 233 kg ha\(^{-1}\) across the MZs for the VYG and the CYG manure management strategies, respectively (Table 3). On average across 3 yr for both manure management strategies, there was an excess of about 21 kg N ha\(^{-1}\). The highest value for excess N was observed in 2006, when the manure used contained the highest levels of N (Table 2). In addition, year 2006 was a dry year and it is likely that mineralization of organic N was lower than 40%, thus resulting in lower yield and overestimated excess N. The N deficit observed in 2007, a wet year, along with the higher yield may be the result of manure organic N accumulated from 2006 resulting in lower yield and overestimated excess N. The N content levels in manure were reflected in excess N values of CYG strategy (i.e., where high manure rates were applied). Excess N was systematically observed every year in the high zones for VYG strategy and in low zones of CYG strategy (i.e., where high manure rates were applied). The N content levels in manure before developing prescription to curb excess N applications.

**Table 3.** Apparent N budget for variable and constant yield goal manure management strategies on limited irrigation maize grown in 2006, 2007, and 2008 across low, medium, and high management zones.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Soil available N in preseason†</th>
<th>Yield goal</th>
<th>Required N for yield goal‡</th>
<th>Recommended N§</th>
<th>Total N applied in manure¶</th>
<th>Actual yield</th>
<th>Estimate of excess N (loss)¶#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha(^{-1})</td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
<td>Mg ha(^{-1})</td>
<td>kg ha(^{-1})</td>
</tr>
<tr>
<td>2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>70</td>
<td>8.8</td>
<td>216</td>
<td>146</td>
<td>128</td>
<td>2.5</td>
<td>38</td>
</tr>
<tr>
<td>Medium</td>
<td>98</td>
<td>10</td>
<td>240</td>
<td>142</td>
<td>261</td>
<td>4.6</td>
<td>129</td>
</tr>
<tr>
<td>High</td>
<td>78</td>
<td>11.3</td>
<td>266</td>
<td>188</td>
<td>389</td>
<td>6.3</td>
<td>223</td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>80</td>
<td>8.8</td>
<td>216</td>
<td>136</td>
<td>91</td>
<td>8.8</td>
<td>–126</td>
</tr>
<tr>
<td>Medium</td>
<td>78</td>
<td>10</td>
<td>240</td>
<td>162</td>
<td>185</td>
<td>8.1</td>
<td>–17</td>
</tr>
<tr>
<td>High</td>
<td>84</td>
<td>11.3</td>
<td>266</td>
<td>182</td>
<td>276</td>
<td>8.3</td>
<td>70</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>77</td>
<td>8.8</td>
<td>216</td>
<td>139</td>
<td>66</td>
<td>5.9</td>
<td>–92</td>
</tr>
<tr>
<td>Medium</td>
<td>72</td>
<td>10</td>
<td>240</td>
<td>168</td>
<td>135</td>
<td>7.5</td>
<td>–55</td>
</tr>
<tr>
<td>High</td>
<td>76</td>
<td>11.3</td>
<td>266</td>
<td>190</td>
<td>202</td>
<td>6.9</td>
<td>24</td>
</tr>
</tbody>
</table>

‡ Organic matter was given 35 kg ha\(^{-1}\) credit by percent point (Waskom and Davis, 1999).

§ Required N was calculated using Davis and Westfall (2009) algorithm, giving zero credit to NO\(_3\)-N and OM.

¶ Recommended N is the required N minus N credits available in soil.

# N applied in manure was computed on a dry matter basis, giving 40% credit to organic N in Year 1, 20% in Year 2, and 10% in Year 3 (Waskom and Davis, 1999).

When the apparent N budget was calculated, it was used to assess the potential damage to the environment as a result of over application of nutrients from manure. The excess N ranged from –126 (a deficit) to 223 kg ha\(^{-1}\) and from –122 to 233 kg ha\(^{-1}\) across the MZs for the VYG and the CYG manure management strategies, respectively (Table 3). On average across 3 yr for both manure management strategies, there was an excess of about 21 kg N ha\(^{-1}\). The highest value for excess N was observed in 2006, when the manure used contained the highest levels of N (Table 2). In addition, year 2006 was a dry year and it is likely that mineralization of organic N was lower than 40%, thus resulting in lower yield and overestimated excess N. The N deficit observed in 2007, a wet year, along with the higher yield may be the result of manure organic N accumulated from 2006 that mineralized at rates higher than the estimated 20% for the second year (i.e., 2007). Excess N was systematically observed every year in the high zones for VYG strategy and in low zones of CYG strategy (i.e., where high manure rates were applied). The N content levels in manure before developing prescription to curb excess N applications.

Excess N [i.e., rates >50 kg N ha\(^{-1}\) over the agronomic N rates (Paris-Convention for the Prevention of Marine Pollution, 1993)] was observed three times in the VYG strategy (i.e.,...
Table 4. Net return sensitivity corresponding to increases and decreases in maize price and grain yield for variable yield goal manure management strategy on low, medium, and high zones under limited irrigation conditions.

<table>
<thead>
<tr>
<th>Maize price, US$ Mg⁻¹</th>
<th>Net return, US$ ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>Low zone</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg ha⁻¹</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>–79.6†</td>
</tr>
<tr>
<td>10.7</td>
<td>–30.2</td>
</tr>
<tr>
<td>11.3</td>
<td>19.2</td>
</tr>
<tr>
<td>11.9</td>
<td>68.6</td>
</tr>
<tr>
<td>12.5</td>
<td>118</td>
</tr>
<tr>
<td>13.2</td>
<td>167.4</td>
</tr>
<tr>
<td>13.8</td>
<td>216.8</td>
</tr>
</tbody>
</table>

† Bold net returns indicate a financial loss based on produced maize grain yield and associated maize price.

for medium and high zones in 2006 and high zone of 2007† and three times for the CYG strategy (i.e., for low zone in 2006 and 2007 and for medium zone in 2006) (Table 3). The excess amount of N observed for the CYG manure management strategy on the low-yielding MZs in 2006 and 2007 may be related to the high amount of manure applied compared with the productivity potential of these zones, but also to the high percentage of N content in manure for these years. Generally, low MZs have been reported to be characterized by lower productivity potential and lower nutrient and water holding capacity as opposed to high MZs (Mzuku et al., 2005; Hornung et al., 2006). This excess N could potentially degrade the environment through leaching of NO₃⁻, should applications of manure be continued on this field.

Constant yield goal manure management strategy was implemented to enhance maize grain yield of historically unproductive or low-yielding MZs. The surplus N loaded on the CYG strategy was because of the higher amount of manure applications that were applied on low MZ of CYG strategy. Although the purpose of enhancing maize grain yield of low MZ with animal manure was achieved to some extent (Fig. 3), the CYG manure management strategy had more excess N on the low-yielding MZs compared with the VYG manure management strategy (Table 3). This indicates that CYG manure management strategy has a potential to negatively impact the environment through excessive N in the soil.

**Economic Analysis**

Massey and Payne (2013) reported that dollars may not be the only metric for discussing costs; however, in this precision manure management study, all costs and revenues have been reported in dollars for simplicity. Table 4 shows the net sensitivity corresponding to increases and decreases in maize price and grain yield for VYG manure management strategy on low, medium, and high MZs under limited irrigation conditions. The net returns to the land and management for maize grain yield were based on a maize market price of US$137.9 Mg⁻¹ (prevailing in October 2008). The grain yield and prices associated with manure were directly proportional to the net return to the land and management (Table 4). Over a 3-yr period, this study averaged maize grain yields of 6.5 Mg ha⁻¹ on VYG manure management strategy. Based on the economic analysis, the study indicates that maize producers can realize a positive net return by marketing maize at US$118.2 Mg⁻¹ or above. However, this price is below the market price that was prevailing in October 2008, which made the VYG approach uneconomically viable at that time (Table 4).

Variable-rate application of manure based on constant and VYG nutrient management strategies under limited irrigation was profitable over time based on net returns to the land and management. In 2006, under the VYG manure management strategy, there was an economic loss, and 2007 averaged a net return to land and management of US$137.9 Mg⁻¹ (prevailing in October 2008). The high-yielding MZs within VYG manure management strategy produced higher grain yield than low and medium yielding MZs, but the net returns were negative because of the total costs for production associated manure transportation and application on high MZs. A similar situation happened in the low-yielding MZ of the CYG manure management strategy where an economic loss was reported, whereas grain yield was higher than that of the medium and high MZs in all 3 yr (Fig. 3; Table 5). Nevertheless, CYG and VYG manure management strategies realized a positive net return to land and management in 2007.
strategy. Koch (2003) reported negative net returns to land and management. This could be attributed to the fact that Koch (2003) performed economic analysis at the then prevailing maize price of US$78.8 Mg⁻¹ vs. US$137.9 Mg⁻¹, the current maize price used to estimate net dollar returns for this study (Table 4).

**CONCLUSIONS**

The underlying hypothesis of this study was that maize yields could be increased in low-producing areas of the field. Maize grain yield of the low-yielding MZs were enhanced with the CYG manure management strategy; however, the apparent N budget revealed that this approach may result in excess or deficit N and pose potential threat for nitrate leaching. Second, the CYG manure management strategy was not financially profitable due to costs associated with animal manure transportation (distance), application, and harvesting on low MZs. Therefore, application of animal manure based on CYG strategy at rates equivalent to the ones used in the study, is not an economic or environmentally sensible strategy for manure input. Agriculture today is under pressure to meet environmental targets and, therefore, the agronomic and economic benefits against environmental burdens must be weighted. The results suggest that both a VYG and CYG manure management strategy be used in conjunction with N fertilizers to meet crop N requirements at early maize growth stages. For profitable crop production and environmental quality under irrigated conditions, it is suggested not to exceed two consecutive manure applications when manure mineral N content is high and N fertilizer is not used in conjunction with CYG manure management strategy. The key to precision manure management is to find a balance between an economical and environmentally sound manure management strategy that is capable of improving soil fertility status of low-producing areas of the field and consequently enhancing grain yield across MZs.

**REFERENCES**


Lambert, D.M., G.L. Malzer, and J. Lowenberg-DeBoer. 2003. A systems approach -
Khosla, R., D. Inman, D.G. Westfall, R.M. Reich, M. Frasier, M. Mzuku, B. -
Inman, D., R. Khosla, R. Reich, and D.G. Westfall. 2008. Normalized difference -
Franzen, D.W., and T.R. Peck. 1995. Field soil sampling density for variable rate -
Hornung, A., R. Khosla, R. Reich, D. Inman, and D. Westfall. 2006. Compari -
Koch, B. 2003. Economic feasibility of variable-rate nitrogen application utiliz -
Lawes, J.B., J.H. Gilbert, and R. Warrington. 1882. On the amount and comp -